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Evaluating Causes of Trends in Long-Term Dissolved Reactive Phosphorus Loads to Lake Erie

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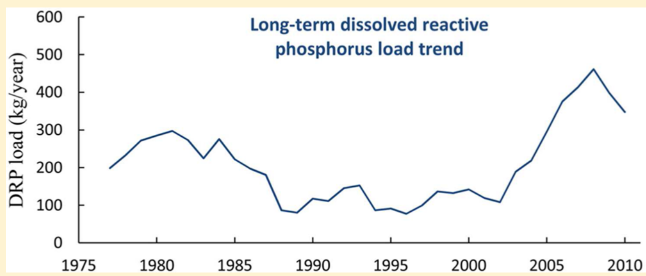
ABSTRACT: Renewed harmful algal blooms and hypoxia in Lake Erie have drawn significant attention to phosphorus loads, particularly increased dissolved reactive phosphorus (DRP) from highly agricultural watersheds. We use the Soil and Water Assessment Tool (SWAT) to model DRP in the agriculture-dominated Sandusky watershed for 1970−2010 to explore potential reasons for the recent increased DRP load from Lake Erie watersheds. We demonstrate that recent increased storm events, interacting with changes in fertilizer application timing and rate, as well as management practices that increase soil stratification and phosphorus accumulation at the soil surface, appear to drive the increasing DRP trend after the mid-1990s. This study is the first long-term, detailed analysis of DRP load estimation using SWAT.



1. INTRODUCTION

In the 1960s and 1970s, Lake Erie experienced significant cultural eutrophication from excessive phosphorus loading from both agricultural runoff and point source discharges.[1] Responding to concerns about the consequences of eutrophication in the 1970s, the governments of the U.S. and Canada, largely through the Great Lakes Water Quality Agreement,[2] implemented a program of phosphorus load reduction. The initial approach of reducing point-source loads alone was not adequate to achieve target loads set by the Agreement,[3] so subsequently, a combination of point and nonpoint phosphorus load reductions was used.[4] This combination of load reductions led to achieving the target load of 11 000 metric tons per year in most years with weather influencing year-to-year variability in nonpoint source loads. The response of the lake was rapid and profound with reduced algal biomass and reduction of low oxygen conditions in the central basin.[4−6] With reductions in point-source loads, in recent decades, nonpoint sources, particularly from agriculture, have become dominant sources of phosphorus.[7]

In the 1980s and 1990s, the main conservation policy goal for limiting nonpoint-source pollution was to reduce sediment runoff and the phosphorus attached to sediments; therefore, most conservation efforts focused on erosion reduction.[8] These efforts, following implementation of the Great Lakes Water Quality Agreement, resulted in reductions in suspended solids and particulate phosphorus in Lake Erie tributaries, especially under low flow conditions compared to high flow conditions in spring.[9] However, despite decades of improvements in nutrient control, there have been unexpected recent increases in harmful algal blooms and poor water clarity in the western basin and summer hypoxia (low oxygen) in the hypolimnion of the central basin.[10] Because of their significant potential impact on food web interactions and fisheries,[11] this has brought renewed policy attention on nutrient control.

While the Great Lakes Water Quality Agreement[2] focused on total phosphorus (TP) as the water quality parameter by which Lake Erie eutrophication is to be managed, recent research indicates that dissolved reactive phosphorus (DRP) is of great importance because it is highly bioavailable.[11,12] The National Center for Water Quality Research (NCWQR) at Heidelberg University has monitored streamflow and water quality daily from 1975 to the present,[13] revealing a perplexing trend in DRP loads, where this highly bioavailable form of phosphorus declined through the early 1990s but then increased since the mid-1990s. This trend is observed in the agricultural tributaries of Lake Erie (Maumee and Sandusky)[12] and is particularly significant in the Sandusky watershed (Figures 1 and 2). Moreover, the rate of oxygen depletion in the central Lake Erie basin is strongly correlated with DRP load since the mid-1990s.[14] It is important to note that, even though DRP load trends can be affected by trends in flow, similar trends are reported for DRP river concentration,[9,12] indicating that changes in the loads of DRP are not solely a function of changes in hydrology.

Herein, we use the Soil and Water Assessment Tool (SWAT) to explore the role of several potential causes of the recent increases in DRP loading suggested by the Ohio P Task Force:[8] (1) changes in fertilizer application rates; (2) widespread adoption of no-till and conservation tillage practices after the mid-1990s; (3) stratification of phosphorus (P) in the

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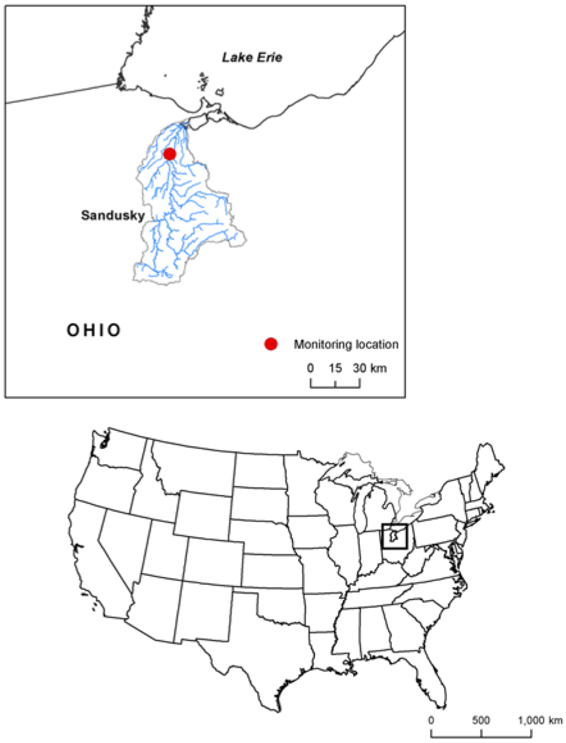

Figure 1. Locator map of the Sandusky watershed, Ohio.

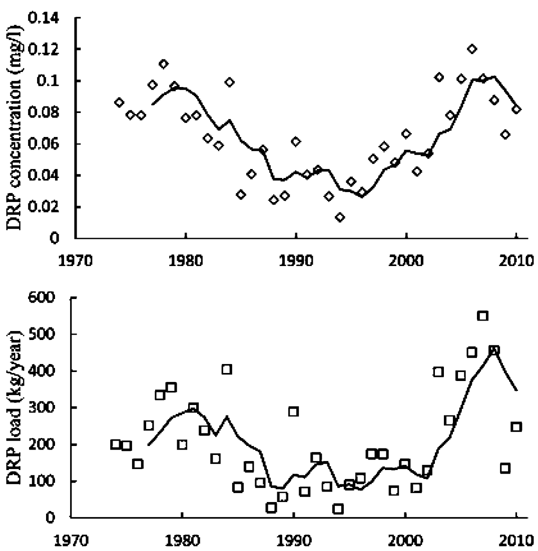

Figure 2. Observed mean annual dissolved reactive phosphorus (DRP) load and concentration in the Sandusky River, OH (1974–2010) with a moving four year average trendline.

soil surface layer; and (4) changes in rainfall patterns. We focus on the Sandusky watershed because it is representative of the other agriculturally dominated watersheds, has extensive (daily) flow and water quality data, and is small enough to allow SWAT to be applied at farm scale resolution. Our approach is to fully calibrate and evaluate the model to 40 years of observations and then explore the impact of hypothetical management and weather scenarios on DRP loading.

1.1. Study Area. The Sandusky watershed, located in northwest Ohio, is a 3926 km^2 watershed (Figure 1) that drains into Lake Erie. The dominant land use is agriculture (77%), where farmers specialize in corn, soybean, and winter wheat rotations, with minor livestock production. Daily discharge as well as sediment, TP, and DRP loads are provided by NCWQR at Heidelberg University for the simulation time period.[13]

2. METHODS

SWAT is a continuous-time, integrated, watershed-scale hydrologic and water quality model that runs at a daily time step.[15] It is a process-based model of weather, surface hydrology, sedimentation, soil temperature, crop growth, nutrients, pesticides, and groundwater that can simulate the effects of climate and agricultural management changes on nutrient and sediment delivery from watersheds.[16]

SWAT is considered suitable for simulating long-term impacts of agricultural best management practices (BMPs)[17] and land management measures on water, sediment, and agricultural nutrient loss from large, complex watersheds with varying soils, land use, and management measures.[18] SWAT simulates the transformation and movement of nitrogen and phosphorus in several organic and inorganic pools,[19] where nutrient losses from soil occur through crop uptake, surface runoff, and eroded sediment.[20]

SWAT is a semidistributed model with the hydrologic response unit (HRU), representing unique combinations of land cover, soil type, and slope, as the fundamental computational unit. Runoff flow, sediment, and nutrient loads are calculated separately for each HRU and summed to determine total load contribution from subwatersheds.[19] We employed the model at a spatial scale such that the average HRU size corresponds to the average farm size in the Sandusky basin (105 ha),[21] resulting in 147 subbasins and 959 HRUs.

Bosch et al.[22] used SWAT to simulate tributary sediment and nutrient loading from six watersheds draining into Lake Erie, including the Sandusky, albeit at a much coarser physical scale and shorter time period. Their simulation period was 1998–2005 and thus not sufficient to capture the significant changes in DRP load, especially during the early and mid-1990s. So, we extended the modeling period to calibrate and evaluate the model with the extensive daily observed flow and water quality data from 1974 to 2010 for stream discharge, sediment, TP, and DRP loads.[13]

We calibrated the model for 1991–2010 and evaluated it for 1974–1990, with 1970–1973 as spin-up years using daily flow discharge, sediment, TP, and DRP loads.[13] We used the extensive empirical data of high quality (10 918 data points for 1975–2010, i.e., on average 303 data points for each year for 36 years). We used the Sequential Uncertainty Fitting (SUFI2) method,[23] a stochastic procedure, and additional manual calibration to first calibrate for flow and then for sediment, TP, and DRP loads. Table 1 shows flow and DRP parameters with their ranges for the sensitivity analysis and calibrated values. Model performance (Tables 2 and 3) was considered satisfactory for use in this study based on the coefficient of determination (R^2), Nash–Sutcliffe efficiency (NSE), and percent bias (PBIAS), based on criteria developed by Moriasi et al.[23]

2.1. Baseline Scenario. Our baseline scenario uses a realistic representation of trends in weather and agricultural landscape in the Sandusky watershed between 1970 and 2010. Agricultural operations for tillage practices, fertilizer inputs and application timing, and crop choices for the simulation period are generalized from the most common agricultural land management practices in the watershed. In this region, cash-crop agriculture production with rotations of soybean, corn,

Table 1. Sensitivity Analysis Results for Flow and DRP Parameters

parameter	min	max	rank flow	rank DRP	calibrated value	definition
ESCO	0	1	1		0.99	soil evaporation compensation factor
REVAPMN	0	500	2		278.50	threshold depth of water in the shallow aquifer for percolation to the deep aquifer (mm H_2O)
CN2	35	98	3		86.97	initial SCS runoff curve number for moisture condition
SMFMX	0	10	4		4.52	melt factor for snow on June 21 (mm H_2O/°C day)
SOL_AWC	0	1	5		0.02	available water capacity of the soil layer (mm H_2O/mm soil)
EPCO	0	1	6		0.12	plant uptake compensation factor
SOL_K	0	2000	7		571.33	saturated hydraulic conductivity (mm/h)
SMTMP	−5	5	8		2.37	threshold temp for snowmelt (°C)
GW_DELAY	0	500	9		204.83	groundwater delay time (days)
SFTMP	−5	5	10		3.93	snowfall temp (°C)
SMFMN	0	10	11		8.55	melt factor for snow on December 21 (mm H_2O/°C day)
CANMX	0	100	12		15.57	maximum canopy storage (mm H_2O)
TIMP	0	1	13		0.60	snow pack temperature lag factor
CH_K2	−0.01	500	14		39.82	effective hydraulic conductivity in main channel alluvium (mm/h)
SURLAG	0.05	24	15	4	10.44	surface runoff lag coefficient
CH_N2	−0.01	0.3	16		0.02	Manning's "*n*" value
ALPHA_BF	0	1	17		0.98	baseflow recession constant
PHOSKD	100	400		1	292.63	phosphorus soil partitioning coefficient
PSP	0.01	0.7		2	0.44	phosphorus sorption coefficient
P_UPDIS				3	20.00	phosphorus uptake distribution parameter
PPERCO	10	17.5		5	5.48	phosphorus percolation coefficient

Table 2. Calibration and Evaluation Results for Daily Stream Discharge (m^3/s)[a]

		observed mean (m^3/s)	simulated mean (m^3/s)	R^2	NSE	PBIAS (%)
calibration (1991−2010)	daily	34.8	31.2	0.55	0.54	9.79
	monthly	35.8	31.9	0.74	0.72	10.96
	annual	35.8	31.9	0.77	0.61	10.83
evaluation (1974−1990)	daily	33.8	30.4	0.50	0.49	9.91
	monthly	34.1	30.6	0.65	0.63	10.25
	annual	33.9	30.6	0.74	0.59	9.67

[a]Coefficient of determination (R^2), Nash−Sutcliffe efficiency (NSE), and percent bias (PBIAS) are used to evaluate the model performance. Model simulations for flow are accepted as satisfactory if NSE > 0.5 and PBIAS ± 25%.[24]

Table 3. Calibration and Evaluation Results for Annual Sediment Loading (Sed, tons/year), Total Phosphorus (TP, kg/year), Dissolved Reactive Phosphorus (DRP, kg/year), Organic Phosphorus (OrgP, kg/year)[a]

annual		R^2	NSE	PBIAS (%)
calibration (1991−2010)	Sed	0.59	0.55	−7.42
	TP	0.62	0.55	−6.41
	DRP	0.71	0.62	−16.52
	OrgP	0.50	0.37	−4.42
evaluation (1974−1990)	Sed	0.43	0.30	15.71
	TP	0.21	0.11	9.44
	DRP	0.32	0.30	−0.32
	OrgP	0.14	−0.04	11.23

[a]Coefficient of determination (R^2), Nash−Sutcliffe efficiency (NSE), and percent bias (PBIAS) are used to evaluate the model performance. Model simulations are accepted as satisfactory if NSE > 0.5 and PBIAS ± 55% for sediment and PBIAS ± 70% for nutrients.[24]

and winter wheat is widespread. According to Richards et al.,[9] corn acreage in the Sandusky area has not changed significantly, while soybean acreage has increased and winter wheat acreage has decreased since the 1970s. For land cover types other than agriculture, such as residential, industrial, pasture, forest, and wetlands, we constructed operation schedules based on the most common management practices.

Because fertilizer application is the largest input of both nitrogen and phosphorus in the agricultural watersheds of Lake Erie,[25] the amount of phosphorus application is a key management consideration, and these rates have changed over the simulation period in the Sandusky watershed.[26] In our baseline scenario, we used watershed-scale nutrient budgets constructed for the Lake Erie watersheds to represent temporal variation in application rates.[27] Trends in the Sandusky show higher fertilizer application rates in the 1970s and after a reduction in the 1990s, an increase during the past decade.

The baseline scenario also reflects changes in the long term adoption rates of no-till and conservation tillage. Agricultural land under conservation tillage has at least 30% of crop residue from the previous year on the soil surface, and under no-till practices crops are planted with no soil disturbance in the crop residue of the previous year.[8] These practices were minimally adopted in the early 1980s and approached nearly 50% by the mid-1990s.[7,9,28] This increase is due to the Great Lakes Water Quality Agreement that promoted best management practices that reduce sediment runoff from agricultural fields (i.e., conservation tillage and no-till practices), which resulted in reductions in flow-adjusted concentrations of suspended solids and particulate phosphorus in Lake Erie tributaries.[9,12] However, under no-till practices, phosphorus can accumulate in the soil surface layer because crop residue and surface P are not mixed into the soil column.[29−31] Moreover, no-till practices can increase soil stratification and accumulation of residual fertilizer P at the top of the soil profile and potentially intensify DRP runoff.[29] In fact, widespread adoption of no-till and conservation tillage practices corresponds in time with the increased DRP loading after the mid-1990s. In addition to no-till and conservation tillage practices,[29] fertilizer application exceeding crop needs[32] and surface application (broadcasting) of P fertilizer and manure[12] have also lead to an increase in P accumulation in the soil surface layer and to a higher likelihood of P runoff from agricultural fields.[33,34]

SWAT incorporates certain agricultural management practices such as tillage practices, fertilizer input and time of application, and a number of model parameters governing phosphorus generation and transformation in different P pools. After investigating the governing equations and mechanisms for P transformation and generation, both Radcliffe et al.[34] and Vadas and White[35] suggest that certain model parameters should be modified to reflect soil types and soil test phosphorus levels. For example, model parameters such as the P soil partitioning coefficient (PHOSKD), P availability index (PSP), initial labile P concentration (SOL_SOLP), and organic P concentration (SOL_ORGP) in the surface soil layer should be determined by soil types and can be estimated using soil test phosphorus values and soil properties.[35,36] Radcliffe et al.,[34] suggest that the P availability index (PSP), rate of exchange between the inorganic labile P and active P pools in soils, should be spatially dynamic and calculated using the soil P concentration, clay content, and organic C content. Using the suggested methodology by Radcliffe et al.,[34] we calculated the area-weighted average of PSP for the entire Sandusky watershed for the simulation period.

Based on our sensitivity analyses, PHOSKD is the most sensitive parameter for calibrating to DRP observations (Table 1). Because the standard version of SWAT is not capable of representing some of the mechanisms responsible for soil stratification and accumulation of P at the soil surface layer, we used the P soil partitioning coefficient (PHOSKD), the ratio of the soluble phosphorus concentration in the soil surface layer to the concentration in surface runoff,[19] as a proxy representing the vulnerability of P to runoff from the soil surface layer. Increased adoption of no-till and conservation tillage after 1995, coupled with surface application of fertilizers, increased soil stratification and accumulation of P at the soil surface layer. Low values of PHOSKD allow more P runoff, and therefore, decreasing PHOSKD after the mid-1990s reflects this increased susceptibility of P runoff due to soil P stratification (Figure 3).

Loss of DRP from watersheds is likely to be correlated strongly with storm events,[37] and therefore, weather patterns may have influenced trends in DRP runoff from agricultural land.[8] Fertilizer application time, relative to weather patterns, therefore is another potential factor driving increased DRP yields. Traditionally, farmers apply fertilizer before planting crops, usually in spring. However, economic and practical incentives such as lower fertilizer prices and labor and equipment availability motivate farmers for fall application.[8] The runoff potential of nutrients, especially DRP, is higher in fall because the ground is bare and plant roots are not available or deep enough for nutrient uptake.[12] However, because fertilizer sales are reported on an annual basis, there is no

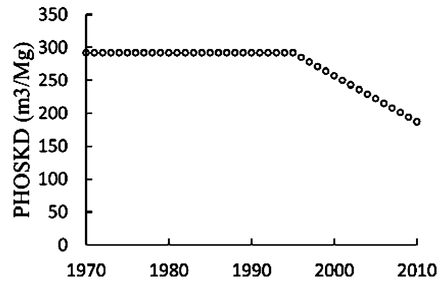

Figure 3. Time-dependent P soil partitioning coefficient, PHOSKD (m^3/Mg) as a proxy to reflect the impact of soil stratification and P accumulation at the soil surface layer.

accurate method to determine month of application. Therefore, for our baseline scenario, we relied on previously conducted surveys with the farmers in the area[38,39] and informal conversation with the extension agents to determine the percentage of spring versus fall application over the 40 year simulation period. Within the dominant crop rotations, winter wheat always has fall fertilizer application. In the early 1980s, corn farmers started broadcasting fertilizers in the fall after harvesting soybean. The transition to fall application started slowly but increased rapidly as farm size increased. Currently, many large farmers choose fall broadcasting; however, there appears to be a more recent trend back to spring application.

3. RESULTS

3.1. Baseline Scenario. While we evaluated the model adequacy against daily, monthly, and annual measurements, we use four year running averages in our scenario analysis because we are more interested in exploring the long-term trends in DRP loads rather than in studying year-to-year fluctuations (Figure 4a). The baseline scenario has satisfactory model statistics for flow discharge, sediment, TP, and DRP loads (Tables 2 and 3) and is in accordance with the long-term DRP trends.

3.2. Fertilizer Application Rate Scenario. The baseline scenario includes a variable fertilizer application rate that decreases in the mid-1980s and then increases in the early 2000s. To understand whether the pattern driving the DRP trend is due to changes in fertilizer application rates, we generated hypothetical scenarios that kept application rates at constant high (1970s) and low (mid-1990s) values (Figure 4b). From this analysis, it is clear that fertilizer input influences the magnitude of DRP load but does not appear to be the major factor responsible for the long-term DRP trend.

3.3. Tillage Practices Scenario. Our baseline scenario used documented historical adoption trends of conservation tillage and no-till practices. We compared those results with two scenarios, one where all agricultural land was under no-till practices and another under conventional tillage. The simulation results indicate that agricultural land under no-till practices yields consistently more DRP compared to the baseline or conventional tillage scenarios (Figure 4c) and that the shift from conventional to no-till appears to contribute to the overall trend because the baseline simulation mimics the 100% conventional tillage curve in early years and the 100% no-till curve in later years.

3.4. P Accumulation in the Soil Surface Layer. To represent the accumulation of soil P in the soil surface layer in the baseline scenario, we varied the P soil partitioning coefficient (PHOSKD) after 1995 (Figure 3) to reflect the

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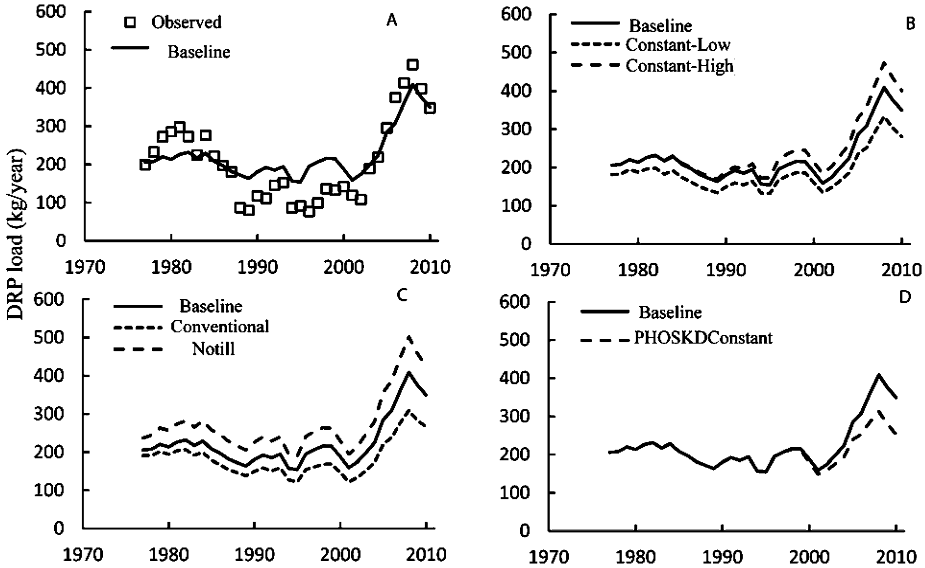

Figure 4. Comparison of mean annual DRP (kg/year) load under the baseline scenario and (a) the observed DRP loads, hypothetical scenarios of (b) constant fertilizer application rate, (c) tillage practices, and (d) without soil stratification. All trends are represented with a moving four year average trendline.

impact of adoption of no-till practices and surface application of fertilizers. To test the sensitivity of the model to that effect, we ran a scenario holding PHOSKD constant at the calibrated value equal to 292 m^3/Mg. In this scenario, DRP load is lower through the early 2000s, unlike the baseline loads, suggesting that soil stratification and buildup at the soil surface layer is a significant driver in long-term DRP runoff (Figure 4d).

3.5. Weather. We evaluated precipitation patterns for the simulation period (1970–2010) to see if the frequency of extreme events in the study area changed during the spring and fall fertilizer seasons. We defined extreme events as events with precipitation magnitude above the 85th percentile for the period of record (1970–2009). The frequency of these extreme events during the first three decades was relatively stable in fall and increased in spring (Figure 5a). It is also clear that the frequency increased more dramatically in both spring and fall fertilizer seasons in the past decade, shortening the fertilizer application window and perhaps increasing the potential for enhanced runoff.

The baseline scenario incorporated daily rainfall, minimum and maximum air temperature, wind speed, relative humidity, and solar radiation for the simulation period (1970–2010). To explore the impact of weather trends, including storm intensity, on the long-term trend in DRP load, we ran two scenarios: one with randomized weather input and one with "reversed weather". In both cases, we retained the within-year variability but modified the orders in which the years were applied. For the random weather case, we ran 10 simulations with weather years randomized and show results for a representative simulation. For the "reversed weather" simulation, we switched 2010 weather with 1970, 2009 weather with 1971, and so forth.

Randomizing weather produced the expected result of flattening the trend, (Figure 5b and data not shown) indicating that weather is an important factor in explaining the observed year-to-year variation in DRP loading. In addition, the "reversed weather" case revealed an interesting potential interaction effect with land cover and land management. While the reversed weather patterns did appear to produce somewhat higher loads in the 1970s and similar loads through the early 2000s, the most dramatic effect was in the latter years (Figure 5b). Apparently, the conditions on the land in the earlier decades, particularly in the 1970s when there was mostly conventional tillage and spring fertilizer application, made runoff less vulnerable to higher-frequency storms that were employed in the "reversed weather" scenario.

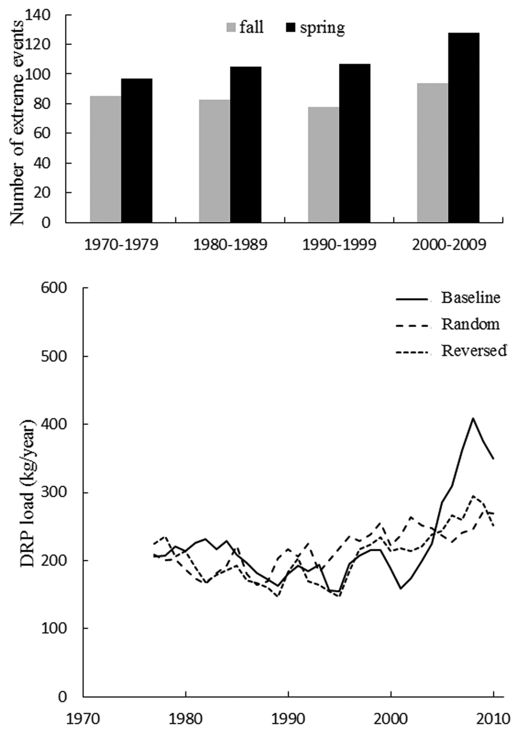

Figure 5. Frequency of extreme events (above 85th percentile) in the spring and fall fertilizer season where x axis denotes decades and comparison of mean annual DRP (kg/year) load under the baseline scenario with observed weather pattern and the hypothetical scenario with reversed and random weather patterns. All trends are represented with a moving four year average trendline.

4. DISCUSSION

The somewhat perplexing trend of increased DRP loading from the Sandusky watershed since the 1990s has attracted significant policy attention. To better understand the impacts of land management (i.e., fertilizer application management and adoption of no-till and conservation tillage) and weather patterns on DRP loading, we compared realistic representations of the agricultural landscape with hypothetical scenarios.

The baseline scenario, with the most representative agricultural operations for fertilizer inputs and application timing, tillage practices, and crop choices for the simulation period (1970–2010), matched the observed loads of sediment and various forms of P well. Our focus was on the long-term DRP loading trend, and our baseline scenario captured the long-term trend well (Figure 4a).

To understand the impact of each potential driver of the long-term DRP load trend, we generated hypothetical scenarios. Keeping the fertilizer application rate constant at high 1970s and low mid-1990s values suggested that, while the input rate influences the magnitude of DRP runoff, it does not appear to be the major factor in shaping the long-term DRP trend. However, if application rates during the 40 year period were held at 15% lower than today's rate, then today's load of DRP would be 25% lower (Figure 4b).

Similar to fertilizer inputs, changes in tillage practices influenced the magnitude of DRP runoff and appear to have had some influence on the overall temporal DRP pattern. However, since the SWAT model does not include all of the impacts of no-till practices and surface application of fertilizers in the soil surface layer P accumulation and stratification, we modified the phosphorus soil partitioning coefficient (PHOSKD). This allowed us to better represent P accumulation in the soil surface layer due to adoption of no-till and conservation practices and broadcasting fertilizers in the baseline scenario. When PHOSKD values are kept constant, the trend in the load is lower through the early 2000s but still increases after 2005, signaling the importance of other possible mechanisms, such as the impact of weather.

Precipitation frequency and intensity influence the loss of nutrients following fertilizer application to agricultural fields. Applying fertilizer before storm events increases nutrient runoff, and fertilizer applied in fall would have longer exposure to precipitation and therefore to runoff.[40] Analyzing the precipitation data for the Sandusky watershed indicates that recent spring and fall fertilizer seasons have had more extreme events compared to previous decades. Similarly, analyses of Midwestern storm events indicate increased number of large storms in the past decade.[41] Our hypothetical scenarios investigating the impact of weather on DRP loading by randomizing as well as reversing the precipitation record showed that the interaction of more storms with changes in agricultural practices adopted in the recent decades, particularly in the mid-1990s (increase in no-till and broadcast fall fertilizer application), have likely led to the observed increase in DRP loads.

While these analyses are important in evaluating the potential causes of long-term DRP loading changes from the highly cultivated agricultural watersheds of Lake Erie, it is important to note that the SWAT model does not allow for the inclusion of other possibly important hydrological mechanisms such as the formation of ephemeral gullies. Moreover, when evaluating the impact of tillage systems on DRP runoff, we need to note that rotational tillage, where the fields are tilled every other year instead of continuous no-till practices, seems to be an increasingly common practice in the study area. More research is needed on the impacts of rotational tillage on DRP runoff. Stratified soil P tests, detailed farmer surveys regarding fertilizer application times, and inclusion of more processes in SWAT to better represent soil stratification and P accumulation would lead to better informed modeling efforts. For example, fertilizer application time was not included as a separate scenario in our analyses due to SWAT limitations. To evaluate the impact of fertilizer application timing, we would have to keep the fertilizer application date the same throughout the simulation period that could result in unrealistic fertilizer application during precipitation events. With this limitation, the outcome of the hypothetical fertilizer application date scenario would depend on the frequency of having a precipitation event on the randomly selected date, which would be biased.

Evaluation of the scenarios demonstrated the importance of P stratification in the soil surface layer and increased frequency of storm events observed in the past decade in the recent rise of DRP exported from western Lake Erie tributaries. Climate projections for the Midwest region indicate trends toward even more intense and frequent storms during the spring and winter seasons.[42] Therefore, attention to actions that remediate nutrient, especially DRP, runoff from the agricultural landscape during such storms is needed.

Our model results emphasize the need to focus on agricultural practices and their impact on water quality. For instance, broadcasting fertilizer on bare ground in fall results in unincorporated nutrient accumulation that is vulnerable to runoff until spring. Moreover, according to Kleinman et al.,[28] broadcasting P fertilizer onto no-till or conservation tillage fields results in higher DRP runoff. Therefore, to reduce P accumulation in the soil surface layer, incorporation of fertilizer especially under no-till practices is highly encouraged. As promoted by the fertilizer industry and the USDA under the Nutrient Stewardship program,[42] adjustments in agricultural management practices to achieve the right rate, time, and place of fertilizer application can attain reduction in DRP runoff from agricultural landscapes.

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Notes

The authors declare no competing financial interest.

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