The synergistic effect of manure supply and extreme precipitation on surface water quality

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Abstract

Over-enrichment of phosphorus (P) in agroecosystems contributes to eutrophication of surface waters. In the Midwest US and elsewhere, climate change is increasing the frequency of high-intensity precipitation events, which can serve as a primary conduit of P transport within watersheds. Despite uncertainty in their estimates, process-based watershed models are important tools that help characterize watershed hydrology and biogeochemistry and scale up important mechanisms affecting water quality. Using one such model developed for an agricultural watershed in Wisconsin, we conducted a $2 \times 2$ factorial experiment to test the effects of (high/low) terrestrial P supply (PSUP) and (high/low) precipitation intensity (PREC) on surface water quality. Sixty-year simulations were conducted for each of the four runs, with annual results obtained for watershed average P yield and concentration at the field scale (220 $\times$ 220 m grid cells), P load and concentration at the stream scale, and summertime total P concentration (TP) in Lake Mendota. ANOVA results were generated for the $2 \times 2$ factorial design, with PSUP and PREC treated as categorical variables. The results showed a significant, positive interaction ($p < 0.01$) between the two drivers for dissolved P concentration at the field and stream scales, and total P concentration at the field, stream, and lake scales. The synergy in dissolved P was linked to nonlinear dependencies between P stored in manure and the daily runoff to rainfall ratio. The synergistic response of dissolved P loss may have important ecological consequences because dissolved P is highly bioavailable. Overall, the results suggest that high levels of terrestrial P supplied as manure can exacerbate water quality problems in the future as the frequency of high-intensity rainfall events increases with a changing climate. Conversely, lowering terrestrial manure P supply may help improve the resilience of surface water quality to extreme events.

1. Introduction

Phosphorus (P) abundance and climate change both pose significant challenges to the ongoing management of freshwater resources. As the chief limiting nutrient in freshwater ecosystems, excess phosphorus (P) causes accelerated eutrophication of streams, rivers, and lakes. Because P is readily bound to, and slowly released from, soils and sediments, accumulated or ‘legacy P’ can affect freshwater bodies for years or decades (Jarvie et al 2013, Motew et al 2017), causing ecological degradation and substantial economic loss (Kudela et al 2015). The problem of legacy P affects many regions in the world, including North America, Europe, Asia, Latin America, and Oceania (MacDonald and Bennett 2009, Sattari et al 2014, Garnier et al 2015, Powers et al 2016). As such, a growing body of literature has evolved in the past several years to address the challenges associated with legacy P and the threat it poses to long-term freshwater quality (Hamilton 2012, Sharples et al 2013, Sharples 2016, Haygarth et al 2014, Rowe et al 2015).
In addition to excessive terrestrial P, surface water quality is also vulnerable to extreme precipitation events, which in some watersheds cause a disproportionate amount of total annual sediment and P to water bodies (Haygarth and Jarvis 1997, Royer et al. 2006, Gonzalez-Hidalgo et al. 2013, Carpenter et al. 2014). Models and theories of climate change have predicted an increase in both mean annual precipitation as well as the frequency of extreme precipitation events in many regions, including the eastern and Midwestern US (Houghton et al. 2001, Karl and Trenberth 2003, Janssen et al. 2014). Observational studies have begun to confirm these expectations (Fischer and Knutti 2016, Usinowicz et al. 2017). Globally, annual maximum daily precipitation has been increasing (Westra et al. 2013). Sub-daily events may also be increasing across regional and global scales, although data and methods to assess sub-daily trends are lacking (Westra et al. 2014). In the Upper Mississippi River Basin as well as elsewhere in the conterminous US, annual changes in precipitation have been dominant controls on runoff generation, overshadowing the effects of temperature, land cover change, and agricultural practices (Frans et al. 2013, Gupta et al. 2015, McCabe and Wolock 2016). An increase in extreme precipitation events and the subsequent increase in surface runoff generation, suggests that managers will have to contend with even greater rates of P mobilization from landscapes in the future.

In addition to surface runoff generation, terrestrial P loss depends on available sources of P such as manure, fertilizer, or P-rich soils. Soil P changes through time according to the mass balance of inputs and outputs of P to the soil system. The largest fluxes to the soil system typically include agricultural inputs of P in the form of manure or fertilizer, and the largest fluxes out include harvested crops, biomass, or animal products. Fluxes of P lost to surface runoff, leached deep into the soil column, or deposited by the atmosphere, are generally much smaller than agricultural inputs and harvested outputs (Bennett et al. 1999). Relatively tiny losses of P to surface waters can however have a significant effect on aquatic ecosystems (Vadas et al. 2004, Carpenter and Lathrop 2008).

Phosphorus lost to surface runoff may be in particulate or dissolved form. Both forms contribute to eutrophication, and together as total P serve as the best indicator of water quality in receiving waters (Correll 1998). Transport of the two forms is controlled by different physical mechanisms. Particulate P is initially transported via erosion. In general, perennial land cover types, vegetative buffer strips, and reduced soil disturbance can be effective ways to reduce erosion and particulate P losses from agricultural lands (Baker and Laflen 1983, McDowell and McGregor 1984, Sharples and Smith 1994, Uusi-Kämppä et al. 2000, Diebel et al. 2009). Dissolved P loss on the other hand moves directly with surface runoff and therefore depends principally on the amount of dissolved P in manure or the surface soil layer. Surface applications of fertilizer and manure that are not physically incorporated can lead to stratification of P in soil and higher losses of dissolved P in runoff. Many studies have shown that compared to conventional tillage methods, reduced tillage approaches increase dissolved P losses to surface waters (Baker and Laflen 1983, McDowell and McGregor 1984, Langdale et al. 1985, Sharples and Smith 1994, Bundy et al. 2001, Zhao et al. 2001, Tiessen et al. 2010).

Some studies have shown a link between extreme weather events and water quality responses, such as massive harmful algae blooms in Lake Erie, US (Michalak et al. 2013), and Lake Taihu, China (Zhu et al. 2014), and changes in riverine P dynamics in the Yongan River, China (Chen et al. 2014). However, evidence for causal connections may be lacking (Michalak 2016). In a modeling study of the effects of legacy P on lake water quality, Motew et al. (2017) found that average watershed soil P concentration compounded the effect of extreme precipitation on in-lake total P concentration, a finding with important implications for regions having both elevated terrestrial P supply and a rising trend in extreme precipitation. The mechanism responsible for that finding however was unclear. Here, using the same models as Motew et al. (2017) that feature important new developments in manure and fertilizer P loss dynamics, we investigated how changes in extreme precipitation might interact with an abundant supply of terrestrial P to affect surface water quality. Using a 2×2 factorial design of high and low levels of each driver, we investigated how both precipitation intensity (PREC) and terrestrial P supply (PSUP) affected P transport at three spatial scales: the field scale, indicated by P loss in runoff from grid-cells of size 220 m by 220 m; the stream scale, indicated by in-stream P loading and concentration; and the lake scale, indicated by summertime total P (TP) concentration in the epilimnion. We focused on the watershed of Lake Mendota, a well-studied lake in southern Wisconsin, USA. This watershed has an excessive amount of P stored in soils and channel bed sediments (Bennett et al. 1999, Kara et al. 2012, Motew et al. 2017), and has also seen a significant increase in the occurrence of extreme precipitation events over the past two decades (Kucharik et al. 2010, Gillion et al. 2016) and elevated runoff (Usinowicz et al. 2017).

While other studies have examined the relationships between manure, fertilizer, and soil P with hydrologic fluxes at the field and laboratory scales (Sharples and Moyer 2000, Kleinman et al. 2004, Vadas et al. 2011), ours is the first to investigate such interactions across multiple scales of a watershed. Because an increase in extreme rainfall is expected with climate change, and because many agricultural watersheds contain an excessive amount of P, it is important to understand if these two factors may exacerbate one another, and across what spatial scales. An interaction at any scale may have important ecological impacts.
as well as management implications. Using process-based models also allows for a deeper inquiry into the mechanisms causing an interaction.

2. Materials and methods

2.1. Study region
Our study region was the 604 km$^2$ Lake Mendota watershed (LMW) (43.1097° N, -89.4206° W) (figure 1), a subwatershed of the Yahara Watershed of southern Wisconsin. The LMW is predominantly agricultural, with 54% of land cover in cropland, 24% in urban or open space, and the remaining 22% in forest, grassland, wetland, or open water. The LMW is characterized by relatively flat slopes (~4%), a predominance of silt loam soils, and has a stream channel density of 1.21 km km$^{-2}$, excluding internally drained areas. High P loads to Lake Mendota have been primarily attributed to the large number of dairy operations located upstream of the lake within its drainage area (Lathrop 2007). Empirical P loading patterns to Lake Mendota are strongly influenced by high input events, with 29 d per year delivering approximately 74% of the annual load (Carpenter et al 2014). Over the 1930–2010 time period, annual precipitation has increased in the Yahara Watershed at a rate of 2.1 mm y$^{-1}$, and the frequency of large storm events (>50 mm) has increased from 9.5 events per decade (1931–1990) to 18 events per decade (1991–2010) (Gillon et al 2016). These trends are consistent with other regional studies (Kunkel et al 2007, Qian et al 2007, Peterson et al 2008, Pryor et al 2009, Kucharik et al 2010, Baker et al 2012, Villarini et al 2013).

2.2. Models
We used a deterministic, process-based watershed modeling framework to simulate field-to-lake flows of water, sediment, and phosphorus, as well as lake water quality in the LMW. The framework consisted of Agro-IBIS, a terrestrial ecosystem model that simulates carbon, water, energy, momentum, nitrogen and phosphorus cycles in the soil-vegetation-atmosphere system (Kucharik et al 2000, Kucharik 2003); THMB (Terrestrial Hydrology and Biogeochemistry Model), a hydrologic and nutrient routing model (Coe 1998, 2000, Donner et al 2002); and the Yahara Water Quality Model (YWQM) that estimates lake water quality conditions in the Yahara lake chain (Carpenter and Lathrop 2014). Agro-IBIS and THMB have been used together previously to study hydrology and nitrogen transport in the Mississippi Basin (Donner and Kucharik 2003, Donner et al 2004, Donner and Kucharik 2008). Recently, phosphorus cycling and
transport were added to Agro-IBIS and THMB, and both models were linked with the YWQM for use in the Yahara Watershed (Motew et al. 2017). The three-model suite was previously calibrated and validated at the stream and lake scales using continuous monthly observations of streamflow, sediment and P loading to the Yahara lakes from six USGS gaging stations spread throughout the Yahara Watershed (Motew et al. 2017). At the field scale, calibration and validation was conducted using Wisconsin-based observations of soil test P (typically single measurements) and annual sediment and P yield made by Andraski and Bundy (2003), Bennett et al. (2004), Stuntebeck et al. (2011), and other local sources (Motew et al. 2017). A sensitivity analysis was also conducted to identify model parameters that exert a strong influence on P yield, streamflow, sediment load, and P load. No parameters were found to exert a disproportionate influence on modeled streamflow or P quantities (Motew et al. 2017).

2.3. Experimental design
The modeling framework was used to conduct a 2 × 2 factorial experiment to test the interaction effect of (low/high) terrestrial P supply and (low/high) precipitation intensity on surface water quality. Sixty-year simulations were conducted for each of the four runs, named HIHI, HILO, LOHI, and LOLO, with the first two characters signifying the P supply regime and the last two characters the precipitation intensity regime. Annual results were obtained for P concentration and P yield at the field scale (220 m by 220 m grid-cell resolution), P concentration and loads in the inlet river to Lake Mendota, and TP in Lake Mendota. A sixty-year simulation period represented an appropriate balance between sample size (n = 60) and computational run-time, and also allowed for many random combinations of storm event timing in relation to nutrient applications. At the field and stream scales, total P concentration, yield, and load were each broken down into their dissolved and sediment forms since the processes controlling the release and transport of each form were different. For each simulation, a land cover rotation for the years 2006–2009 was repeated 15 times. Land cover and nutrient application rates for the Yahara watershed were previously obtained for the 1986–2013 period (Motew et al. 2017). According to the validated simulation of Motew et al. (2017), average soil P concentration in the top 2.5 cm soil layer in croplands was roughly 176 ppm. This value reflects typical rates of manure and fertilizer applied to croplands in the watershed, which averaged 32 and 11 kg P ha⁻¹ y⁻¹, respectively, over the 1986–2013 period. For this study, we chose watershed-averaged surface soil P concentrations of 200 and 65 ppm to represent HI and LO values of terrestrial P supply, respectively. We focused on the surface soil layer because that is the layer that physically interacts with surface runoff. To obtain 200 and 65 ppm average surface soil P concentration, each simulation was preceded by a 25-y spin up to bring the surface soil layer to the desired labile P concentration, assumed to be one half of Bray-1 and Mehlich-3 soil test P (Vadas and White 2010). Surface soil P was then maintained for the remainder of the simulation by multiplying the historical manure and fertilizer application rates in each grid cell by a factor of 1.3 for the high terrestrial P supply runs (HIHI and HILO), and 0.6 for the low terrestrial P supply runs (LOHI and LOLO). Because inputs to the soil system exceeded outputs for both soil P treatments, P in the second soil layer (2.5–15 cm) continually increased, while equilibrium was approximately maintained in the surface soil layer (0–2.5 cm) (supplementary figures 1 and 2). Physical mixing during plowing (to a 10 cm depth), and leaching of fertilizer and manure P into the soil led to the increase in the second layer. An increase in total soil P across all layers agrees with previous studies showing that P, averaged over the Yahara watershed as a whole, is accumulating in soils (Bennett et al. 1999, Kara et al. 2012, Motew et al. 2017).

In all simulations, dairy cow manure was applied three times per year to croplands, including corn, soy, wheat, and alfalfa. The spatial variability in application rate, dry matter content, and manure P fraction for each application was previously determined by Motew et al. (2017). Grasslands including hay and pasture did not receive manure or fertilizer. In grid cells receiving manure, ten percent of the annual rate was surface applied in mid-February, 45% was applied and tilled to a 10 cm depth at the time of spring planting, and the remaining 45% was surface applied in the beginning of October. Fertilizer applications were made once per year at the time of planting, using a pelletized, highly-soluble form of phosphate.

Two 60 year climate scenarios consisting of daily precipitation, maximum and minimum air temperature, wind speed, relative humidity, and incoming shortwave radiation were generated with the following characteristics: (1) very similar mean annual values for each variable reflecting the current climate (1996–2015) of Madison, Wisconsin (Menne et al 2012); and (2) contrasting daily precipitation distributions where one had more intense rainfall events (the HI regime) compared to the other (the LO regime). The contrasting precipitation regimes therefore varied in average length between storm events yet summed to similar annual values. Simulated runoff for the two regimes showed a greater event-based runoff to rainfall ratio in the HI case (figure 2). A greater runoff to rainfall ratio was a plausible biophysical response since rainfall rates would be more likely to exceed infiltration rates as storm intensity increased. Details on the generation of the climate scenario data are provided in appendix C. Details on the analysis, including data transformations and the use of 2 way ANOVA, are provided in appendix D.
3. Results

At the field and stream scale, we detected significant interactions between precipitation intensity and terrestrial P supply for both dissolved and total P concentration. An interaction for total P concentration was also detected at the lake scale, signifying that the interaction was persistent in both dissolved and total P at all scales of the watershed (table 2, figure 3). Testing the three sources of P (soil, fertilizer, and manure) individually for an interaction revealed that the positive interaction in dissolved P concentration stemmed only from dissolved P loss from manure, i.e. not from fertilizer or soil. The interaction also did not apply to sediment P loss or to mass-based quantities like P yield and load.

Aside from the significant interactions detected for dissolved P concentration at field and stream scales, as well as total P concentration at all three scales, no other P quantities had significant interactions (table 2). Dissolved P yield (field scale) and load (stream scale) had removable interactions, as did total P yield and load. Removable interactions are interactions that are significant prior to transformation, but not significant after transformation (de González and Cox 2007). Sediment P yield at the field scale and sediment P load and concentration at the stream scale had no interaction whether transformed or not. Sediment P concentration at the field scale had a removable interaction. Interaction plots showed that for all quantities having a significant interaction between precipitation intensity and P supply, the interaction was synergistic (figure 3).
This means that when P supply was high, the effect of precipitation intensity was greater than it was when P supply was low.

The probability distributions of annual P quantities having a significant interaction showed that for the HIIHI run, the distribution was spread wider and was centered at the highest value of all four runs. This indicated a higher probability of very high annual P concentration at each scale, and relatively low probability of low P concentration at each scale (figure 4). Likewise for the LOLO run, there was a high probability of low P concentration events and conversely a low probability of very high P concentration events. The HILO and LOHI runs had similar mean values across the P concentration variables, but at the grid–cell level LOHI had a narrower distribution than HILO. This may suggest that PSUP played a bigger role in determining the spread of the distribution at the grid–cell level (since HILO was spread wider than LOHI). At the stream level, HILO and LOHI had very similar distributions, suggesting that the effects of PREC and PSUP effectively countered one another at that scale. At the lake scale, both of the HI PSUP runs caused very long, high–valued tails compared with the LO PSUP runs. HILO and LOHI had similar distribution shapes at the lake scale, but LOLO was highly skewed toward low values of TP.

The proportions of mean annual total P concentration in dissolved and sediment forms varied across model runs, but were similar between the field and stream scales (figure 5). Dissolved P constituted more than 60% of annual total P concentration at the grid cell scale for the runs with high precipitation intensity. For the runs with low precipitation intensity, the proportions were roughly half and half, with the LOLO run having the lowest proportion of dissolved P (49%) and the HILO run having the second-lowest (54%). At the stream scale, the HIIHI run had the highest proportion of dissolved P (67%), while LOLO had the lowest (41%). Across the four runs (HIIHI, HILO, LOHI, and LOLO), the proportion of sediment P increased. A higher proportion of sediment P may have been the result of lower amounts of fertilizer and manure being applied, which are both rich in dissolved P. Additionally, a higher proportion of sediment P with decreased rainfall intensity may reflect the importance of heavy rainfall events in the process of dissolved P leaching, as evident in the synergistic interaction for dissolved P concentration at the field and stream scales. In the absence of both high terrestrial P supply and heavy rainfall, mean annual dissolved P loss was at its lowest amount, which was reflected in its low proportion relative to sediment P.

The relative proportions of mean annual dissolved P from manure, fertilizer, and soil are shown in figure 6 for cropland cells. Soil contributions were the largest overall, followed by manure and then fertilizer. We found the interaction between P supply and precipitation intensity to be significant for manure but not for fertilizer or soil. This suggested that dissolved P loss from manure to runoff was the causal mechanism driving the synergy within the watershed. This can be understood in terms of the nonlinear relationships governing dissolved P loss from manure to runoff (equations 1–4, appendix A.1 available at stacks.iop.org/ERL/13/044016/mmedia). Despite being governed by similar equations, losses from fertilizer did not display an interaction. This is likely because fertilizer was applied in a highly soluble form that leaches quickly into the soil once it comes into contact with water, and was generally not present long enough at the ground surface to be exposed to subsequent overland flow (Vadas et al. 2008). Losses from soil are governed by a simple linear extraction coefficient,

### Table 1. Parameter multipliers for the rectangular Poisson pulse model used to generate daily precipitation amounts for the two contrasting climate regimes along with summary statistics for each regime (mean annual precipitation and 99th percentile of daily precipitation).

| Regime | Mean storm intensity, $T$ (mm hr$^{-1}$) MULTIPLIER | Mean storm duration, $T_s$ (hr) MULTIPLIER | Mean interstorm period, $T_i$ (hr) MULTIPLIER | Mean annual precipitation (mm) | 99th percentile daily precipitation (mm) |
|--------|-------------------------------------------------|------------------------------------------|-------------------------------------------|---------------------------------|----------------------------------------|
| HI flashiness | 1.80                                             | 1                                        | 1.49                                      | 894.9                           | 32.8                                   |
| LO flashiness | 0.90                                             | 1                                        | 0.71                                      | 892.5                           | 25.9                                   |

### Table 2. ANOVA results for simulated annual phosphorus quantities including coefficient of determination and F score associated with an interaction between PSUP (P supply) and PREC (precipitation intensity). Significant F scores ($p < 0.05$) are shown in bold.

| Field | Stream | Lake | $R^2$ | F     | $R^2$ | F     | $R^2$ | F     |
|-------|--------|------|-------|-------|-------|-------|-------|-------|
| Diss. P Conc. (mg L$^{-1}$) | 0.49 | 7.75* | 0.42 | 9.07* |       |       |       |       |
| Sed. P Conc. (mg L$^{-1}$) | 0.38 | 0.68c | 0.06 | 1.46  |       |       |       |       |
| Tot. P Conc. (mg L$^{-1}$) | 0.62 | 51.76b | 0.27 | 8.37a | 0.14  | 7.42a |       |       |
| Diss. Yld or Load (kg ha$^{-1}$ or kg) | 0.33 | 3.42c | 0.46 | 0.04a |       |       |       |       |
| Sed. Yld or Load (kg ha$^{-1}$ or kg) | 0.24 | 1.24  | 0.12 | 0.34  |       |       |       |       |
| Tot. Yld or Load (kg ha$^{-1}$ or kg) | 0.31 | 2.02c | 0.31 | 0.23c |       |       |       |       |

* $p < 0.05$

a $p < 0.01$
b $p < 0.001$
c significant interaction ($p < 0.05$) removed after log 10 transformation
Figure 3. Interaction plots for mean annual values of P response variables for LO and HI levels of terrestrial PSUP and PREC. Only those P indicator variables in table 2 having a significant interaction are shown ($p < 0.05$). P response variables include total annual dissolved P (DP) concentration in runoff at the field scale (a), total annual DP concentration in the inlet river to Lake Mendota (b), total annual TP concentration in runoff at the field scale (c), total annual TP concentration in the inlet river to Lake Mendota (d), and TP concentration in Lake Mendota (e). Error bars indicate ±1 standard deviation.

which likely explains why they displayed no interaction between P supply and precipitation intensity.

4. Discussion

Our study reveals a potential danger posed by climate change where extreme precipitation may exacerbate losses of dissolved P from manure, an important source of P in many watersheds (Hansen et al. 2002). The synergy between P supply and precipitation intensity was linked to the relationships governing dissolved P loss from manure that specifically involved the runoff to rainfall ratio (figure 2). The results indicated that a greater runoff to rainfall ratio will increase P loss from manure at a faster-than-linear rate, as the supply of manure P increases.

The importance of the runoff to rainfall ratio in driving P loss from manure was previously demonstrated by Vadas et al. (2011). In that study, SurPhos was used to simulate the experimental conditions and outcomes of nine published studies investigating manure P loss in runoff. Using those simulations, the authors investigated how different factors affect P loss from manure during the time following application. The results showed a dominant role played by storm event intensity, surpassing the mitigating effects of soil P adsorption over time. The results suggested that, for
Figure 4. Probability density distributions of annual phosphorus variables. Distributions \((n = 60)\) are shown for each of the four factorial simulations combining HI and LO terrestrial PSUP and PREC. Only the P indicator variables in table 2 having a significant interaction \((p < 0.05)\) are shown. Variables include total annual dissolved P (DP) concentration in runoff at the field scale \((a)\), total annual DP concentration in the inlet river to Lake Mendota \((b)\), total annual TP concentration in runoff at the field scale \((c)\), total annual TP concentration in the inlet river to Lake Mendota \((d)\), and summer TP concentration in Lake Mendota \((e)\).

example, a strong rain-runoff event occurring one month after application can release more P into runoff than a weak rain-runoff event occurring immediately after application (Vadas et al. 2011). Our study showed that there is a synergistic interaction between manure P supply and rainfall intensity attributable to the important role of the runoff to rainfall ratio. The synergy was evident in total P concentration at field, stream, and lake scales, demonstrating the pervasive effect of this interaction throughout all scales of the watershed.

The equations governing manure P loss into runoff were first derived in laboratory and field studies (Sharpley and Moyer 2000, Kleinman et al. 2002a, 2002b, 2004, Kleinman and Sharpley 2003, Sharpley et al. 2004, Vadas et al. 2007b), and have since been incorporated into the SurPhos model, which predicts dissolved P loss from fields (Vadas et al. 2004, 2005, 2007a). The SurPhos equations were designed to be modular and easily integrated into daily time-step models. Collick et al. (2016) implemented the SurPhos equations into the Soil and Water Assessment Tool (SWAT2012 Version 586) and found an improvement in the sensitivity of dissolved P loss to key factors in nutrient management, including timing, rate, method, and form of application. The important role of manure interactions with water fluxes in our study further emphasizes the benefit of including the SurPhos equations into watershed models to more accurately capture the effects of
manure P applications in conjunction with changes in hydrology. In watersheds such as the LMW, where dissolved P loss from manure constitutes a relatively large proportion of total P delivered to surface waters (e.g. Galeone 1999), proper characterization of manure dynamics, transformations, and interactions with the hydrologic cycle is essential.

In a study of Lake Erie, Michalak et al (2013) found that long-term trends in agricultural management practices and extreme precipitation during spring contributed to an historic algae bloom in 2011. Using the SWAT model, they found that dissolved reactive P (DRP) yields, which were a likely factor driving the blooms, were sensitive to precipitation intensity, fertilizer application timing, and tillage practices, with precipitation having the strongest influence and fertilizers the weakest. To our knowledge, the version of SWAT used did not have the SurPhos equations, which include explicit representation of surface manure and fertilizer pools. As simulated by SurPhos, these pools have their own transformations and unique interactions with surface hydrologic fluxes that are independent of the soil pools. In the version of SWAT used by Michalak et al 2013, fertilizer and manure P are added directly into the surface soil pools. Applications of manure or fertilizer P would still be expected to increase labile P and DRP loss, but the effect may be underestimated compared to simulations that use explicit representation of surface fertilizer and manure pools. For example, the sensitivity of dissolved P loss to the timing of application may have been underestimated in the Lake Erie study given that there was little difference in cumulative P loss when the application was shifted by several weeks (Michalak et al 2013,
Prospects of climate change, these trends may pose a risk to water quality remediation efforts. On the other hand, if surface applications can be reduced or eliminated, there may be protective benefits to counter extreme precipitation. Future research should evaluate the effectiveness of incorporation technologies, such as manure injection, or other management strategies in mitigating the synergy. And, future research may also focus on further characterisation of the synergy including the possible existence of thresholds of P supply or precipitation intensity at which the synergy disappears.

A common limitation in watershed studies such as ours that investigate the effects of land management on water quality is the uncertainty associated with the specific management practices used on individual fields. For a watershed the size of the LMW (approximately 604 km$^2$), the data required to represent the full diversity of practices on 220 m × 220 m fields, and their spatial distribution, are substantial and difficult to acquire. Motew et al. (2017) developed spatially distributed estimates for manure and fertilizer application rates and consulted with local experts to understand typical tillage practices and crop rotations. However, despite satisfactory validation of annual streamflow and lake P loads, it remains unknown to what extent improved management data would impact our study’s results. Future research should investigate how a lack of spatially-explicit management data might affect the water quality results and conclusions in studies such as ours.

5. Conclusion

In this simulation experiment, the supply of P in manure and extreme precipitation interacted synergistically to affect dissolved P concentration in the LMW. In the simplest terms, the results suggest that the effects of extreme precipitation on water quality are exacerbated in the presence of manure, and, vice-versa, that the effects of manure on water quality are exacerbated by extreme precipitation. Despite a mechanistic link with dissolved P losses only, the interaction was statistically significant for total P at the field scale, stream scale, and lake scale. This implies that manure management choices can have important implications for water quality at all spatial scales of a watershed. There is already a need for improved nutrient management in watersheds such as the LMW to curtail the effects of excessive terrestrial P supply. Our results further underscore the importance of improved manure management to mitigate the compounding effects of extreme precipitation. Practices that reduce the amount of manure P applied, and/or avoid unincorporated surface application may potentially mitigate the synergy, although further research is recommended.

Given the difficulty in measuring and attributing the effects of changing climate, land use, and land management on water quality, process-based, spatially explicit models provide a way to isolate,
identify, and scale-up important mechanisms affecting water quality; in this case the specific interaction between terrestrial nutrient supply and the hydrologic cycle. Watershed models are however dependent on observations, such as the field studies of manure, fertilizer, and soil P leaching that formed the basis for the P cycling routines in SurPhos and Agro-IBIS. A lack of spatially-explicit land management data, such as nutrient application rates and tillage information, represents a common yet important limitation to watershed modeling efforts. In this study we demonstrated a mechanistic link between extreme precipitation and an overabundance of terrestrial P, yet it remains unknown to what extent absolute estimates of P loss would be affected by higher (or lower) quality nutrient and tillage management data. These data limitations coupled with the complexity of representing watershed hydrology and biogeochemistry contribute to uncertain model estimates of water quality (Zheng and Keller 2007). Despite these limitations, field observations and modeling will continue to represent an important, complementary approach for furthering watershed and ecosystem science. Continued advancements in modeling and access to high quality data will be needed to better understand the challenges facing freshwater resources in the future.

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