The implications of environmental policy on nutrient outputs in agricultural watersheds

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INTRODUCTION

Since the 1980s, more than $1 billion per year has been spent on agricultural conservation programs nationwide aimed at improving water quality. These programs have focused on removing land from production, trapping nutrients in farm fields via practices like conservation tillage, shifting the timing of nutrient applications, and other practices. For example, the Conservation Reserve Program (CRP), which began in the 1980s, is aimed at removing highly erodible land from agricultural production. By the early 1990s, over 30 million acres had been set aside in CRP nationwide. Many of these fields remain out of agricultural production today. In addition to CRP, conservation tillage has long been promoted as a management practice that can reduce soil erosion. Now, conservation tillage is widely adopted, with about 63% of all cropped acres in the US having some form of conservation or reduced tillage (CTIC, 2013).

The 1996 Farm Bill substantially increased the subsidies available to farmers to reduce pollution. Nationally, payments for conservation programs doubled from $1.7 billion to $3.5 billion from 1996 to 2010, or around $10 per acre of farmland. The largest program, the Environmental Quality Incentive Program (EQIP) provides a wide range of incentive payments, but in particular aims to reduce pollution from large livestock operations. By law, 60% of the funds in EQIP are to be used to assist farmers in reducing the impact of livestock waste. In 2000, quality regulations were implemented nationwide by the Environmental Protection Agency to reduce pollution from large livestock operations. These regulations required the nation's largest livestock operations to obtain permits to emit nutrients into waterways, in an attempt to treat them similarly to other large sources of pollution, like municipal waste water treatment plants.

Given all these efforts, there should be some measurable improvement in water quality, however, over the past several decades, water quality actually appears to have worsened. In 1996, for example, 36% of measured rivers and streams were impaired (USEPA, 1996), and in 2010 56% of measured streams were impaired (USEPA, 2010). The leading source of impairment in 1996 and 2010, according to the US EPA, was agriculture. Detailed analysis of water quality samples in the Mississippi river basin illustrates that that the concentration of nutrients continues to rise (Sprague et al., 2011). Industrial and urban sources contribute to loading, but modeling studies estimate that agriculture contributes over 75% of the nitrogen (N) and phosphorus (P) in the Mississippi River Basin (Alexander et al., 2008) and the Great Lakes (Robertson and Saad, 2011). Much of the land in the United States is devoted to agriculture. With strong growth in the agricultural sector in recent years, these trends are likely to continue.

Numerous economic simulation models have been constructed to assess the effects of installing best management practices in agricultural watersheds (e.g., Piper et al., 1989; Wu and Segerson, 1995; Wu et al., 2004). Few, if any, studies have used empirical data to examine whether these policies have improved water quality. There are a number of reasons for this, but perhaps the most important is that it is difficult to find data with a long enough record to assess water quality changes before and after implementation of programs. To address this issue, we use detailed data from several watersheds in Ohio that are primarily agricultural, with more than 80% of the land being used for crops. Water quality in these two watersheds has been continually assessed on a daily basis since the 1970's by the National Center for Water Quality Research at Heidelberg College (Heidelberg University, 2012).

For the analysis in this paper, we focus on the concentration of phosphorus in two Midwestern streams. Phosphorus is one of the most important crop nutrients, particularly for Midwestern row crops, but it is also is one of the most harmful nutrients, causing harmful algal blooms in freshwater ecosystems. Over the past several years, Lake Erie has experienced a number of harmful algal blooms, and other smaller lakes in Ohio have been similarly affected by phosphorus.

Our analysis models the concentration of phosphorus in agricultural streams as a function of a number of economic, ecological, and policy variables. We hypothesize that nutrient outputs from watersheds result from nutrient inputs by farmers, weather, water flow, and policy variables. The model illustrates that phosphorus emissions are inversely related to phosphorus prices, and positively correlated with corn prices. The policy variables illustrate that despite years of effort, there is little discernible effect of agricultural conservation programs on phosphorus concentrations in the river systems we analyze. There have been some modest changes in seasonality of phosphorus concentrations, but the improvements likely have little to do with conservation programs, and more to do with broader economic trends.

MODEL AND DATA

The key output measure of interest in this analysis is the nutrient concentration at the outflow of a watershed. The data we use on nutrient concentrations is obtained from the National Center for Water Quality Research at Heidelberg University (Heidelberg University, 2012). As noted above, they have collected data on a number of streams in Ohio and surrounding states for many years. The two watersheds we examine are the two they have monitored for the longest period of time, the Maumee river watershed and the Sandusky river watershed, which both have been monitored by Heidelberg College since the mid-1970s (Table 1). These watersheds are primarily agricultural, and have annual concentrations of phosphorus that are actually higher than the typical emission level allowed by point sources.

Nutrient concentrations are measured in mg/L, or parts per million (ppm). The specific nutrient concentration variable used in this analysis is the average daily concentration of phosphorus. Within our dataset, the daily concentration is obtained from a single observation or from multiple observations over the course of the day. During low flow periods, typically a single observation of water quality is taken each day. Because the flow does not vary much over the day when flows are low, a single measurement taken at a fixed time is assumed to be a representative estimate of the concentration of phosphorus on that day. During storm events, however, the flow will vary during the course of a day, and it is useful to take multiple water quality measurements. Each measurement is assumed to be representative of a given amount of time during the day. The flow weighted concentration can then be calculated for each day in which there are multiple measurements.

The daily concentration of nutrients in a watershed is function of the flow of water (cubic feet per second), weather variables (e.g., temperature and precipitation), the input of nutrients into crop production, the types of crops that are grown, the effort farmers put into reducing nutrient outputs, and the other sources of nutrients, such as point sources of pollution. For this paper, we conduct analysis on three different nutrient concentration measurements for two watersheds. The nutrient measures are for the concentration of soluble phosphorus, attached phosphorus, and total phosphorus (attached plus soluble). It is important to assess these measures separately because policies will have had different effects on each of them. For instance, point source regulations have focused on reducing soluble phosphorus while nonpoint source programs have focused on reducing attached phosphorus.

Perhaps the most important influence on nutrient outputs in the agricultural watersheds we examine is the input of nutrients by farmers. Unfortunately, we cannot measure nutrient inputs directly, particularly on a daily basis. We do, however, know prices for nutrient inputs, such as phosphorus. In a watershed where the farmers are price takers, nutrient prices should be inversely related to nutrient outputs from the watershed. Nutrient price increases will cause farmers to use fewer nutrient inputs. For our price variable we use the average price of phosphorus over the preceding three month period. We only have access to monthly data on phosphorus prices, obtained from the World Bank (World Bank Data, 2013), so many days in our sample have the same price.

To account for changes in crop types within the watershed, we utilize crop prices, focusing on corn. For this analysis, we use the corn price received by farmers, averaged for the state of Ohio on a monthly basis (USDA-NASS, 2013). Corn is one of the most prevalent crops in the two watersheds we model, and it is also one of the most nutrient intensive crops. Changes in corn prices should only influence crop choices at times of the year when farmers can actually make management changes in response, namely during the winter and early spring. Crop price changes are likely to have little effect in late spring and summer because crops are already growing and it is too late to change. We thus model seasonal price effects with interaction terms.

The flow of water in a watershed influences the concentration of nutrients. Typically, hydrology models suggest that there is a positive relationship between the flow of water and phosphorus concentration. Because there could be other factors correlated both with flow and nutrient concentration, such as temperature and precipitation, we also include temperature and precipitation in our model. Temperature and precipitation can have a large range of effects, from causing farmers to change management (alter the timing of nutrient inputs), to changing the rate of decay of plant material in fall and winter. For temperature and precipitation we use the previous 30 day average daily temperature and precipitation for the weather station at the Toledo Airport (National Climate Data Center). This airport is in the Maumee river basin, and within 30 miles of the Sandusky watershed. We use data from only one airport because it is the only airport in the region with continuous measurements over the entire time period.

We use dummy variables to account for policy and other factors not included directly in the analysis. First, we use annual dummy variables to capture trends over time. One of the most important trends is the reduction in point source pollution. Starting in the 1970s, the Clean Water Act required waste water treatment plants to reduce emissions of phosphorus into watersheds. These changes had relatively rapid impacts in Lake Erie watersheds (Dolan, 1993; Dolan and McGunagle, 2005). They should be having cumulatively larger effects over time as well since point source permits continue to be renewed with lower and lower limits on phosphorus pollution outputs. Nonpoint source pollution programs have also gotten more important over time. Efforts to increase conservation tillage started in earnest in the 1980s, as did the CRP. By the mid-1990s, the Farm Bill added new programs and substantially increased the funding for voluntary pollution control on farms. By the early 2000s, the new programs to regulate large livestock waste were in place. Taken together, one expects to see an increasing reduction in nutrient concentrations in these watersheds, via both point source and non-point source reductions.

To test for this, we introduce cumulative dummy variables that take on a 1 for all future years and a 0 for all previous years. Thus, the dummy variable for 1976 is a 1 for each observation in 1976 to 2011, and the dummy variable for 1977 is a 1 for each observation from 1977 to 2011, etc. The parameters on these dummy variables then can be interpreted as the marginal effect of our environmental policies in each year. If water quality improvement programs are being effective, these parameters should lie mostly below 0, and hopefully they are getting smaller and smaller. If water quality improvement programs are not working, these parameters will be 0 or above.

Second, we use monthly dummy variables to capture seasonal effects. There should be seasonality in phosphorus concentrations based on management needs and weather. For example, conservation tillage is a practice that should reduce soil erosion during fall, winter and spring months, and thus should reduce phosphorus that is attached to soil particles during those time periods. Over time, one would expect to see the monthly dummies in our equation for attached phosphorus falling for these time periods (November through March) relative to other months.

Alternatively, phosphorus is most likely to be spread in fall to early spring, after the crops have been harvested and before planting. It could be spread via either chemical means, or via manure fertilizer, but in both cases, it is likely to be spread when crops are not growing. Farm Bill conservation programs focus on getting farmers to put nutrients on their fields closer to the time when the nutrients will be used, that is later in the spring. This is particularly true for nutrients applied via manure. Farmers who use manure are not supposed to apply manure in winter, and when they do apply it they are supposed to incorporate the manure via plowing in order to keep the nutrient on the field until the crop starts to grow. USDA conservation programs have provided significant funding over the years for farmers to store manure for longer periods, so they can put it on fields closer to the time the crop grows. This policy should shift the timing of phosphorus outflows away from winter and towards spring and summer. In addition, there has been effort over the years to get farmers to change the timing of their chemical nutrient applications closer to the time when the crop is planted. These efforts, as well, should shift the outflow of nutrients away from fall and winter and into the late spring and summer. If these policies are being effective, we should also see a reduction in soluble nutrient concentrations during the winter months.

Given the incentives of agricultural policies, phosphorus emissions should have shifted away from winter. While this suggests that late fall and winter emissions should have declined, the same policies may or may not have increased emissions in spring and summer. Crop yields over the same time period more than doubled, so increased crop production would have used up a large proportion of the available phosphorus. We suspect actually that the increase in crop yields will have led to a reduction in phosphorus concentration during summer.

To test for changes over time, we interact the monthly dummy variables with three fixed effects representing different time periods. To isolate seasonal effects in the period before 1980 when point source pollution was the dominant contributor to phosphorus pollution, one seasonal dummy is included for the years before 1980. Then we include a seasonal dummy for the period 1980 – 1995. This represents the period before the implementation of the 1996 Farm Bill, which significantly increased funding for non-point source pollution reductions in farming. The final period is from 1996 to the present.

The following model is estimated with the log of nutrient concentrations on the left hand side:

$$\boldsymbol{lnQ_t = intercept + \sum_{m=1}^{11} \gamma_m\, d_{m,t} + \sum_{m=1}^{11} \varphi_m\, d_{m,t}\pi_{t=2} + \sum_{m=1}^{11} \rho_m\, z_{m,t}\omega_{t=3} + \sum_{m=1}^{34} \alpha_m\, year_{m,t} + \beta\, lnX_t + \epsilon_t}$$

In the model, Q_t is the concentration of phosphorus, measured in mg/L, or parts per millions (ppm). The first set of dummies are for the months in the base period (before 1980), the second set are for the months in the second period (1980 – 1995), and the third are for months in the third period (1996-2011). The yearly dummies are cumulative dummies that capture the cumulative effect of policy over time. The additional explanatory variables in X_t include nutrient price, crop price, water flow, temperature, and precipitation, as discussed above. All these variables are transformed by the natural logarithm.

RESULTS

The full set of regression results are shown in the appendix. For reporting purposes, we extract results from the full set of data and present them separately here. The results on effects of price changes, water flow, and the climate variables are shown in Table 2. The price of P has a negative and significant effect in the Maumee watershed for all three regressions; however, the size of the effect varies by regression. It is largest for the soluble P (SRP) regression and smallest for the attached P regression. Soluble P may arise from numerous sources, but one of the most important sources is the application of P by farmers. Attached P on the other hand is the phosphorus attached to soil particles. Because it takes some time for applied P to become attached to soil, and then it takes some time for soil to move through the system, there is a less direct link between the price of P and the movement of attached P in the watershed. The results are similar for the Sandusky watershed, however for that watershed, the P price is only significant in the case of the SRP regression. In the Sandusky watershed, changes in P prices have little effect on total P and attached P output.

A seasonal interaction effect on the 3 month lagged corn price has been included to test whether corn prices have a differential effect on P outputs across the seasons. The corn price parameter for fall and winter is positive for the attached P regression, which makes sense given that higher corn prices will induce more planting of corn and thus more plowing. Most planting decisions, however, are made by February or March at the latest, so it is not expected that the price of corn in spring or summer will have much of an impact on nutrient outputs. Interestingly, corn prices in all months have a negative effect on the soluble P concentration for the Maumee regression over most of the year, and they have a negative effect in for the fall price in the Sandusky equation. They are insignificant in other time periods in the Sandusky. These results follow research which suggests that plowing reduces dissolved P runoff (Zhao et al., 2001; Gilley et al., 2007a, 2007b).

Higher temperatures increase attached P and reduce soluble P in both watersheds. Greater precipitation increases soluble P runoff and reduces attached P runoff in both watersheds. This may seem a bit counter-intuitive, given that heavy rainfall is often associated with more soil runoff (and hence more attached phosphorus runoff), but the precipitation variable is an average over an entire month, so does not capture the effect of episodic storms that cause sediment runoff. We find that higher flow increases nutrient concentrations.

To assess whether environmental regulations have had an effect on nutrient concentrations, we examine the cumulative annual fixed effects in figures 1 and 2. The parameters are marginal effects, illustrating the additional change in average nutrient concentrations with each additional year. Trend lines are also shown. If the trend line is consistently below 0, then policies have been driving average P concentrations downward. Given that agricultural conservation programs have strengthened over time (at least in terms of dollar contributions from the federal government), we hypothesize that the effects of these programs on nutrients should become more prominent over time. The cumulative dummy variables used in this analysis allow us to test whether the effects of pollution abatement programs are increasing.

In both watersheds, soluble P concentrations were trending downward over the first half of our observation period. The most logical explanation for the reduction in soluble P concentrations is increase in regulations on point sources. Annual reductions in soluble P slowed over time, and by the mid-1990s, soluble P concentrations were again rising. These increases are not due to rising point source loads, which continued to decrease over time (Dolan and McCunagle, 2005). Given the different regulatory approaches over this time period, where regulations were imposed on point sources but not on agriculture, agricultural contributions to soluble P began to outstrip point source contributions over the time period.

Agricultural programs focused mostly on reducing attached P, and attached P trends are modestly negative for both watersheds over the observation period. In neither case, however, are the trends significantly negative. There are at least as many dummies that are positive and significantly greater than 0 as there are dummies that are negative and significantly smaller than 0. Given the strong focus in the farming community on reducing sediments through conservation tillage in order to reduce P loads over the past 30 – 40 years, this is very surprising. Richards et al. (2009) suggest that sediment has trended downward, but unfortunately this has not resulted in a significant reduction in attached P.

A second set of evidence to examine revolves around the monthly fixed effects, shown in Figures 3 and 4 for the Maumee and Sandusky river basins. With the interaction effects in the model, we plot the monthly fixed effects for the periods before 1980 (pre), 1980-1995 (mid), and 1996-2011 (post). The plots also provide confidence intervals to facilitate assessment of differences. For soluble phosphorus in the Maumee river basin, there was a large, statistically significant reduction in all months between the pre and the mid period. The most plausible explanation for these changes is the large reduction in point source contributions that occurred in the 1970s to the early 1980s (most point source contribution would be in the form of soluble phosphorus). The monthly dummies for the Sandusky watershed do not display the same type of change, that is there is no across the board reduction in the monthly dummies from one time period to the next for that watershed. The Sandusky watershed does not have a significant point source load, so it actually makes sense that the effects of point source reductions are not as obvious there.

From the 1990s to the 2000s (i.e., from the mid to the post periods), there is a reduction in soluble phosphorus from June through November in the Maumee watershed. We attribute this to rising crop yields (which use up more and more nutrient) and declining phosphorus inputs. There has been a relatively continuous 1-2% per year increase in crop yields over time, and greater crop yields should lead to greater use of nutrient. At the same time, survey data indicates that nutrient inputs have fallen since the 1970s (Bruuselma et al., 2011). Given these changes, it makes sense that soluble phosphorus would decline during the summer months in particular from the 1980s to the present. Although the change is not as great, a similar effect over the summer months is observed for the Sandusky watershed from the mid to the post period.

We should be able to observe some effects of agricultural policies. First, the most important policies have focused on getting farmers to adopt conservation tillage. Increasing levels of conservation tillage should reduce sediment losses in late fall, winter and spring, and therefore also reduce attached P during those time periods. In contrast to what we should see, we actually see an increase in attached P concentrations in both of these watersheds in the winter and spring. This is exceedingly surprising given the received theory on how conservation tillage is supposed to work.

Second, agricultural policies have also focused on getting farmers to shift their nutrient inputs from the fall and winter to the spring, that is, closer to the time when they are planting their crops. There is no evidence in our results that these efforts have had any impact on the intra-annual concentration of P in these watersheds. In the Maumee watershed, winter and spring soluble emissions fell from the 1970s through the 1980s, most likely due to reductions in point source emissions. They have not continued to fall since then in the Maumee. In the Sandusky watershed, soluble P concentrations in the winter may have increased since the mid-1990s.

POLICY ANALYSIS

In recent years, harmful algal blooms have increased in Lake Erie, with the primary culprit being phosphorus loading. Phosphorus loading increased by 17-22% in the watersheds we examine between the 1982-1995 period and the 1996-present period (Table 3). Interestingly, total water flow also increased in these two watersheds over this same time period, rising 20-27%. The increase in loadings could result from an increase in P emissions from farms, or it could result from the increase in water flow. The results in this table suggest that a large share of the increase in actual loadings resulted from the increase in flow. We are also able to use data from the same source to assess a nearby watershed that has substantially less agricultural activity, and which has more forest and urban land, the Cuyahoga river watershed. The sampling for this watershed is done well upstream from the city of Cleveland, so this does not include industrial emissions from the city itself. Flows did increase in the Cuyahoga watershed (+ 8%) over the same time period, but total P emissions did not increase. Higher flows actually lead to lower P emissions in the watershed that is only modestly influenced by agriculture.

One policy that could be used to reduce P emissions in these watersheds would be to tax P inputs. Our results indicate that P concentrations are inversely related to P prices. This makes sense given that one would expect higher prices to cause farmers to use less P on their fields and vice versa if prices are lower. The parameter on P price is more negative and more significant for the soluble P measure than the attached P measure. Thus, a10% increase in P prices will reduce soluble P concentrations by 3.3 to 4.3%. This result also makes sense given that there should be a fairly direct link between P inputs on farm fields and soluble P, while the link between P inputs on farm fields and attached P is influenced by a larger range of ecological and hydrological components. The effects of price changes on P outputs are of more than passing interest. The most important negative ecological effects result from soluble P. Thus, a tax policy that aims to reduce P inputs will have its most important impacts on soluble P emissions. The effect of a 25% tax on P inputs on total and soluble P is shown in Table 4. From just these two watersheds, this P tax can reduce soluble P concentrations by around 700 metric tons per year.

CONCLUSION

This paper assesses the role that environmental policies have played in reducing the concentration of nutrients in agricultural watersheds. Historical data on nutrient concentrations from two large watersheds is used to test whether nutrient prices, crop prices, environmental variables, and policy variables influence nutrient concentrations. One of the most interesting results we find is that nutrient prices are inversely related to nutrient concentrations in these agricultural watersheds. This indicates that higher nutrient prices will lead to lower nutrient concentrations in watersheds, a result that is not unexpected given the underlying demand relationship. We also find that the nutrient price elasticity is greater for soluble forms of P, suggesting that nutrient price policies, such as nutrient taxes, could have their largest impact on the output of the most ecologically harmful component of nutrients.

The results on crop prices indicate that higher fall and winter corn prices have a positive effect on attached P concentrations, while they have a potentially negative effect on soluble P concentrations. The attached P result follows if farmers shift more land into corn when they see higher corn prices. Shifting land into corn generally requires some plowing to prepare fields, while shifting to soybeans does not. This additional plowing likely causes more sediment to move into streams and with it, additional attached P. Soluble P, on the other hand, falls when plowing occurs

We use a series of annual dummy variables to assess whether policies that have been in place since the 1970s to reduce P pollution have had much of an effect on P pollution. The answer appears to be no. Soluble P fell in the 1970s and 1980s, but it has increased in the 1990s to the present. Attached P fell modestly in both watersheds, although the effects are not statistically significant. It is very difficult to show that policy has had any cumulative effect looking at these annual dummy variables.

Monthly dummy variables provide evidence that efforts to reduce point source pollution have had an impact on nutrient concentrations in these watersheds. In the Maumee watershed there is a statistically significant decrease in the monthly fixed effects for the soluble scenario in all months for the pre (1970s) to the mid (1980s to mid-1990s) period. There is a continued reduction in concentrations in the summer months for the mid to the post period (mid 1990s to present). This reduction in soluble P concentrations in summer and fall months potentially results from rising yields and falling nutrient inputs, both of which are phenomena that have been observed. There is a reduction in the Sandusky as well during the summer and fall months, although the reduction is not as prominent. The reduction in the Sandusky does become more prominent in the mid to post period, potentially illustrating the effects of rising yields and falling P input levels.

There is no evidence that agricultural policies to improve the environment have led to reductions in P. Attached P concentrations actually have risen over time in some winter and spring months in both watersheds, in contrast to what is expected to happen with the increase in conservation tillage. Soluble P concentrations have not fallen in recent years in fall and winter months, despite efforts to get farmers to shift their nutrient inputs from the fall and winter closer to the time they plant their crops.

In general, these result suggest that agricultural pollution abatement programs have had very little effect on water quality. In fact, relative to the perceived benefits of various programs (e.g. conservation tillage reducing attached P, nutrient management plans shifting P emissions towards spring), few trends are observed. We do find evidence that point source pollution reduction programs have had an impact on nutrient concentrations. There also is evidence that rising yields and falling P inputs in general have had an impact. Our results suggest that efforts to reduce P inputs via a tax mechanism would have the greatest impact on future water quality. A 25% tax on P in fact would reduce future loads by around 8% in the two watersheds

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Table 1: Watershed characteristics, years for samples, and flow information

	Total Area	Agricultural Area	Years	Average Annual Flow	Average Annual Total P
	hectares	hectares		$m^3 s^{-1}$	$mg L^{-1}$
Maumee[1]	1,640,162	1,474,506	1976-2011	156	0.40
Sandusky[1]	324,664	273,042	1976-2011	34	0.41

1) For the Maumee river watershed data for 1979 and 1980 are missing; for the Sandusky river watershed data for 1980 are missing.

Table 2: Parameter estimates for price and weather variables. Standard errors are shown in parentheses. Bold estimates are significant at 0.001 level; italic estimates are significant at 0.05 level.

	Maumee			Sandusky		
	Total	SRP	Attached	Total	SRP	Attached
Phosphorus	**-0.26** **(0.034)**	**-0.425** **(0.108)**	**-0.141** **(0.043)**	-0.074 (0.049)	*-0.331* *(0.105)*	0.031 (0.06)
Corn P winter	**0.453** **(0.041)**	**-0.188** **(0.131)**	**0.51** **(0.051)**	**0.423** **(0.055)**	0.394 (0.119)	**0.306** **(0.067)**
Corn P spring	0.156 (0.038)	**-0.409** **(0.125)**	0.211 (0.048)	0.156 (0.052)	0.393 (0.115)	-0.006 (0.063)
Corn P Summer	**0.08** **(0.044)**	-0.035 (0.144)	*0.106* *(0.055)*	0.021 (0.061)	0.128 (0.138)	-0.058 (0.074)
Corn P Fall	**0.229** **(0.037)**	**-0.257** **(0.121)**	**0.394** **(0.046)**	*0.069* *(0.051)*	*-0.089* *(0.114)*	**0.118** **(0.062)**
Temp	**-0.073** **(0.025)**	**-1.559** **(0.081)**	**0.535** **(0.032)**	**0.323** **(0.037)**	**-0.569** **(0.079)**	**0.747** **(0.044)**
Precip	-0.001 (0.008)	**0.364** **(0.026)**	**-0.092** **(0.01)**	**0.027** **(0.011)**	**0.219** **(0.023)**	*-0.039* *(0.013)*
Flow	**0.311** **(0.003)**	**0.320** **(0.011)**	**0.344** **(0.004)**	**0.475** **(0.004)**	**0.458** **(0.009)**	***0.491*** ***(0.005)***

Table 3: Estimates of average annual flow and average annual P loading over two time periods.

		Flow	Total P
		Billion Liters/yr	Metric tons/yr
Maumee	1982-1995	4,754	38,021
Maumee	1996-2011	5,717	44,341
	% change	*1.20*	*1.17*
Sandusky	1982-1995	1,070	7,759
Sandusky	1996-2011	1,364	9,523
	% change	*1.27*	*1.23*
Cuyahoga	1982-1995	898	2,589
Cuyahoga	1996-2011	967	2,595
	% change	*1.08*	*1.00*

Table 4: Policy effects of a 25% tax on P inputs purchased for agricultural use on Total and Soluble P emissions in the two watersheds examined.

		Total P	Soluble P
		Metric tons/yr	Metric tons/yr
Maumee	Base Annual	23,639	6,409
Maumee	25% P Tax	22,306	5,829
	Change	*(1,333)*	*(579)*
Sandusky	Base Annual	6,661	1,791
Sandusky	25% P Tax	6,552	1,663
	Change	*(109)*	*(128)*

Figure 1: Cumulative annual fixed effects for Maumee River Basin. The bars represent 95% confidence intervals for the parameter estimates, and the trend line is presented. Note that 1978-1979, and 1995 are omitted for Maumee.

Figure 1A: Total P fixed effectts Maumee River Basin

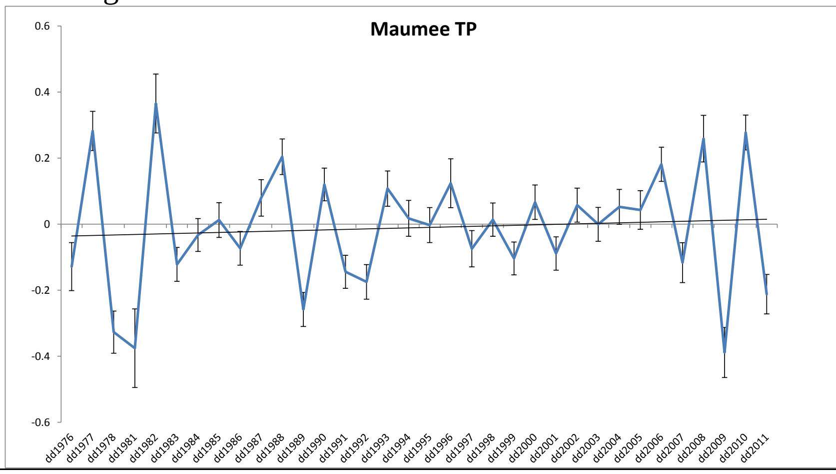


Figure 1B: Soluble Reactive P fixed effects in Maumee River Basin

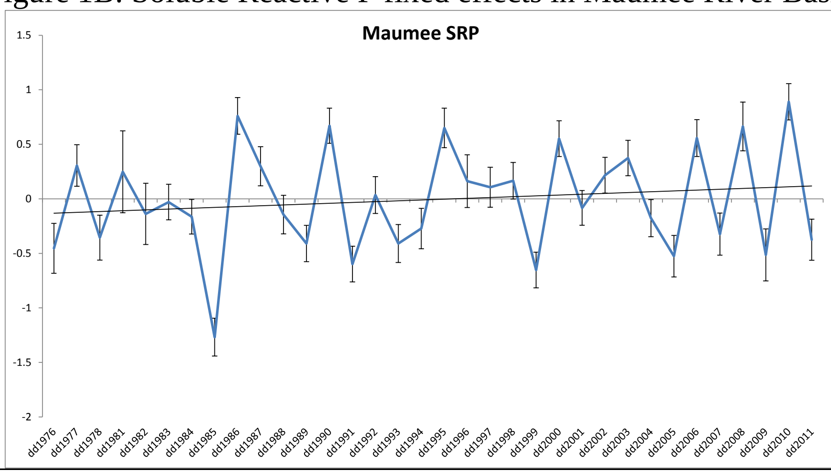


Figure 1C: Attached P fixed effects in Maumee River Basin

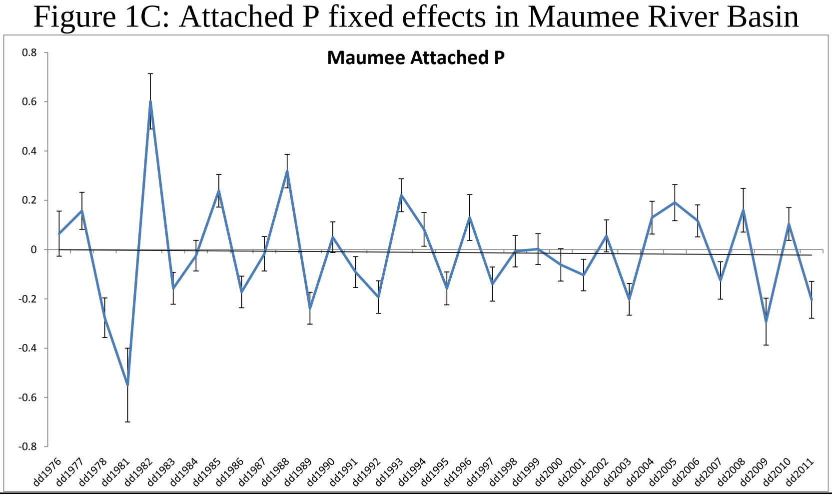


Figure 2: Annual fixed effects for Sandusky River Basin. The bars represent 95% confidence intervals for the parameter estimates, and the trend line is presented. Note that 1995 is omitted for Sandusky.

Figure 1A: Total P fixed effects in Sandusky River Basin

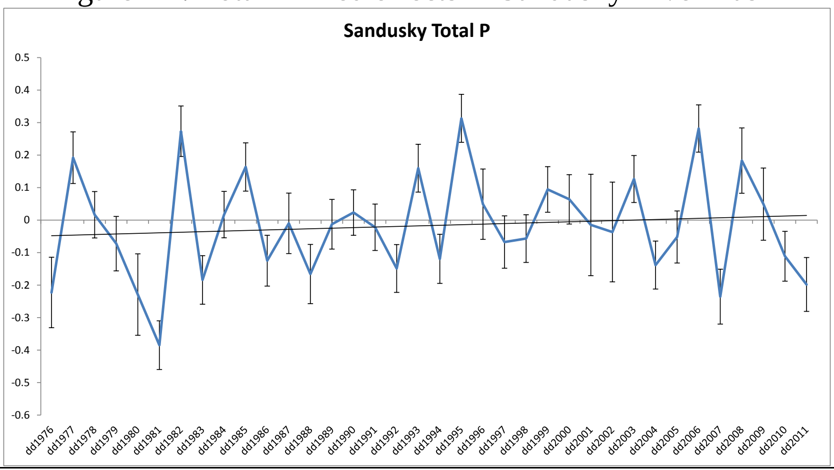


Figure 1B: Soluble Reactive P fixed effects in Sandusky River Basin

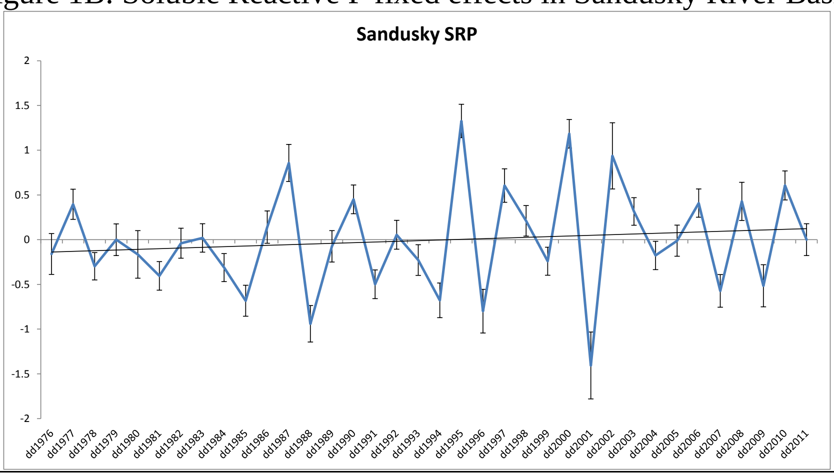


Figure 1C: Attached P fixed effects in Sandusky River Basin

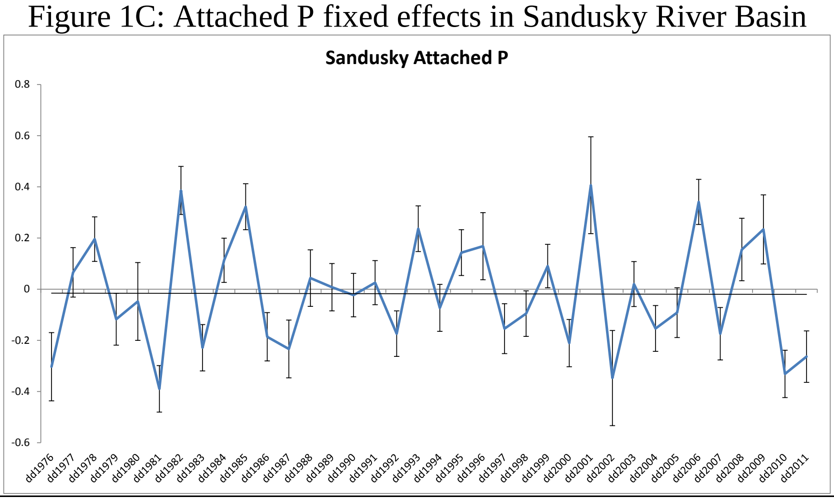


Figure 3: Maumee river basin monthly fixed effects for three time periods. Pre = before 1980; Mid = 1980-1995; Post = 1996-2011.

Figure 3A: Total P Concentration in Maumee River Basin

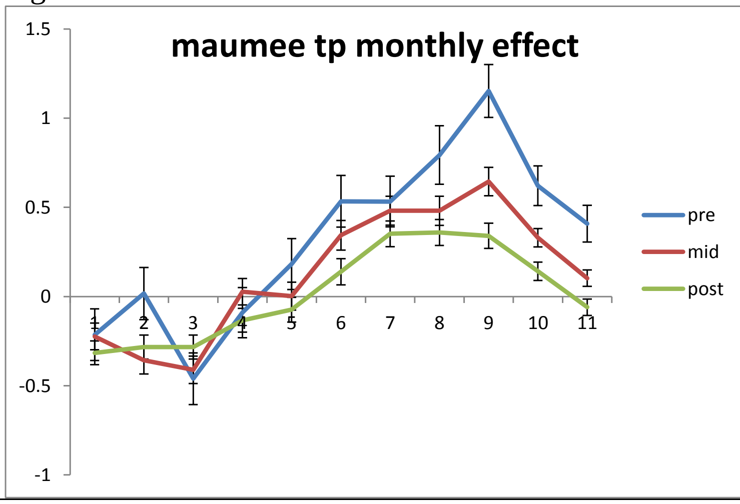


Figure 3B: Soluble Reactive P Concentration in Maumee River Basin

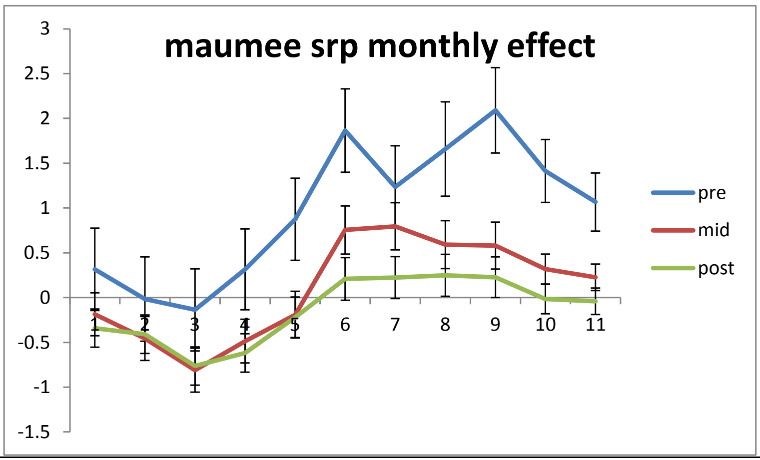


Figure 3C: Attached P Concentration in Mauemm River Basin

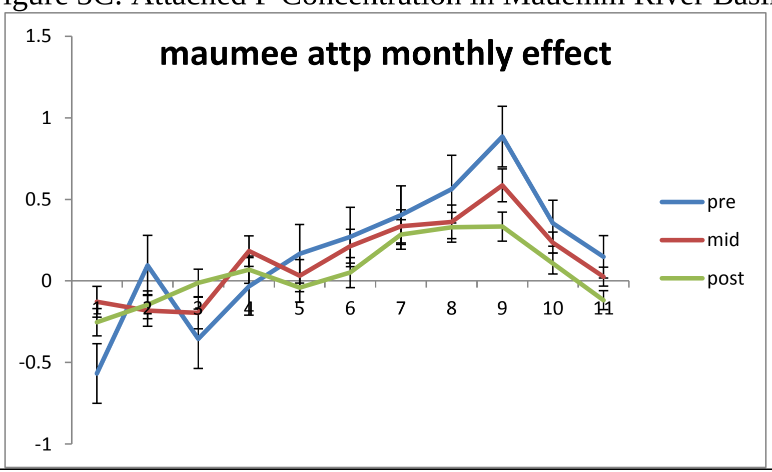


Figure 4: Sandusky river basin monthly fixed effects for three time periods. Pre = before 1980; Mid = 1980-1995; Post = 1996-2011.

Figure 3A: Total P Concentration in Sandusky River Basin

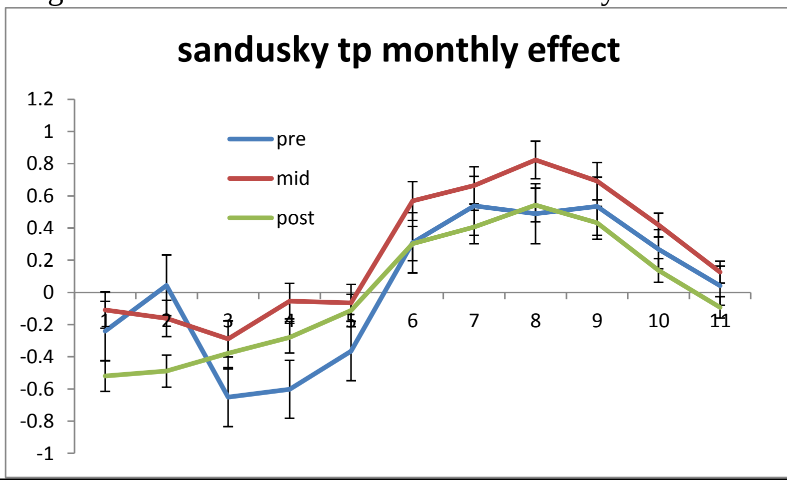


Figure 3B: Soluble Reactive P Concentration in Sandusky River Basin

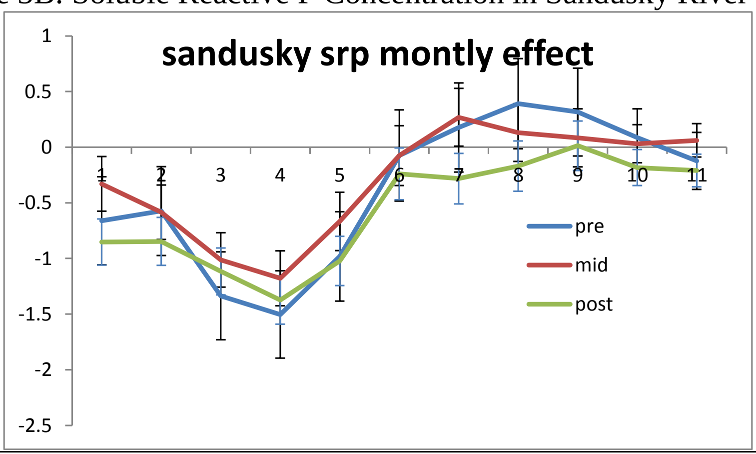
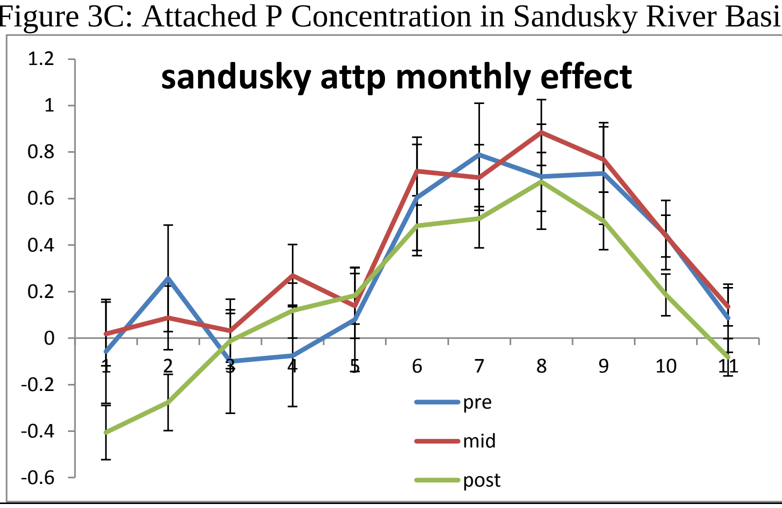


Figure 3C: Attached P Concentration in Sandusky River Basin



APPENDIX: Regression results

Table 1. Variable Descriptions

Variable	Description
Ln(TP)	Log of total phosphorus concentration (mg/L) • Source: National Center for Water Quality Research (Heidelberg University, 2012), http://www.heidelberg.edu/academiclife/distinctive/ncwqr
Ln(SRP)	Log of soluble reactive phosphorus concentration (mg/L) • Source: Heidelberg University (2012)
Ln(ATTP)	Log of (TP-SRP) (mg/L)
Ln(dapp3m)	Log of Diammonium phosphate preceding 3month average price (real 1982 US$) • Source: World Bank Data (2013)
Ln(corn3m)	Corn 3 preceding month average price (real 1982 US$) • Source: US Department of Agriculture, National Agricultural Statistics Service (USDA-NASS, 2013)
Ln(cfstp)	Log of flow rate for samples on with TP is available (cubic feet per second) • Source: Heidelberg University (2012)
Ln(cfssrp)	Log of flow rate for samples on with SRP is available (cubic feet per second) • Source: Heidelberg University (2012)
Ln(temp)	Log of preceding 30day average temperature for all weather stations • Source: National Climate Data Center
Ln(prec)	Log of preceding 30 day average precipitation per day for all weather stations • Source: National Climate Data Center
Cornwinter	Ln(corn3m)* S_w Where $S_w = 1$ *if month = Jan, Feb, and Mar,* $= 0$ *otherwise*
Cornspring	Ln(corn3m)* S_s Where $S_s = 1$ *if month= Apr, May, and June,* $= 0$ *otherwise*
Cornfall	Ln(corn3m)* S_f Where $S_f = 1$ *if month= Oct, Nov, and Dec,* $= 0$ *otherwise*
$m^1 - m^{11}$	Monthly dummy variables $m^i = 1\ if\ month = i,$ $= 0\ otherwise$
$mmid^1 - mmid^{11}$	$mmid^i = m^i * dmid$ Where $dmid = 1\ if\ 1980 \leq year \leq 1995,$ $= 0\ otherwise$
$mpost^1 - mpost^{11}$	$mpost^i = m^i * dpost$ Where $dpost = 1\ if\ year > 1995,$ $= 0\ otherwisre$
$dd^{1976} - dd^{2011}$	$dd^i = 1\ \ if\ year \geq i,$ $= 0\ \ otherwise$
$y^{1976} - y^{2011}$	$y^i = 1\quad if\ year = i,$ $= 0\quad otherwise$

Table 2. The regression results for Maumee

Model 1.

	Ln(TP)		Ln(SRP)		Ln(ATTP)	
Variables	**Estimate**	**t-Value**	**Estimate**	**t-Value**	**Estimate**	**t-Value**
intercept	−2.307***	-10.060	4.167***	5.750	−6.310***	-21.890
m^1	−0.214***	-2.900	0.315	1.350	−0.567***	-6.100
m^2	0.017	0.230	−0.016	-0.070	0.096	1.020
m^3	−0.461***	-6.250	−0.137	-0.590	−0.355***	-3.830
m^4	−0.090	-1.250	0.316	1.370	−0.033	-0.370
m^5	0.182**	2.500	0.874***	3.750	0.166*	1.820
m^6	0.534***	7.230	1.866***	7.860	0.269***	2.900
m^7	0.533***	7.330	1.234***	5.230	0.404***	4.400
m^8	0.793***	9.440	1.659***	6.170	0.563***	5.330
m^9	1.153***	15.240	2.091***	8.600	0.884***	9.310
m^{10}	0.621***	10.910	1.413***	7.890	0.354***	4.940
m^{11}	0.408***	7.750	1.067***	6.420	0.148**	2.240
$mmid^1$	−0.009	-0.150	−0.502***	-2.640	0.440***	5.790
$mmid^2$	−0.374***	-6.180	−0.440**	-2.260	−0.277***	-3.630
$mmid^3$	0.050	0.850	−0.673***	-3.600	0.159**	2.130
$mmid^4$	0.117**	2.020	−0.802***	-4.360	0.216***	2.980
$mmid^5$	−0.180***	-3.130	−1.065***	-5.800	−0.134*	-1.860
$mmid^6$	−0.190***	-3.360	−1.111***	-6.170	−0.057	-0.790
$mmid^7$	−0.052	-0.900	−0.438**	-2.370	−0.069	-0.940
$mmid^8$	−0.313***	-4.420	−1.067***	-4.780	−0.201**	-2.260
$mmid^9$	−0.508***	-8.330	−1.511***	-7.840	−0.298***	-3.890
$mmid^{10}$	−0.291***	-4.940	−1.095***	-5.870	−0.119	-1.600
$mmid^{11}$	−0.306***	-5.410	−0.842***	-4.720	−0.123*	-1.730
$mpost^1$	−0.101	-1.620	−0.657***	-3.330	0.314***	3.990
$mpost^2$	−0.300***	-4.790	−0.393*	-1.950	−0.242***	-3.070
$mpost^3$	0.178***	2.900	−0.627***	-3.240	0.343***	4.460
$mpost^4$	−0.043	-0.720	−0.934***	-4.910	0.102	1.360
$mpost^5$	−0.256***	-4.300	−1.094***	-5.810	−0.207***	-2.770
$mpost^6$	−0.395***	-6.700	−1.658***	-8.860	−0.218***	-2.940
$mpost^7$	−0.181***	-3.030	−1.009***	-5.260	−0.119	-1.570
$mpost^8$	−0.434***	-5.990	−1.411***	-6.140	−0.233**	-2.560
$mpost^9$	−0.812***	-12.840	−1.864***	-9.270	−0.552***	-6.940
$mpost^{10}$	−0.479***	-8.130	−1.430***	-7.680	−0.247***	-3.330
$mpost^{11}$	−0.468***	-8.330	−1.108***	-6.240	−0.266***	-3.770
Ln(dapp3m)	−0.260***	-7.630	−0.425***	-3.940	−0.141***	-3.290
Ln(corn3m)	0.080*	1.830	−0.035	-0.250	0.106*	1.920
Ln(cfstp), or Ln(cfssrp)[1]	0.311***	89.130	0.320***	28.520	0.344***	78.370
Ln(temp)	−0.073***	-2.870	−1.559***	-19.260	0.535***	16.770

Ln(prec)	−0.001	-0.150	0.364***	14.270	−0.092***	-9.370
Cornwinter	0.372***	9.120	−0.153	-1.160	0.405***	7.890
Cornsspring	0.076**	1.980	−0.373***	-2.980	0.105**	2.190
Cornfall	0.149***	4.080	−0.222*	-1.840	0.289***	6.270
dd^{1976}	−0.129***	-3.470	−0.454***	-3.880	0.065	1.380
dd^{1977}	0.282***	9.320	0.306***	3.140	0.157***	4.110
dd^{1978}	−0.327***	-10.010	−0.355***	-3.390	−0.277***	-6.740
dd^{1981}	−0.376***	-6.180	0.248	1.290	−0.550***	-7.190
dd^{1982}	0.365***	8.020	−0.137	-0.960	0.602***	10.510
dd^{1983}	−0.122***	-4.640	−0.030	-0.350	−0.157***	-4.770
dd^{1984}	−0.033	-1.290	−0.164**	-2.030	−0.025	-0.770
dd^{1985}	0.013	0.470	−1.268***	-14.350	0.239***	7.080
dd^{1986}	−0.073***	-2.800	0.761***	8.880	−0.172***	-5.240
dd^{1987}	0.080***	2.820	0.299***	3.260	−0.017	-0.480
dd^{1988}	0.204***	7.410	−0.145	-1.610	0.319***	9.210
dd^{1989}	−0.258***	-9.850	−0.409***	-4.810	−0.238***	-7.220
dd^{1990}	0.120***	4.760	0.670***	8.160	0.050	1.580
dd^{1991}	−0.144***	-5.650	−0.598***	-7.150	−0.091***	-2.850
dd^{1992}	−0.175***	-6.530	0.035	0.410	−0.193***	-5.730
dd^{1993}	0.108***	3.960	−0.409***	-4.600	0.221***	6.460
dd^{1994}	0.017	0.630	−0.272***	-2.880	0.082**	2.350
dd^{1995}	−0.003	-0.100	0.650***	7.040	−0.157***	-4.630
dd^{1996}	0.124***	3.280	0.162	1.310	0.130***	2.740
dd^{1997}	−0.074***	-2.650	0.106	1.130	−0.140***	-3.970
dd^{1998}	0.014	0.530	0.166*	1.940	−0.007	-0.210
dd^{1999}	−0.104***	-4.080	−0.653***	-7.810	0.002	0.070
dd^{2000}	0.066**	2.500	0.552***	6.600	−0.062*	-1.850
dd^{2001}	−0.089***	-3.440	−0.083	-1.020	−0.103***	-3.180
dd^{2002}	0.058**	2.190	0.217***	2.600	0.056*	1.690
dd^{2003}	−0.001	-0.020	0.374***	4.510	−0.202***	-6.150
dd^{2004}	0.053*	1.950	−0.177**	-2.030	0.130***	3.820
dd^{2005}	0.043	1.450	−0.526***	-5.400	0.191***	5.100
dd^{2006}	0.181***	6.860	0.557***	6.470	0.117***	3.520
dd^{2007}	−0.116***	-3.770	−0.324***	-3.280	−0.125***	-3.230
dd^{2008}	0.259***	7.190	0.664***	5.820	0.160***	3.530
dd^{2009}	−0.389***	-10.060	−0.514***	-4.230	−0.292***	-6.020
dd^{2010}	0.277***	10.280	0.890***	10.480	0.104***	3.060
dd^{2011}	−0.212***	-6.950	−0.375***	-3.890	−0.204***	-5.320

Note: ***, **, * indicate statistical significance at 1, 5, and 10% levels, respectively.
1. Ln(TP) and Ln(ATTP) are associated with Ln(cfstp), and Ln(SRP) is associated with Ln(cfssrp)

Table 3. The regression results for Sandusky

Model 1.						
	Ln(TP)		**Ln(SRP)**		**ln(ATTP)**	
Variables	**Estimate**	**t-Value**	**Estimate**	**t-Value**	**Estimate**	**t-Value**
intercept	−5.389***	−16.34	−0.992	−1.41	−8.391***	−20.91
m^1	−0.240**	−2.55	−0.661***	−3.27	−0.057	−0.5
m^2	0.044	0.46	−0.574***	−2.81	0.257**	2.2
m^3	−0.651***	−6.97	−1.336***	−6.64	−0.101	−0.89
m^4	−0.602***	−6.55	−1.504***	−7.51	−0.076	−0.68
m^5	−0.365***	−3.88	−0.981***	−4.8	0.079	0.7
m^6	0.309***	3.22	−0.075	−0.36	0.604***	5.2
m^7	0.538***	5.74	0.177	0.86	0.788***	6.94
m^8	0.489***	5.15	0.391*	1.89	0.694***	6.03
m^9	0.535***	5.81	0.316	1.57	0.708***	6.34
m^{10}	0.269***	4.35	0.085	0.64	0.443***	5.83
m^{11}	0.042	0.68	−0.124	−0.95	0.086	1.15
$mmid^1$	0.131*	1.76	0.331**	2.09	0.076	0.84
$mmid^2$	−0.206***	−2.72	−0.01	−0.07	−0.17*	−1.86
$mmid^3$	0.362***	5.06	0.323**	2.11	0.132	1.53
$mmid^4$	0.548***	7.64	0.326**	2.11	0.345***	3.96
$mmid^5$	0.300***	4.16	0.315**	2.03	0.059*	0.67
$mmid^6$	0.260***	3.63	0	0	0.114	1.3
$mmid^7$	0.127*	1.74	0.091	0.58	−0.097	−1.1
$mmid^8$	0.335***	4.39	−0.26	−1.6	0.19**	2.06
$mmid^9$	0.156**	2.12	−0.232	−1.46	0.06	0.68
$mmid^{10}$	0.150**	2.24	−0.055	−0.37	−0.004	−0.05
$mmid^{11}$	0.084	1.23	0.185	1.25	0.049	0.58
$mpost^1$	−0.279***	−3.54	−0.192	−1.15	−0.349***	−3.65
$mpost^2$	−0.533***	−6.72	−0.273*	−1.65	−0.534***	−5.56
$mpost^3$	0.273***	3.61	0.22	1.37	0.088	0.96
$mpost^4$	0.323***	4.31	0.129	0.81	0.195**	2.14
$mpost^5$	0.253***	3.36	−0.041	−0.26	0.104	1.14
$mpost^6$	−0.005	−0.07	−0.166	−1.03	−0.121	−1.33
$mpost^7$	−0.132*	−1.73	−0.459***	−2.81	−0.274***	−2.97
$mpost^8$	0.054	0.69	−0.561***	−3.32	−0.022	−0.23
$mpost^9$	−0.103	−1.34	−0.302*	−1.83	−0.204**	−2.19
$mpost^{10}$	−0.132**	−1.98	−0.269*	−1.87	−0.257***	−3.15
$mpost^{11}$	−0.134**	−1.97	−0.085	−0.59	−0.168**	−2.04
Ln(dapp3m)	−0.074	−1.51	−0.331***	−3.17	0.031	0.52
Ln(corn3m)	0.021	0.34	0.128	0.93	−0.058	−0.78
Ln(cfstp), or Ln(cfssrp)[1]	0.475***	110.02	0.458***	48.61	0.491***	93.75
Ln(temp)	0.323***	8.83	−0.569***	−7.25	0.747***	16.84
Ln(prec)	0.027***	2.58	0.219***	9.39	−0.039***	−3.05

Cornwinter	0.402***	7.3	0.266**	2.24	0.364***	5.45
Cornspring	0.135***	2.61	0.265**	2.31	0.052	0.83
Cornfall	0.048	0.94	−0.216*	−1.89	0.176***	2.85
dd^{1976}	−0.223***	−4.03	−0.16	−1.37	−0.303***	−4.45
dd^{1977}	0.192***	4.74	0.395***	4.62	0.066	1.33
dd^{1978}	0.016	0.45	−0.297***	−3.82	0.196***	4.41
dd^{1979}	−0.073*	−1.7	0	0	−0.117**	−2.27
dd^{1980}	−0.229***	−3.59	−0.165	−1.21	−0.048	−0.62
dd^{1981}	−0.385***	−10.06	−0.405***	−4.96	−0.39***	−8.4
dd^{1982}	0.273***	6.89	−0.04	−0.47	0.386***	8.03
dd^{1983}	−0.184***	−4.83	0.019	0.23	−0.229***	−4.96
dd^{1984}	0.017	0.46	−0.312***	−3.9	0.113**	2.55
dd^{1985}	0.163***	4.32	−0.683***	−7.72	0.322***	7.03
dd^{1986}	−0.125***	−3.13	0.14	1.52	−0.186***	−3.85
dd^{1987}	−0.01	−0.21	0.857***	8.13	−0.234***	−4.06
dd^{1988}	−0.166***	−3.58	−0.94***	−9.06	0.043	0.77
dd^{1989}	−0.013	−0.33	−0.074	−0.83	0.008	0.16
dd^{1990}	0.023	0.65	0.45***	5.51	−0.023	−0.54
dd^{1991}	−0.022	−0.61	−0.499***	−6.09	0.025	0.57
dd^{1992}	−0.149***	−3.98	0.054	0.65	−0.174***	−3.83
dd^{1993}	0.160***	4.24	−0.228***	−2.62	0.236***	5.18
dd^{1994}	−0.119***	−3.1	−0.678***	−6.86	−0.073	−1.57
dd^{1995}	0.313***	8.31	1.326***	13.95	0.143***	3.13
dd^{1996}	0.049	0.88	−0.799***	−6.43	0.168**	2.51
dd^{1997}	−0.068*	−1.65	0.604***	6.32	−0.155***	−3.1
dd^{1998}	−0.057	−1.52	0.21**	2.4	−0.096**	−2.1
dd^{1999}	0.094***	2.63	−0.241***	−3.01	0.09**	2.08
dd^{2000}	0.064*	1.65	1.184***	14.49	−0.211***	−4.49
dd^{2001}	−0.015	−0.19	−1.406***	−7.38	0.406***	4.21
dd^{2002}	−0.037	−0.47	0.937***	4.97	−0.348***	−3.66
dd^{2003}	0.126***	3.42	0.315***	3.99	0.02	0.44
dd^{2004}	−0.139***	−3.67	−0.177**	−2.19	−0.154***	−3.37
dd^{2005}	−0.052	−1.27	−0.012	−0.13	−0.092*	−1.85
dd^{2006}	0.282***	7.59	0.408***	5.07	0.341***	7.59
dd^{2007}	−0.236***	−5.47	−0.573***	−6.16	−0.174***	−3.34
dd^{2008}	0.183***	3.57	0.428***	3.94	0.155**	2.48
dd^{2009}	0.049	0.86	−0.516***	−4.3	0.233***	3.39
dd^{2010}	−0.111***	−2.85	0.607***	7.34	−0.331***	−7
dd^{2011}	−0.198***	−4.69	0	0	−0.264***	−5.15

Note: ***, **, * indicate statistical significance at 1, 5, and 10% levels, respectively.
1. Ln(TP) and Ln(ATTP) are associated with Ln(cfstp), and Ln(SRP) is associated with Ln(cfssrp)