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Seasonal Manure Application Timing and Storage Effects on Field- and Watershed-Level Phosphorus Losses

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Abstract

Timing of manure application to agricultural soils remains a contentious topic in nutrient management planning, particularly with regard to impacts on nutrient loss in runoff and downstream water quality. We evaluated the effects of seasonal manure application and associated manure storage capacity on phosphorus (P) losses at both field and watershed scales over an 11-yr period, using long-term observed data and an upgraded, variable-source water quality model called Topo-SWAT. At the field level, despite variation in location and crop management, manure applications throughout fall and winter increased annual total P losses by 12 to 16% and dissolved P by 19 to 40% as compared with spring. Among all field-level scenarios, total P loss was substantially reduced through better site targeting (by 48–64%), improving winter soil cover (by 25–46%), and reducing manure application rates (by 1–23%). At the watershed level, a scenario simulating 12 mo of manure storage (all watershed manure applied in spring) reduced dissolved P loss by 5% and total P loss by 2% but resulted in greater P concentrations peaks compared with scenarios simulating 6 mo (fall-spring application) or 3 mo storage (four-season application). Watershed-level impacts are complicated by aggregate effects, both spatial and temporal, of manure storage capacity on variables such as manure application rate and timing, and complexities of field and management. This comparison of the consequences of different manure storage capacities demonstrated a tradeoff between reducing annual P loss through a few high-concentration runoff events and increasing the frequency of low peaks but also increasing the annual loss.

Core Ideas

- Spring manure application had less field-level P loss than fall or winter application.
- The impact of application timing depended on precipitation and field characteristics.
- Changes in manure storage capacity did not significantly affect annual watershed P loss.
- Twelve-month storage barely reduced P loads but created greater P concentration peaks.
- Optimizing site targeting and soil cover is needed for all seasonal applications.

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Land application of livestock manure contributes to phosphorus (P) loss in surface runoff and is therefore a concern to water quality (Eghball and Gilley, 1999; Kleinman et al., 2015). Ideally, manure is applied at times when nutrients can be best used by crops, in places where soils are not P saturated, and under conditions where offsite nutrient losses are minimized (Ehmke, 2012; IPNI, 2014). Availability of long-term storage would provide options for farmers to apply manure at selective timings. However, on-farm manure storage capacities are not always available on small farms lacking investments in equipment and labor, particularly in the US Northeast, where 45% of all operations farm <800 ha and median farm size is <40 ha (NASS, 2012). Dou et al. (2001) found that many dairy farms in Pennsylvania had limited, if any, permanent storage facilities and land applied manure on a daily to monthly frequency. Despite the age of that survey, manure storage trends in Pennsylvania have not changed dramatically.

Winter manure applications, which experience minimal, if any, nutrient crop uptake, often coincide with active transport pathways created by frozen and water-saturated soils (Fleming and Fraser, 2000; Srinivasan et al., 2006; Williams et al., 2011; Vadas et al., 2017). Due to the resulting high risks for nutrient loss, many countries constrain or even ban winter manure applications (Webb et al., 2012). However, prohibiting manure applications over winter means requiring at least a 6-mo storage facility on every livestock farm. As compared with daily or monthly haul, such prohibition necessitates increasing application rates in the fall when crop uptake is minimal and in the spring when many areas face "first flush" risks from large runoff events.

Although manure application during the fall, when soils are unfrozen, allows more opportunity for infiltration and volatilization of nutrients before offsite runoff loss than in the winter, when soils may be frozen, considerable nutrient loss after fall application was reported. Within a corn (*Zea mays* L.) production

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Abbreviations: DM, dry matter; HRUs, hydrologic response units; NSE, Nash-Sutcliffe efficiency; PBIAS, percent bias; RSR, ratio of the root mean square error to the standard deviation of observed data; SWAT, Soil and Water Assessment Tool; TI, topographic index; WEP, water-extractable phosphorus.

system, for example, Liu et al. (2016) found that short-term total P and total nitrogen (N) surface losses doubled when poultry litter was broadcast in fall with a shorter interval between litter application and rainfall compared with spring application. Fall application of liquid manure also elevated P and nitrate concentrations in drainage from field plots (van Es et al., 2004, 2006; Sørensen and Rubæk, 2012). Despite reported advantages by these field-level studies of spring application reducing nutrient losses, as compared with fall application, concerns arise when weather patterns create cold, wet winters or springs. Strong seasonal cycles and orographic effects in the US Northeast and similar regions routinely result in extreme storm events and flash flooding during early spring (Kunkel et al., 2013). Additionally, short time intervals between manure application and rainfall in spring can lead to significant nutrient runoff losses (Smith et al., 2007; Vadas et al., 2007; Komiskey et al., 2011). Such losses, particularly when coinciding with extreme precipitation or flooding events, can be detrimental to stream ecology and downstream water quality (Wang et al., 2007; Griffith et al., 2009).

Seasonal restrictions on land application of manure are at the center of debate in the Chesapeake Bay Watershed, where six US states are required to address nutrient load reductions by 2025 (USEPA, 2010). Livestock in the Bay Watershed produce 36 million Mg of animal manure annually, contributing an estimated 20 and 30% of the total N and P loadings, respectively, to the Bay (Chesapeake Bay Program, 2010). Within the Bay states, there are notable differences in seasonal policies for nutrient management. For example, Maryland prohibits winter manure application from early November through February for farms with >50 animal units (MD-DA, 2012). In contrast, Pennsylvania restricts winter manure application on the basis of site-specific factors such as distance from stream, existence of ground cover, and percentage slope (PA-DEP, 2011a).

In this study, we used the Topo-SWAT model (Easton et al., 2008; Fuka, 2013), a variation of the conventional Soil and Water Assessment Tool (SWAT2012; Arnold et al., 1993, 2015), to assess effects of manure management on P loss at both field and watershed scales. Objectives were: (i) to examine effects of seasonal application timing (spring, fall, or winter) on field-level P losses under various conditions of weather, crop management, and topography; (ii) to investigate differences in manure application timing associated with 3-, 6-, and 12-mo manure storage capacities on watershed P dynamics; and (iii) to identify conservation practices for minimizing P loss associated with winter manure applications.

Materials and Methods

Study Watershed

The 7.3-km^2 study watershed, WE38, an upland agricultural subwatershed of the Chesapeake Bay Watershed, is located in south-central Pennsylvania (Fig. 1a). Its climate is temperate and humid, with 1065 mm mean annual precipitation (Buda et al., 2011b). Elevations range from 216 to 503 m asl (mean: 286 m). Land use is 40% forest and 55% agriculture (Bryant et al., 2011). Soils derive from fine sandstones and shales, ranging from well-drained Dystrudepts and Hapludults to poorly drained Fragiudults and Fragiudalfs, primarily with silt loam surface horizons derived from loess (Soil Survey Staff, 2013). Hydrology is characterized by restrictive infiltration and promoted subsurface lateral flow due to substantial fragic soil expanses at depths of 0.5 to 1.0 m in lower landscape positions (Gburek et al., 2006; Buda et al., 2009). At the WE38 outlet, stream flow depths have been recorded at 5-min intervals since 1968 (Buda et al., 2011a); orthophosphate concentrations have been obtained by grab sampling about thrice weekly since 1976, typically during baseflow (Church et al., 2011). Detailed information on field management, including crop rotations, fertilization, tillage, and planting and harvesting operations, have been recorded since 1999 (Veith et al., 2015) and were used to define unique rotations for each field within the Topo-SWAT simulation. Typically, corn is cultivated continuously or rotated with soybean [*Glycine max* (L.) Merr.] and small grain crops (wheat [*Triticum aestivum* L.], barley [*Hordeum vulgare* L.], and rye [*Secale cereale* L.]), with small grain crops also used as non-harvested cover crops in some rotations. In high-slope areas, fields are narrow and row crops alternate with hay or alfalfa (*Medicago sativa* L.) so that the hillslope becomes strip cropped. Although chisel disking and no-till cropping are used on several of the farms and contour cropping is common, others still use moldboard plow tillage. Overall, winter cover cropping has remained infrequent throughout the study period.

WE38 is in a region of low animal intensity (Northumberland County Conservation District, 2014). From 2000 to 2010, amendments of cattle, swine, and poultry manure accounted for roughly 20% of total N and 30% of total P applications in the watershed, whereas chemical fertilizers made up the rest of the nutrient applications (Supplemental Table S1). Manure was surface applied to roughly 20% of the total cropland, with tillage incorporation of spring and fall applications, but no incorporation for winter application. Chemical fertilizers were predominately surface applied in spring, with some application to winter grain crops, to meet agronomic needs. About 50% of manure was applied to corn residue during late fall and winter months to meet future crop needs while reducing stored volume.

Model Setup and Parameterization

The semi-process-based SWAT model is used worldwide to assess effects of agricultural management practices on water quality at field (Gitau et al., 2004; Veith et al., 2008) and watershed scales (Gitau and Veith, 2006; Gassman et al., 2007; Ullrich and Volk, 2009). The characteristics of SWAT to simulate nutrient transport from individual hydrologic response units (HRUs), which are unique combinations of soil, slope, and land management at the subfield level, enhance its ability for field-level simulations (Veith et al., 2008). In this study, Topo-SWAT was used to ensure representation of the variable source area hydrology within WE38 while simulating daily nutrient losses (Easton et al., 2008; Fuka, 2013).

Topo-SWAT uses topographic indices (TI) to represent the propensity of a landscape unit to soil water saturation and subsequent runoff generation by combining upslope contributing area (α) and local slope gradient ($\tan\beta$) [i.e., $TI = \ln(\alpha/\tan\beta)$]. Topo-SWAT reclassifies the watershed into 10 equal-area wetness classes ranging from the driest class (1 = lowest runoff potential) to the wettest class (10 = highest runoff potential). Specifically, we delineated watershed boundary and drainage network based on a 10-m digital elevation model (DEM) and created six subbasins by specifying subbasin outlets at the locations of the

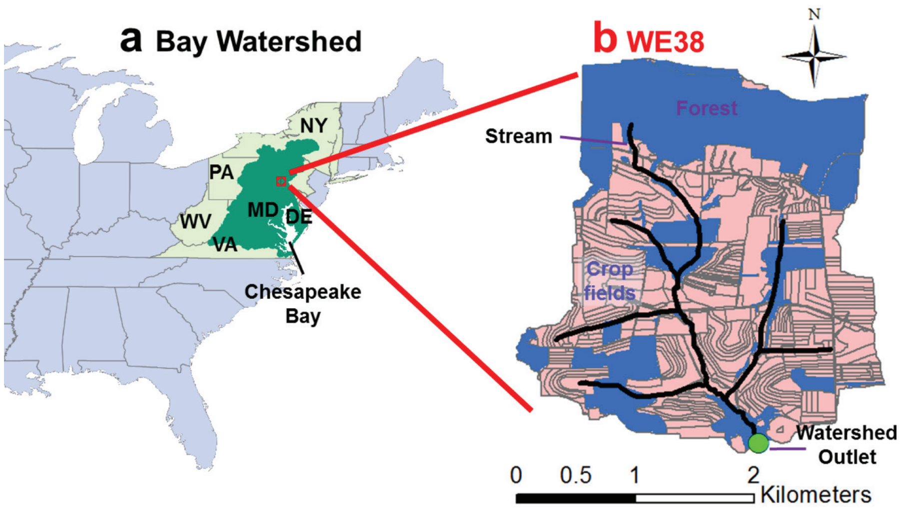


Fig. 1. The 730-ha WE38 watershed, located in the Chesapeake Bay Watershed, was used to study seasonal manure application timing and storage effects on field- and watershed-level P losses. (a) Location of WE38 and the Chesapeake Bay Watershed in the northeastern United States, and (b) land uses, streams, and main outlet of WE38.

monitoring stream flumes. When creating HRUs, we overlaid a TI layer with the FAO-UNESCO (United Nations Educational, Scientific and Cultural Organization) Digital Soil Map of the World layer (FAO, 2007) instead of conventional SWAT slope classes and soil layers (Collick et al., 2015; Amin et al., 2017).

Phosphorus cycling was simulated using equations (SWAT Revision 637) developed by Vadas et al. (2007, 2012) with in-house code corrections by coauthors Veith and Collick (referred to as new P routines hereafter). Compared with the previous P routines, the new P routines are advantageous in simulating manure applied on the soil surface and P loss directly from manure. In brief, surface-applied manure is partitioned into four interactive pools: water-extractable inorganic P and organic P, which are leachable by rain, and stable inorganic P and stable organic P, which are not leachable by rain but can be transformed to water-extractable P pools in the processes of decomposition and mineralization. Moreover, the new P routines allow infiltration of manure that has a dry matter content of <15% into the soil layer below the effective depth of interaction at the time of application (i.e., 60% of manure infiltrating and 40% remaining on the soil surface). Owing to the improvement in simulating surface manure, the new P routines greatly improve sensitivity of P transport in response to manure management practices including source, rate, timing, and placement compared with previous routines (Collick et al., 2016).

Using daily precipitation, temperature, relative humidity, photosynthetically active radiation, and wind speed monitored in the watershed, we simulated streamflow and P transport from 2000 to 2010 for both field-level and watershed-level simulations. Daily stream flow at the watershed outlet was used for calibration and validation from 2000 to 2004 and 2005 to 2010, respectively. Orthophosphate P from triweekly grab samples during baseflow was used to adjust P simulation parameters (Supplemental Tables S2 and S3).

Field-Level Simulations

To obtain a comprehensive analysis of seasonal manure application timing effects on field-level P loss, we investigated a total of 54 scenarios to represent conditions with various site-specific factors and management practices (Table 1). Our simulation scenarios were designed based on the Pennsylvania guidelines for winter manure management (PA-DEP, 2011a). Specifically, Pennsylvania guidelines restrict winter application to sites with a 10-m-width permanent vegetated buffer or with a minimum application setback of 30 m from environmentally sensitive areas. Manure can only be applied on fields with <15% slope and with at least 25% crop residue cover or an actively growing cover crop. The maximum allowable winter application rate is 47 m^3 ha^{-1} for liquid manure.

We selected three fields in the WE38 watershed with varying proximities to streams (near, distant, and distant), slope gradients (4, 4, and 16%), and average TI classes (10, 4.7, and 5.5). Soil cover outside of the primary growing season was either minimal stubble or substantial residue in the continuous corn system, or substantial residue cover plus use of a rye cover crop in corn and soybean rotation, respectively (Table 1). In both cropping systems, a generic conservation tillage (a mixing depth of 0.1 m and mixing efficiency of 0.25) was used prior to planting corn or soybean in spring. Dairy slurry was surface applied to corn only, at the conventional average rate in WE38 or the maximum allowable rate for winter application in Pennsylvania. The dairy slurry contained 10% dry matter (DM) with 0.8% total P in DM and a water-extractable P (WEP) to total P ratio of 0.6. For each field location and management combination, three slurry application scenarios were simulated: spring application, fall application, or winter application. To represent winter application and enable parallel comparisons between different application timings, manure was not incorporated in any of the field-level scenarios. Seasons were based on the standard water year, as defined by USGS (2016). Slurry application was conducted on days without precipitation and for which trace or no precipitation (<5 mm) occurred on the previous or following day.

Watershed-Level Simulations

At the watershed level, four scenarios were simulated with Topo-SWAT: baseline (status quo across watershed), spring application (12 mo storage), fall-spring application (6 mo storage), and four-season application (3 mo storage). These scenarios simulated the watershed-wide impact of when and where manure was applied to accommodate manure storage capacities while still meeting Pennsylvania manure spreading guidelines (PA-DEP, 2011a). The baseline scenario was based on farmers' records of form, timing, rate, and location of manure and fertilizer applications (Veith et al., 2015). This scenario reflected the range of existing manure storage capacities, and current application practices, among farms. Specifically, the manures included dairy (DM: 10%; total P: 0.8% DM; WEP/total P: 0.6), beef (DM: 40%; total P: 1.1% DM; WEP/total P: 0.43), swine (DM:

12%; total P: 1.6% DM; WEP/total P: 0.37), and poultry layer (DM: 60%; total P: 1.9% DM; WEP/total P: 0.2).

Three scenarios were derived from the baseline scenario to simulate the effect of changing on-farm manure storage capacity by reallocating manure across seasons and fields as needed to meet the storage restriction under Pennsylvania guidelines without changing manure form, application rate, or application method. In the 12-mo storage scenario, all manure generated in the watershed was applied in spring. In the 6-mo storage scenario, half of the watershed manure was applied in spring and half in fall. In the 3-mo storage scenario, all manure generated was evenly divided into fall, winter, spring, and summer applications. Ranges of specific dates for manure applications are summarized in Table 2. As in the field-level simulations, manure was only applied on days without precipitation and for which trace or no precipitation (<5 mm) occurred on the previous or following day.

To the extent possible in the three manure storage capacity scenarios, manure was applied to the fields that were actually manured by farmers, with a few exceptions where manure and fertilizer were exchanged between some crops. Specifically, some manure fall applied to winter crops in the baseline scenario was replaced with fertilizer, and the manure was spring applied instead to corn in the 12-mo storage scenario. Also, because manure was summer applied to only a few fields in the baseline, the 3-mo storage scenario required some manure that had been spring or winter applied in the baseline to instead be summer applied to grassed or fallow fields.

Data Analysis

Watershed-level calibration and validation of streamflow were evaluated visually by daily hydrography in addition to calculating Nash-Sutcliffe efficiency (NSE; Nash and Sutcliffe, 1970; Moriasi et al., 2007), coefficient of determination (r^2), percent bias (PBIAS; Gupta et al., 1999), and ratio of the RMSE to the standard deviation of observed data (RSR; Singh et al., 2004). Simulated dissolved P losses were compared with baseflow P losses measured in grab samples. For field-level P loss, data were square-root transformed, and a complete, general linear model with SAS (Version 9.2; SAS Institute, 2000) was used to assess significant ($\alpha = 0.05$) effects of annual precipitation amounts, field location and slope, soil cover practices, manure application rate and timing, and their interactions. To control for differences due to crop type, only results from the 5 of 11 simulated years in which corn was grown were analyzed. Those 5 yr were divided into two groups according to annual precipitation: high (1230 $\pm$ 66 mm, $n = 2$) and low (900 $\pm$ 54 mm, $n = 3$). Application

Table 1. Field-level P losses simulated by Topo-SWAT for a total of 54 scenarios comprising the described field characteristics, crop management, and manure application practices.

Category	Item†	Characteristics and model applications‡
Field	STRM	0.51 ha; 2 HRUs; along stream, <30 m; gentle slope, area-weighted slope 4%, TI 10.
	FLAT	0.87 ha; 9 HRUs; away from stream, >100 m; gentle slope, area-weighted slope 4%, TI 4.7.
	SLOP	0.56 ha; 9 HRUs; away from stream, >100 m; steeper slope, area-weighted slope 16%, TI 5.5.
Crop management	Minimal cover	Continuous corn silage, harvested with little residue remaining for soil cover.
	Corn residue	Continuous corn grain, harvested with substantial crop residue remaining for soil cover.
	Residue + cover crop	Corn grain and soybean rotation (manure applied to corn only); corn crop residue remaining as cover, plus a winter rye cover crop after both corn and soybean crops.
Manure rate	Conventional	Farmers' average rate of dairy slurry in WE38: 2.5 Mg ha^{-1} (dry weight), supplying 95 kg N ha^{-1} and 20 kg P ha^{-1}. Additional chemical starter of 35 kg N ha^{-1} and 6 kg P ha^{-1} applied to corn.
	Maximum	Maximum rate allowed for winter slurry application in Pennsylvania: 3.75 Mg ha^{-1} (dry weight), supplying 143 kg N ha^{-1} and 29 kg P ha^{-1}. An additional of 10 kg N ha^{-1} and 6 kg P ha^{-1} applied as a chemical starter to corn.
Application timing§	Spring	Between 16 Apr. and 15 May
	Fall	Between 16 Oct. and 15 Nov.
	Winter	Between 16 Jan. and 15 Feb.

† STRM, the field along the stream; FLAT, the gently sloped field away from the stream; SLOP, the steeper-sloped field away from the stream.

‡ HRUs, hydrologic response units; TI, topographic index.

§ All slurries were surface applied. Specific dates of application were adjusted, if needed, to exclude rainy and snowy days or days with considerable precipitation before or after.

Table 2. Manure application timing for the four manure storage capacity scenarios simulated at the watershed level for WE38 using Topo-SWAT. Seasons are based on the water year.

Scenarios	Fall			Winter			Spring			Summer		
	Oct.	Nov.	Dec.	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.
Baseline	m† m	m m	m m	m m	m m	m m	m m	m m	m m	m m	m m	m m
	Actual application timing reflects the range of storage capacities among farms											
12 mo (spring application)							m	m				
	All manure applied in spring, reflecting 12-mo capacities across watershed											
6 mo (fall-spring application)	m	m					m	m				
	1/2 of all manure applied each in fall and spring (i.e., 6 mo storage)											
3 mo (four-season application)	m	m		m	m		m	m		m	m	
	1/4 of all manure applied each in fall, winter, spring, and summer (i.e., 3 mo storage)											

† m represents manure.

timing effects among individual fields and management practices were determined with the least square means method using Tukey's test, with years serving as replicates.

Results and Discussion

Baseline Stream Flow and Phosphorus Transport: Simulated versus Measured

Over 11 yr, Topo-SWAT slightly overpredicted mean annual total stream flow (472 mm yr^{-1} simulated versus 434 mm yr^{-1} observed). On a daily basis, Topo-SWAT matched but underpredicted the storm peaks, while consistently predicting slightly elevated baseflow (Supplemental Fig. S1). This is primarily a result of representing the subdaily measured precipitation as a daily value in Topo-SWAT without precisely capturing the storm intensity distributions. The impact is exaggerated in this small, flashy watershed, particularly when the storms occurred overnight (i.e., across Topo-SWAT days). The watershed runoff to precipitation ratio averages 45% with wide variability across fields due to unevenly distributed restrictive layers (Veith et al., 2008). The model performed similarly throughout the 2000 to 2004 calibration period (daily NSE = 0.55, r^2 = 0.59, PBIAS = 16%, and RSR = 0.67) and the 2005 to 2010 validation period (daily NSE = 0.61, r^2 = 0.61, PBIAS = 22%, and RSR = 0.63). The slight overpredictions during low flows are apparent in the positive PBIAS values. Furthermore, Topo-SWAT simulated sediment load (1.36 Mg ha^{-1} yr^{-1}) in the magnitude of those reported for the region (0.45–2.4 Mg ha^{-1} yr^{-1}; Veith et al., 2008; PA-DEP, 2011b).

Overall, Topo-SWAT simulated dissolved P loss fairly well in baseflow (<0.155 m^3 s^{-1}), when 85% of grab samples were taken (Supplemental Fig. S1). During the baseflow period, the monitored and simulated dissolved P concentrations ranged from <0.005 (detection limit) to 0.26 mg L^{-1} and from <0.005 to 0.84 mg L^{-1}, respectively, and for both ~70% of the concentrations were low (<0.1 mg L^{-1}, data not shown). Dissolved P accounted for 22% of total P, which was consistent with the 26% reported by Sharpley et al. (2008) for a subbasin of our study watershed. Topo-SWAT seemed to "overestimate" peaks of dissolved P loss during storm events (Supplemental Fig. S1). As reported previously, grab sampling may considerably underestimate water quality indicators (Jarvie et al., 2002; Harmel and King, 2005; Cassidy and Jordan, 2011). Due to the very fast hydrological response time of WE38 and sampling frequency, the grab sampling often misses important storm events, which dominate P loss in WE38 (Sharpley et al., 2008). In recent studies with the continuous sampling method, elevated stream P concentrations were observed after manure applications (unpublished data). Therefore, the "overestimated" peaks of dissolved P loss by Topo-SWAT seem to represent the reality. Indeed, Collick et al. (2015) found that use of Topo-SWAT with the new P routines incorporated well-simulated dynamics of P loss in response to field management practices in our study region.

Field-Level Phosphorus Losses

Field-level simulations demonstrate that all factors in the scenarios (annual precipitation amount, field characteristics, soil cover during nongrowing season [i.e., fall and winter], manure application rate, and manure application timing) significantly affected P loss ($p < 0.0001$, Supplemental Table S4). Across the range of combined factors, P loss differed by up to ninefold. For instance, the largest total P loss (20.0 ± 2 kg ha^{-1} yr^{-1}) occurred during the two high-precipitation years, from the field adjacent to the stream and without a cover crop, after a high rate of manure was applied in the fall (Fig. 2a, solid-line highlight rectangle). In contrast, the smallest total P loss (2.3 ± 1 kg ha^{-1} yr^{-1}) happened in low-precipitation years on the gently sloping field set back from the stream, with dense soil cover (corn residue plus rye cover), when manure was spring applied at the lower rate (Fig. 2b, solid-line highlight). The contrasting total P losses result from differences in runoff and sediment transport between the two scenarios. The scenario with the largest total P loss had a runoff/precipitation ratio of 0.75 (field TI: 10) and an annual sediment loss of 4.9 Mg ha^{-1}, whereas the scenario with the lowest total P loss had a runoff/precipitation ratio of 0.38 (field TI: 4.7) and an annual sediment loss of 0.26 Mg ha^{-1}. However, despite variation in annual precipitation, impacts of adopting best management practices are clear. Among all field-level scenarios and water years, total P loss can be substantially reduced through better site targeting (by 48–64%), improving winter soil cover (by 25–46%), and reducing manure application rates (by 1–23%).

Manure Application Timing Effects

Field-scale findings support previous generalizations that winter and fall applications pose a greater risk to P loss than spring application (Phillips et al., 1981; van Es et al., 2006; Sørensen and Rubæk, 2012; Vadas et al., 2017). In both high (Fig. 2a) and low (Fig. 2b) precipitation years, fall or winter application resulted in 12 to 16% greater annual total P loss than did spring application (high-precipitation years: 11.8–12.2 vs. 10.2 kg ha^{-1} yr^{-1}; low-precipitation years: 8.9 vs. 6.1 kg ha^{-1} yr^{-1}). Differences in dissolved P losses were even more pronounced, with 40% increase in the high-precipitation years between fall or winter and spring application scenarios and, similarly, a 19 to 29% increase during the low-precipitation years (Supplemental Fig. S2). The significantly lower dissolved P loss in spring application could be explained by a smaller number of intensive rainfall events occurring shortly after manure applications than in fall and winter. The difference in dissolved P loss between fall or winter and spring application is more pronounced in high precipitation years with greater runoff/precipitation ratio (on average 0.58) than low precipitation years (0.52). An example of precipitation effect on runoff, sediment, and P loss is given in Supplemental Fig. S3a.

Factors Associated with Winter Applications

Our results demonstrate the opportunities for reducing P loss from winter manure application by reducing manure application rates and targeting fields that are away from streams, have lower slopes, and have extensive soil cover. In this study, the highest runoff potential and sediment loss were observed in the field along the stream, followed by a sloped field, and then a flat field located far away from stream (Supplemental Fig. S3b). Therefore, when winter manure was targeted to the flat field located away from the stream, as suggested in Pennsylvania manure management guidelines, total P loss was reduced by 48 to 54% (Fig. 2a and 2b, dashed-line highlight rectangle), compared with application on fields that were within 30 m of the stream. Additionally, applying winter manure to the flat field versus the sloped field reduced total P loss by 36 to 41% (Fig. 2a and 2b, dashed-line highlight

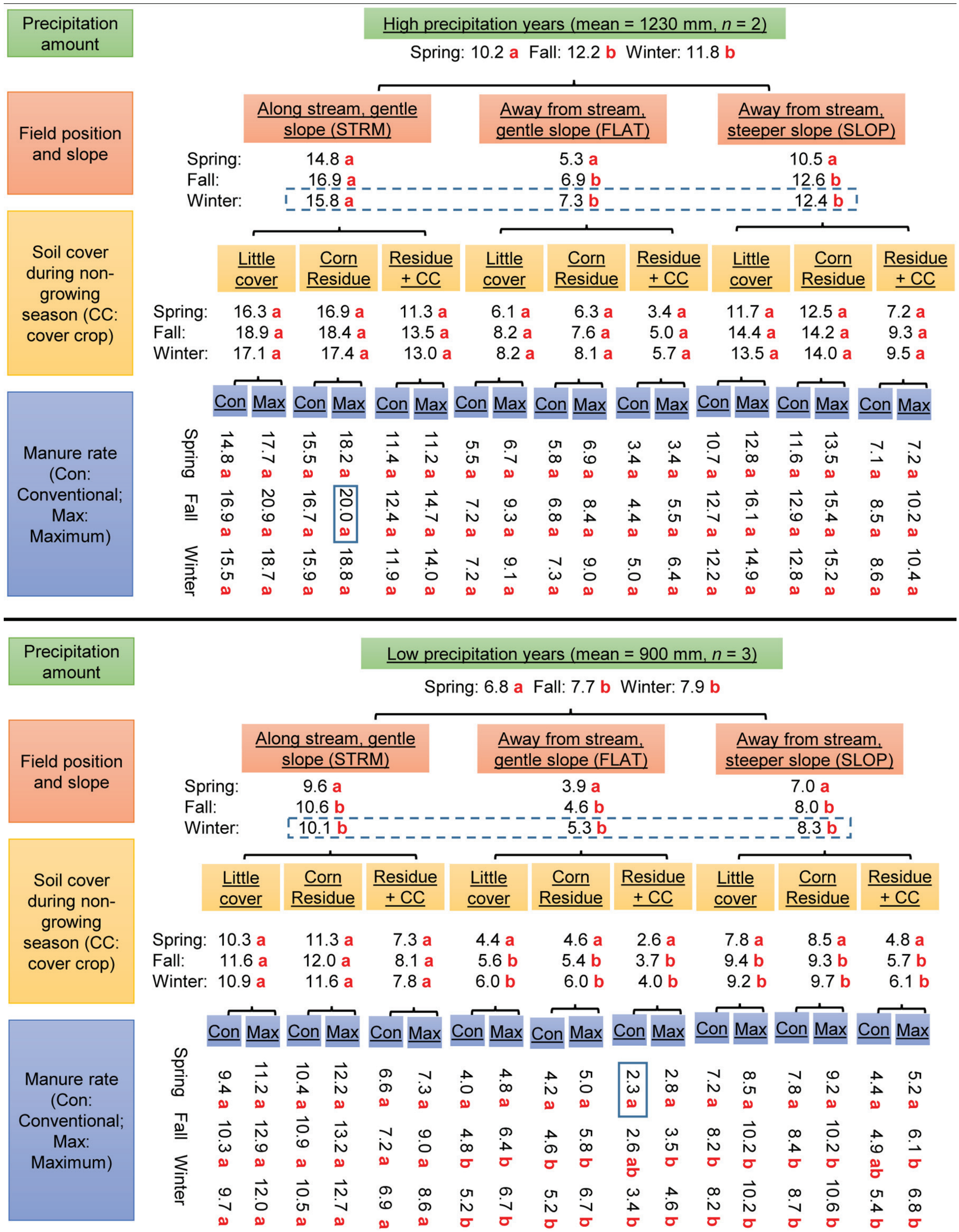


Fig. 2. Mean annual field-level total P losses (kg ha^{-1}) simulated by Topo-SWAT. Seasonal manure application timings were compared at each level, with significant differences ($p < 0.05$) between timings identified by different letters (a and b).

rectangle). Moreover, application of dairy slurry at lower, conventional rates reduced total P loss by an average of 16% and dissolved P loss by 29% in all years, as compared with slurry application at the maximum allowable rate for winter application in Pennsylvania (Fig. 2a and 2b, Supplemental Fig. S2a and S2b, no highlights). Thus, farmers with flexibility in field selection and with sufficiently low animal densities to allow reduced manure application rates can potentially substantially reduce their annual P loss risks through targeting placements and rates of manure application.

Compared with the fields where corn grain was harvested and the crop residue was left as a soil cover, the addition of a rye cover crop reduced total P loss after winter application by 25 to 41% (Fig. 2a and 2b, no highlights). This was mainly due to efficient reduction of soil erosion and sediment loss by the cover crop (Supplemental Fig. S3c). Although dense corn residue after corn grain harvest substantially reduced erosion (Supplemental Fig. S3c), SWAT incorporates nutrients from the additional residue into the surface soil pools. Thus, total P loss remained in this case similar to that from sparse soil cover after harvesting corn as silage (Fig. 2a and 2b, Supplemental Fig. S2a and S2b, no highlights), albeit for different reasons. The results represent the well-established effectiveness of crop residue in reducing the loss of sediment-bound P while simultaneously providing organic P loss from the residue biomass, both of which are included in the total P values. These findings highlight the need for future work in separating the nonorganic sediment-bound soil P pools and the organic soil P pools, as modeled in SWAT, to more precisely categorize the various mechanisms of nutrient loss from a particular management practice.

Following existing Pennsylvania manure spreading guidelines (PA-DEP, 2011a) would reduce mean total P loss in runoff by ~38%, compared with manure application to all field conditions during the winter or the fall (Table 3, winter—allowable fields vs. winter—all fields or fall—all fields). Indeed, in this study, applying manure to fields that are to be avoided in the winter under the Pennsylvania guidelines would increase total P losses by 45% over losses from fields targeted by the guidelines (Table 3, winter—vulnerable fields vs. winter—allowable fields). Reduction of total P in allowable fields is mainly due to reduction of sediment-bound P as a result of decreasing sediment loss, but it is also due partly to changes in runoff (Table 3).

The simulations also highlight drawbacks of forcing manure application in fall and spring seasons. While unrestricted winter applications have the greatest average annual P loss over the long term, dense cover can potentially reduce these losses to less than the losses occurring from spreading at other times on less cover (Fig. 2a and 2b, Supplemental Fig. S2a and S2b). Vadas et al. (2017) also found that nonwinter manure application to fields with medium or high runoff potential resulted in greater dissolved P loss than winter application to low-runoff fields. Maximum annual P losses simulated in all scenarios demonstrate the potential for major P loads at any time of the year (Table 3). Notably, up to 46% of total P and 85% of dissolved P loss occurred during the season of manure application regardless of the application scenario. Over 11 yr, the largest annual P load from any of the scenarios simulated was actually associated with fall application (20.4 kg ha^{-1}), during fall 2009, after a sequence of five extreme storm events (28–46 mm precipitation event^{-1}). Clearly, prudent guidelines and short-term strategies are required to supplement long-term strategies to protect water quality in all seasons.

Influence of Manure Storage Capacity on Watershed Phosphorus Losses

Compared with the baseline scenario, the 12-mo storage scenario, in which all manure was spring applied, reduced average dissolved P loss at the watershed outlet only by 5% (0.04 kg ha^{-1} yr^{-1}) and average total P loss by 2% (0.06 kg ha^{-1} yr^{-1}) over 11 yr (Table 4). The percentages of reduction were much lower than that of our field-level simulation, indicating that other factors such as field slope, location, and soil cover collectively played a more dominant role than manure application timing in determining total P loss in the watershed. Indeed, the WE38 watershed has sloping topography with >60% of the 145 agricultural fields having a mean slope (calculated as the mean of the slope means of the multiple HRUs within each individual field) >10%, and absence of a cover crop during fall and winter has been frequently observed. As a result, sediment-bound P accounted for up to 78% of total P. When manure was spread across seasons, the marginal advantage of spring application in reducing dissolved P loss was often "contradicted" by fall or winter application. As a result, the 6-mo storage (fall-spring application) scenario and the 3-mo storage (four-season application) scenario did not reduce watershed P loads compared with the baseline scenario (Table 4). Notably, the current modeling study was conducted on a watershed with relatively low manure nutrient inputs that accounted for only 30%

Table 3. Simulated P losses (mean [min.–max.])) after the maximum Pennsylvania allowable rate of dairy slurry (3.75 Mg ha^{-1} in dry weight).

Scenario	Manure application season					Annual				
	Precipitation	Runoff	Sediment	Dissolved P	Total P	Precipitation	Runoff	Sediment	Dissolved P	Total P
	mm	mm	t ha^{-1}	kg ha^{-1}	kg ha^{-1}	mm	mm	t ha^{-1}	kg ha^{-1}	kg ha^{-1}
Spring application to all fields	262 (212–364)	138 (66–267)	0.6 (0.1–2.4)	2.4 (0.4–5.0)	4.4 (0.9–10.7)	1032 (800–1295)	558 (262–928)	1.8 (0.2–5.0)	2.8 (0.6–5.5)	8.8 (2.0–18.4)
Fall application to all fields	267 (188–327)	140 (57–240)	0.4 (<0.1–1.3)	3.5 (1.3–6.5)	4.7 (1.4–9.8)	1032 (800–1295)	557 (262–928)	2.0 (0.2–6.0)	4.0 (1.6–7.2)	10.5 (2.4–21.6)
Winter application to all fields	192 (98–287)	123 (40–289)	0.3 (<0.1–1.3)	3.7 (3.0–4.4)	4.6 (3.1–7.5)	1032 (800–1295)	558 (262–928)	1.9 (0.2–5.1)	4.3 (3.3–5.5)	10.4 (4.3–19.4)
Allowable fields†	192 (98–287)	107 (40–230)	0.1 (<0.1–0.4)	3.4 (3.0–3.9)	3.8 (3.1–3.5)	1032 (800–1295)	420 (264–560)	0.6 (0.2–1.0)	4.0 (3.3–4.8)	6.4 (4.3–9.5)
Vulnerable fields‡	192 (98–287)	127 (40–289)	0.4 (<0.1–1.3)	3.8 (3.0–4.4)	4.9 (3.3–7.5)	1032 (800–1295)	597 (262–928)	2.3 (0.5–5.1)	4.4 (3.4–5.5)	11.6 (5.6–19.4)

†Allowable fields include any acceptable for manure application under Pennsylvania winter manure guidelines: slopes < 15%, >30 m from stream, >25% soil cover (PA-DEP, 2011a).

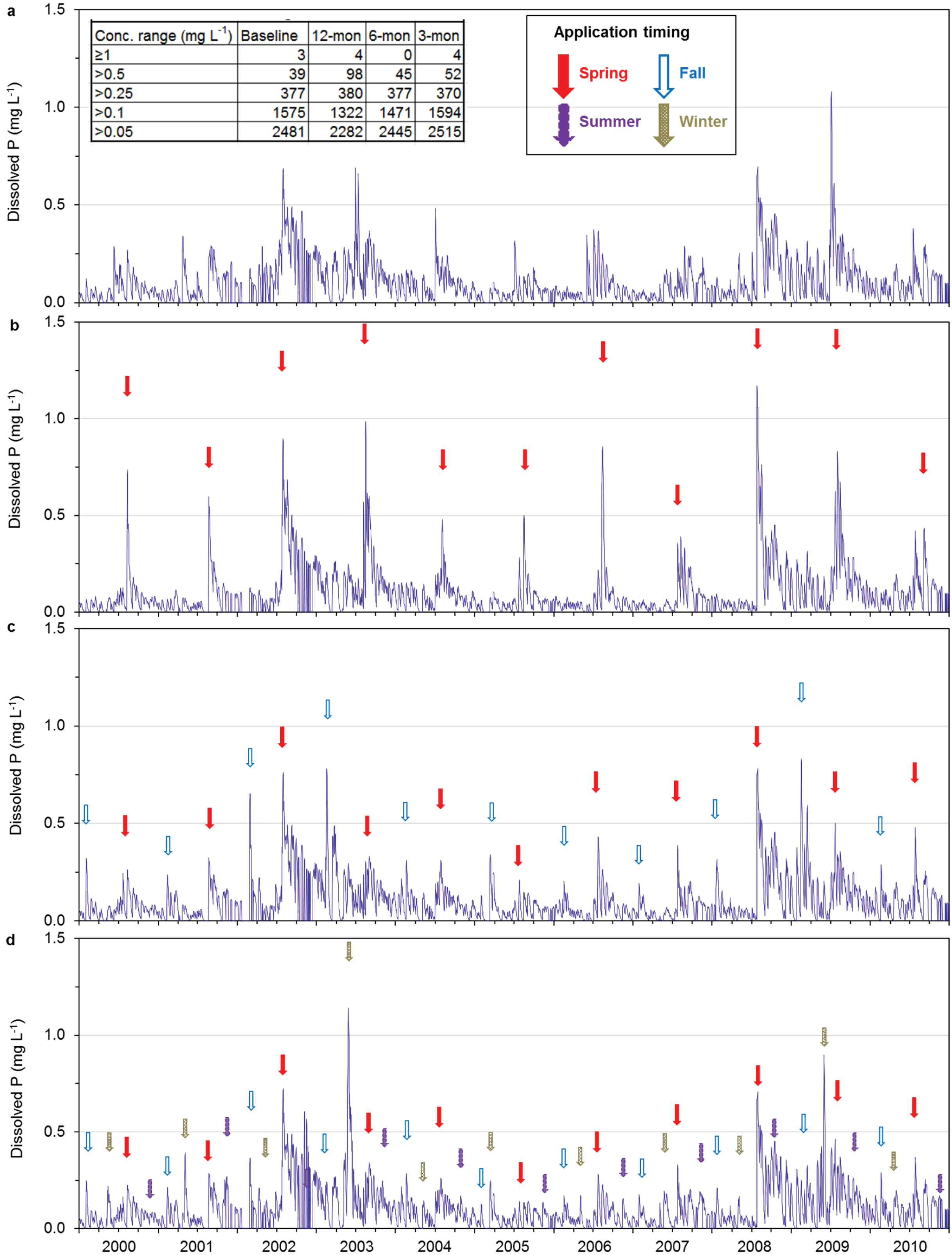
‡ Vulnerable fields include any fields that do not follow Pennsylvania guidelines.

Table 4. Average annual (min.–max.) streamflow, sediment, and P simulated by Topo-SWAT at the WE-38 outlet for four manure application scenarios corresponding to a range of manure storage capacities, as described in Table 2.

Scenario	Flow	Sediment	Dissolved P	Total P
	mm	t ha^{-1}	kg ha^{-1}	kg ha^{-1}
Baseline	473 (96–758)	1.36 (0.62–2.44)	0.75 (0.34–1.43)	3.47 (1.57–5.35)
12-mo storage (all manure application in spring)	473 (96–758)	1.36 (0.61–2.44)	0.71 (0.28–1.36)	3.41 (1.49–5.30)
6-mo storage (manure application in spring-fall)	473 (96–758)	1.36 (0.62–2.43)	0.74 (0.29–1.46)	3.44 (1.49–5.37)
3-mo storage (manure application each season)	473 (96–758)	1.36 (0.62–2.43)	0.73 (0.33–1.52)	3.44 (1.54–5.40)

of total P applications in the watershed. However, for watersheds with large animal densities, manure storage capacities would likely affect downstream water quality more substantially.

Different manure storage scenarios at the watershed scale greatly affected temporal dynamics of dissolved P concentrations in stream flow at the WE38 outlet. Dissolved P concentrations in the stream peaked in response to seasonal manure application, and the peaks were generally higher when more manure was applied in one season and declined consistently with time until the next application (Fig. 3). In the 12-mo scenario, when all manures



Conc. range (mg L^{-1})	Baseline	12-mon	6-mon	3-mon
≥1	3	4	0	4
>0.5	39	98	45	52
>0.25	377	380	377	370
>0.1	1575	1322	1471	1594
>0.05	2481	2282	2445	2515

Fig. 3. Temporal dynamics of dissolved P concentrations in stream flow at the study watershed outlet, as simulated with Topo-SWAT, for four manure storage scenarios: (a) baseline, (b) 12 mo storage (spring application), (c) 6 mo storage (fall-spring application), and (d) 3 mo storage (four-season application). Inset: frequencies of daily mean dissolved P concentrations for each scenario.

were near-simultaneously applied in spring, there was consistently a "first-flush" effect whereby the additive P loss from all fields resulted in the greatest (but fewest) peaks of P concentrations in the stream among all scenarios. When manure was evenly partitioned across fall and spring (6 mo storage) or over all four seasons (3 mo storage), more frequent but lower peaks of dissolved P concentration were generated corresponding to the increased number of manure application events. Over 11 yr, daily dissolved P concentrations >0.5 mg L^{-1} peaked for 98 times in the 12-mo scenario, versus only 39 to 52 times elsewhere (Fig. 3). In contrast, the 3-mo scenario resulted in 2515 peaks with daily dissolved P concentrations > 0.05 mg L^{-1} compared with 2282–2481 peaks among the other scenarios. In all scenarios, the highest peaks of total P concentration were directly associated with manure applications, but there were also many peaks that were associated with soil erosion driven by rain storms (Supplemental Fig. S4).

Scale issues should be considered when evaluating manure application timing impacts on nutrient losses. At the field level with certain weather, field, and soil management conditions, we found very promising potential improvements in P water quality by replacing fall and winter application by spring application. At the watershed level, however, evaluations are complicated by aggregate spatial and temporal effects of manure storage capacity on variables such as manure application rate and timing, as well as by complexity of field and management factors. This comparison of the consequences of different manure storage capacities demonstrated a tradeoff between reducing annual dissolved P loss or reducing the frequency of high-P-concentration runoff events. Overall the local environmental consequences of increased manure storage capacities may be marginal in watersheds like WE38, where animal densities and manure P inputs are relatively low. However, in some cases, the target of watershed management is a downstream lake or reservoir having a rapid turnover rate (low water residence time). That water body might be especially sensitive to P inputs in spring and summer that promote eutrophic conditions during hot summer months. In this case, the best scenario for reducing P losses that drive eutrophication might be to reduce spring and summer manure applications by applying some manure during fall and winter months. Clearly, the different patterns of seasonal P concentrations at the mouth of the watershed resulting from the different manure management scenarios evaluated in this study could be used to inform watershed management with specific objectives in mind.

Implications for Watershed Management

Regional watershed management objectives for the small catchment that is the site of this study are twofold: (i) maintain relatively good water quality in the local stream network, and (ii) reduce total P delivery to the Chesapeake Bay, the sensitive water body to which this catchment eventually drains (USEPA, 2010). Of those manure application scenarios that were evaluated at the field level, spring application best addressed the first objective by reducing both annual dissolved P and total P losses, as compared with applications in fall or winter. However, banning winter and fall applications across the watershed would increase concentration peaks of dissolved P at the watershed outlet—a potential detrimental to stream ecology and downstream water bodies—with marginal reductions of annual average total P and dissolved P losses. Such a ban also affects farm costs and operations by requiring 12-mo storage facilities. Therefore, the overall cost effectiveness of different manure storage options need to be further evaluated. However, it is clear that efficient reductions of P loss through better targeting of manure to gently sloped fields away from streams, enhancing soil cover by cover cropping, and minimizing manure application rates offer additional benefits toward meeting watershed management objectives, regardless of application timing.

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