THE IMPLICATIONS OF ENVIRONMENTAL POLICY ON NUTRIENT OUTPUTS IN AGRICULTURAL WATERSHEDS

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Abstract—We examine whether federally sponsored voluntary environmental programs have reduced phosphorus pollution from agriculture over the past 30 years. We do so using a unique dataset derived from daily observations on nutrient emissions taken over 37 years in several tributaries to Lake Erie. These data are linked to important ecological, hydrological, and economic factors that influence nutrient concentrations in agricultural watersheds. To identify the influence of federal programs on nutrient concentrations, we separate nutrient outputs into attached and soluble components, and test for structural changes in key estimated parameters over time. Federal programs have long focused on trapping attached phosphorus in farm fields with conservation tillage and conservation set-asides, and we show that these programs and their effects have strengthened over time, as expected. In contrast, we find that soluble phosphorus fell for many years, but has increased since 1995. We show this is partly due to the increase in the amount of phosphorus attached to sediment, and also due to an increasing release of soluble phosphorus. In the Lake Erie basin, the increasing release of phosphorus has negated many of the benefits of conservation tillage.

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INTRODUCTION

Federally sponsored voluntary pollution reduction programs have become an important pillar of environmental protection policy in the United States. For example, over 1200 manufacturing firms signed up for 33/50, a program started in 1991 by the US Environmental Protection Agency (EPA) to achieve voluntary pollution reductions by regulated businesses (Innes & Sam, 2008). In the realm of agricultural operations, the US Department of Agriculture (USDA) and the EPA partnered to create AgStar and PestWise programs to induce meaningful voluntary pollution reduction by farmers. AgStar is designed to help concentrated animal feeding operations reduce methane emissions through voluntary investments in biogas recovery technologies while PestWise's primary goal is to reduce pesticide risk by promoting the adoption of integrated pest management practices. Similarly, the meat processing industry has benefitted from workshops/training sessions and detailed brochures from the EPA to facilitate voluntarily implementation of environmentally friendly practices.

Several papers have explored empirically whether such voluntary programs curb pollution from levels that would otherwise have been produced. The empirical research has mostly focused on firms' participation in the EPA's 33/50 program (e.g, Khanna & Damon, 1999; Gamper-Rabindran, 2006; Sam, Khanna, & Innes, 2009; Bi & Khanna, 2012), the Green Lights and WasteWise programs (Brouhle, Graham, & Harrington, 2013), the Climate Challenge program (Welch, Mazur, & Bretschneider, 2000), the Energy Star program (Smith & Jones, 2003) and firms' motives for adoption of environmental management systems (e.g., Dasgupta, Hettige, & Wheeler, 2000; Khanna & Anton, 2002). Thus far, the evidence on the effectiveness of the voluntary approach is mixed (see e.g., Koehler, 2007 for a review).

This paper expands this literature by focusing on federal efforts designed to achieve significant water pollution reductions. Since the 1980s, more than $1 billion per year has been spent on programs designed to improve water quality through voluntary agricultural conservation programs nationwide. These programs have focused on removing land from production and trapping nutrients in farm fields via practices like conservation tillage, installing manure management structures, and shifting the timing of nutrient applications, among other practices. The Conservation Reserve Program (CRP), which expanded substantially in the 1980s, focuses on removing highly erodible land from agricultural production. By the early 1990s, over 30 million acres had been set aside in CRP nationwide, and many of these fields remain out of agricultural production today. In addition to CRP, for over 40 years conservation tillage has been promoted as a management practice that can reduce soil erosion and phosphorus emissions. Now, conservation tillage is widely adopted, with about 63% of all cropped acres in the US having some form of conservation or reduced tillage (Conservation Tillage Information Center (CTIC), 2013).[1]

The 1996 Farm Bill substantially increased the subsidies available for farmers to reduce pollution voluntarily. Nationally, payments for agricultural conservation programs almost tripled from $1.7 billion to $5 billion per year from 1996 to 2010 (Pavelis, Helms, & Stalcup, 2011). Current payments are about $14 per acre of farmland in the US. The largest program, the Environmental Quality Incentive Program (EQIP), provides payments for a range of activities, focusing heavily on capital expenditures for long-lived practices like manure storage facilities, grass waterways, new drainage structures, and on manure and nutrient management practices, particularly from large livestock operations. There are some strings attached to these payments; for example in the EQIP program, 60% of the funds must be used to assist farmers to reduce pollution from manure. There have also been some regulatory approaches in the last 15 years

[1] Conservation tillage is one of the most widely used conservation practices. The conservation programs typically do not subsidize the adoption of conservation tillage, but it has been so widely adopted because it is a money saving practice that requires fewer tilling operations, and hence lower fuel and labor costs for farmers.

that should have increased the effectiveness of the voluntary programs. In 2000, new regulations on the largest of the livestock operations nationwide were implemented by the EPA to reduce pollution. The regulations required the nation's largest livestock operations to obtain permits to emit nutrients into waterways, similarly to permits issued to waste water treatment plants.

Given the increasing funding for both voluntary and mandatory pollution abatement, there should be some measurable improvement in water quality nationally. Over the past several decades, however, water quality actually appears to have worsened. In 1996, 36% of measured rivers and streams were impaired (USEPA, 1996), but in 2010, 56% of measured streams were impaired (USEPA, 2010). The leading source of impairment in 1996 and 2010, according to the EPA, was agriculture. Detailed analysis of water quality samples in the Mississippi river basin illustrates that the concentration of nutrients continues to rise (Sprague, Hirsch, & Aulenbach, 2011). Industrial and urban sources contribute to loading, but modeling studies estimate that agriculture contributes over 75% of the nitrogen and phosphorus in the Mississippi River Basin (Alexander et al., 2008) and the Great Lakes (Robertson & 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.

The main method used to assess the effectiveness of these programs are modeling studies that assume the relationship between various agricultural practices and changes in the quality of water run-off from farms (e.g., Piper, Huang, & Ribaudo, 1989; Wu & Segerson, 1995; Wu et al., 2004; Rabtyagov et al., 2014). Few studies have used empirical data to examine whether these policies have in fact improved water quality, in part because it is difficult to find data with a long enough record to assess water quality changes before and after implementation of programs. Another reason is the difficulty to observe environmental outcomes for “control” watersheds, i.e. watersheds that are not subject to the voluntary programs but are similar in characteristics to those that are.

In this paper, we address the first issue by utilizing long-term, detailed data from two 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). The time length of our dataset allows us to control for economic, ecological, and policy factors that affect nutrient concentrations in watersheds and that do change over time. The economic variables include nutrient input and crop output prices. The ecological variables focus on weather, water flow, and seasonality. For the policy variables, we use annual and monthly fixed effects to capture their impacts.

Addressing the second issue--finding an appropriate "control group" for the watersheds covered by the federal policies, is more difficult because of the national scope of these policies. We focus on three approaches to identify the influence of conservation programs on water quality, and specifically on phosphorus concentrations. First, we note that all the observable trends imply that phosphorus concentrations should be declining. If phosphorus concentrations are increasing *after* implementation of conservation programs when relevant ecological and economic factors are controlled for, it is reasonable to conclude that the programs are likely not successful. Second, we consider the timing of pollution abatement efforts in industry and agriculture. Industrial efforts started in the 1970s and had their main effect before 1981. This is clearly evident in the data. Agricultural efforts began in earnest with the 1996 Farm Bill, and increased in the 2000s with higher funding levels. Third, we identify the effects of agriculture specifically by considering trends in soluble phosphorus, attached phosphorus, and suspended sediments. For instance, agricultural efforts have focused heavily on reducing soil erosion, so we should see larger effects in suspended sediments than in other pollution variables. Finally, conservation programs focus on reducing the emissions in particular seasons, so we test for changes in the seasonality of phosphorus emissions.

This paper focuses exclusively on phosphorus which is one of the most important crop nutrients, particularly for Midwestern crops like corn, 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 (Michalak et al., 2013). Harmful algal blooms affect more than the Lake Erie ecosystem and recreation, having just recently (August, 2014) caused the city of Toledo, Ohio to declare a water emergency and advise their residents not to use city provided tap water, for any purpose, for several days.

Our results indicate that phosphorus emissions are inversely related to phosphorus prices, and positively correlated with corn prices. These results are not un-expected given the underlying economic relationships. The parameters on ecological variables also display the signs that one would expect. Policy variables illustrate that the expansion of conservation tillage over the past 20 years has worked to reduce phosphorus attached to soil. In contrast, soluble phosphorus fell significantly in the 1970s and 1980s as waste water treatment plants were regulated, but has risen since the mid-1990s even as federal conservation programs expanded. The increase in soluble phosphorous has far exceeded the modest reduction in attached phosphorous. Thus, despite significant federal funding for the agricultural community to reduce pollution, the aggregate impacts are negative. Since soluble phosphorus is the main form of the nutrient that causes damages like harmful algal blooms, the environmental trend over the past several decades has undoubtedly been down, despite a significant investment in voluntary conservation programs.

MODEL AND DATA

The amount of nutrient exiting a watershed is a function of inputs from human and natural sources, less the amount used by crops and the amount stored in the ecosystem. In agricultural watersheds, farm conservation programs in recent years have focused on trying to reduce nutrient outflows by storing nutrients that are not used by crops in the ecosystem. This storage can occur either in soils, or in in living or decomposing plant material. The quantity of nutrients emitted from an agricultural watershed is:

$$Q_t^W = (Q_t^F - Y_t^F - C_t^F) + Q_t^U + Q_t^E \qquad (1)$$

where Q^w is the quantity of nutrients emitted from a watershed, Q^F is the input of nutrients into farming through fertilizer applications, Y^F is the removal of nutrients through crop growth and harvest, C^F is the storage of nutrients in the ecosystem through the implementation of conservation practices, Q^U is the input of nutrients from factories and human sewage, and Q^E is the net input of nutrients due to the fluctuation of natural systems.

Of the variables in (1), only Q^W and Q^U can be measured directly. The rest of the variables can only be measured indirectly. For example, we do not know exactly the amount of nutrients used by farmers in any given watershed. Survey data on nutrient use by farmers was collected annually for many years, but now is collected only every few years by the USDA National Agricultural Statistics Survey (Taylor, 1994; USDA-NASS, 2014). Annual consumption data from fertilizer dealers (see Bruuselma et al., 2011) can also be used, but it may or may not be directly related to the outputs of a particular watershed since farmers can transport nutrients into and out of the watershed, and they can store nutrients from one year to the next.

Nutrient use by farmers, Q^F, can be measured indirectly using demand theory, however. In small watersheds, farmers are price takers and respond to exogenous price changes for fertilizer by altering their consumption. Q^F in equation (1) thus is a function of the price of the nutrient input (P^N), the prices of outputs such as corn, soybeans or wheat (P^O), and other demand factors (Z):

$$Q_t^F = f(P_t^N ; P_t^O, Z_t). \tag{2}$$

All else equal, higher nutrient prices (P^N) will reduce the quantity of nutrient demanded. Other factors, such as corn prices, or P^O in equation (2) also will change the quantity of nutrient demanded by farms, including crop types and crop yields. While we cannot incorporate Q^F directly into our empirical model, we can incorporate prices for corn and for phosphorus in the model.

In equation (1), the trend in each of the constituents of Q^W suggests that Q^W should be trending downward. Aggregate measures of phosphorus inputs in Midwestern farms have fallen over the past 30 years (Bruuselma et al.2011), while crop yields have increased 1-2% per year, increasing the amount of nutrients exported from watersheds as food. As a result, the intensity of phosphorus use on farms has declined since the 1960's (Figure 1), and these gains in efficiencies should be driving phosphorus outputs from agricultural watersheds down.

The use of conservation practices, C^F, has become more widespread over time, and should reduce phosphorus emissions from watersheds. Data from Pavelis et al. (2011) indicate that conservation programs have increased from around $1 billion per year to over $5 billion per year (in real terms) since the 1980s. These increases were driven by the CRP in the 1980s and early 1990s, and the growth in working lands programs since the 1996 Farm Bill. Working land programs apply conservation practices to “working” farmland. Presumably, with rising funding, these programs have become more effective over time, leading to increases in C^F in our model, and consequent reductions in nutrient outputs from watersheds.

Conservation practices have heavily focused on reducing suspended sediments through support for conservation tillage and CRP. Given this approach, we should be able to identify the effects of conservation practices on suspended sediments and the phosphorus that is attached to soil particles ("attached phosphorus"). Practices like conservation tillage should have larger effects in winter than summer because conservation tillage holds soil in place during the non-growing seasons. The CRP should also have its primary effect on suspended sediments and attached phosphorus because it provides cover throughout the year, and can slow overland flows of water from upstream catchment areas in fields. Other conservation practices have focused on nutrients directly. For instance, nutrient management planning focuses mostly on planning for animal waste by recommending that farmers test their soils for nutrient levels and plan annual nutrient applications in accordance with these tests. Nutrient management plans also encourage farmers who have animals to increase their manure storage capability so they do not apply their manure in winter or on frozen ground. Nutrient management plans thus should decrease the amount of phosphorus held in soils, and soluble phosphorus concentrations throughout the year, but particularly in the winter given the focus on avoiding winter-time manure applications.

Urban and industrial emissions of phosphorus (Q^U) were controlled heavily in the 1970s and 1980s. Data from the Ohio Phosphorus Task Force (2013), Dolan and Chapra (2012), and DePinto et al. (2006) indicate that phosphorus emissions in the Lake Erie basin from point sources fell by around 80% from the 1970s to the early 1980s (Figure 1). They have remained fairly stable since then. Emissions from nonpoint source, on the other hand, have fluctuated substantially but with no discernable trend.

Emissions from natural sources and variation due to environment (Q^E) will depend on a range of factors, but perhaps most importantly the flow of water in the watershed. As Dolan and Richards (2008) illustrate, there is a strong positive relationship between flow and nutrient concentrations in rivers. The effect is likely to be non-linear, since large rainfall events, which have the largest flows, carry the largest concentrations of nutrients in watersheds dominated by agriculture. In addition to flow, temperature and precipitation also will influence nutrient concentrations because they affect farmer decisions, crop management (e.g., the timing of nutrient inputs), and the rate of decay of plant material.

To estimate the model in equation (1), we use daily water quality data from 1975 to 2011 in the Maumee and Sandusky watersheds which are influenced primarily by agricultural production, and are located in Northwestern Ohio. The Maumee watershed is roughly 1.64 million hectares and 90% agricultural, while the Sandusky watershed is 0.32 million hectares and 84% agricultural. The Maumee is the largest watershed by water volume entering Lake Erie (aside from flow entering from the upstream Great Lakes). Daily observations of nutrient concentrations in these watersheds have been collected from 1975 to the present by the National Center for Water Quality Research at Heidelberg University, although data for 1979 and 1980 are missing for the Maumee watershed (Heidelberg University, 2012).

We estimate the following model:

$$lnQ_t^W = \alpha^0 + \alpha^1\, ln(temp)_t + \alpha^2\, ln(precip)_t + \alpha^3\, ln(flow)_t + \alpha^4 lnQ_t^F + \alpha^5 Policies_t + \epsilon_t \quad (3)$$

The variables used in the regression analysis have been described above and are summarized in Table A1 in appendix A. The left hand side variable (Q^W) is the flow weighted average daily concentration of phosphorus or sediments, measured in mg/L, or parts per million (ppm). The daily concentration is obtained from a single observation or from multiple observations over the course of the day. During low flow periods, only one sample is taken at a fixed time each day because the flow does not vary much when flows are low. During storm events, however, the flow will vary during the course of a day, and multiple water quality measurements are taken. 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 environmental variables included in our model are the flow of water *(flow)*, temperature *(temp)*, and precipitation *(precip)*. Flow is contemporaneous with the observation of concentration on the left hand side and is also obtained from Heidelberg University (2012). For temperature and precipitation we use estimates of 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 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. The 30 day average is used because the watersheds under consideration are fairly large, and it takes time for water further up in the watershed to make its way to the observation point. As noted below, we do test specifically for the time length over which temperature and precipitation have an effect, and we find that the effects are uni-directional within 30 days and that the 30 day measure captures the bulk of the impact. Thus, when biological or chemical processes that are governed by temperature and precipitation occur in the watershed, we assume it takes some time for them to have an effect on downstream water quality measurements, and the effect is captured within 30 days.

The quantity of phosphorus input by farmers (Q^F) is modeled as a function of the price of phosphorus and the price of crop outputs:

$$\alpha^4 lnQ_t^F = \beta^1 ln(dapp3m)_t + \beta^2\, ln(corn3m)_t + \beta^W\, ln(corn3m)_t S^W + \beta^{SP}\, ln(corn3m)_t S^{SP} + \beta^F\, ln(corn3m)_t S^F. \tag{4}$$

The phosphorus price *(dapp3m)* used in the analysis is a moving average 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. For this analysis, we use the corn price *(corn3m)* received by farmers, averaged for the state of Ohio on a monthly basis (USDA-NASS, 2014). Not only is corn the most valuable row crop in the region, it has represented 62% of the phosphorus use in the watersheds since the 1970s (USDA-NASS, 2014). Landowners can only make crop choices during fall or early spring before crops are planted, so we also include interaction terms to account for differential effects of prices on farm decisions during different seasons of the year. S^W, S^{SP}, and S^F are dummies for winter, spring, and fall, respectively.

A set of annual and monthly fixed effects allow us to test for trends in urban and industrial emissions, crop yields, and policies. The fixed effects are:

$$\alpha^5 Policies_t = \sum_{d=1}^{11} \Upsilon^{1,d}\, m_t^d + \sum_{d=1}^{11} \Upsilon^{2,d}\, mmid_t^d + \sum_{d=1}^{11} \Upsilon^{3,d}\, mpost_t^d + \sum_{i=1976}^{2011} \Upsilon^{4,i}\, dd_t^i. \qquad (5)$$

The annual dummy variables are incremental dummies, dd^i , which take on the value 1 for the year *i* in question and for all subsequent years, and a 0 for all previous years. Thus, the dummy variable for 1976, dd_t^{1976}, equals 1 for each observation in 1976 to 2011, and the dummy variable for 1977, dd_t^{1977}, equals 1 for each observation from 1977 to 2011, etc. Specifying the dummy variables this way allows us to measure the incremental annual effect of policies on Q_t^W for each year separately. Given the logged specification of the model, the fixed effects can be interpreted as the percentage change in Q_t^W attributable to the year *i* relative to the baseline year of 1975. If water quality improvement programs are effective, the incremental dummies should lie mostly below 0, and they should get more negative over time. If water quality improvement programs are not working, the incremental dummies will be 0 or above. Given regulations that dramatically reduced point source loads in the 1970s, we expect to the see a significant downward trend in the 1970s for the soluble phosphorus model.

We rely on three approaches to identify the effects of markets and conservation in our model. First, we examine trends over observables (aggregate nutrient applications, adoption of practices, funding, etc.), and note that these trends should cause the annual fixed effects in our models to trend downward. Other factors that could explain the trends are controlled by our models through the price, flow, and weather effects. Second, we break our analysis into different components of phosphorus emissions that will be affected differentially by conservation policies, economic variables, flow and weather. These components are attached phosphorus, attached phosphorus per unit of sediment, units of sediment themselves, and soluble phosphorus. Each of these components should behave in different, but expected, ways with respect to market forces and conservation. Finally, we rely on monthly fixed effects to capture the role of agricultural management on phosphorus. These should change in expected ways over time with the application of conservation programs. For the remainder of this section, we discuss these three approaches for identification in order.

Observable Trends

Observable trends and policy actions in cities and farming imply that the attached and soluble phosphorus should be declining in farmed watersheds. Once we have controlled for other factors like annual market variation observed through prices, weather effects, and flows, phosphorus concentrations should be falling. First, and most obviously, point source emissions fell dramatically in the late 1970s and early 1980s. Second, yields have increased and phosphorus inputs have declined nation-wide suggesting that soil phosphorus levels should be declining (for instance, see Bruuselma et al., 2011). Since this phosphorus is largely attached to soils, one would expect to see a reduction in attached phosphorus over time. Third, through the widespread adoption of conservation tillage and the CRP, conservation policy started to have observable impacts in the landscape starting in the 1980s. Between 1984 and 1996, the CRP gained 13.8 million hectares nationally, with over 69,000 hectares in the two Lake Erie watersheds examined in this study (USDA-FSA, 2013). A newly revitalized CRP substantially increased rental rates and increased enrollments in the two watersheds we examine from 2002 through 2011. Similarly, conservation tillage adoption rose from around 25% to around 41% of all cropped acres between the 1980s and the present. The total proportion of crops under reduced tillage, a broader measure than conservation tillage, has remained fairly constant since 1996 at around 60-65% of all cropped acres (CTIC, 2013).

Fourth, the 1996 Farm Bill added a new suite of conservation programs intended to reduce nutrient pollution in farming, and it ushered in a period of rising conservation subsidies for farmers. The most important new program, EQIP, sought to provide "assistance to farmers and ranchers in making beneficial, cost-effective changes to cropping systems, grazing management, manure, nutrient, pest, or irrigation management, land uses, or other measures needed to conserve and improve soil, water, and related natural resources" (Title III, Section 334 of Public Law 104–127—APR. 4, 1996). Among other things, the subsidized practices included the development of nutrient management plans and the installation of manure storage facilities, which would enable farmers to hold manure for longer periods of time and thereby spread it on their fields closer to planting; the installation of grassed waterways and riparian zones, which store nutrients in plants and soils as it leaves fields and before it enters streams; and the planting of cover crops, which would hold nutrients on the landscape during the winter. Funding for working lands programs like EQIP expanded from around $200 million per year before 2002 to over $2 billion per year by 2011 (USDA-ERS, 2013).

Finally, regulatory programs expanded in the 2000s when the EPA used the Clean Water Act to regulate large livestock facilities. These regulations were formally adopted in 2003, requiring large livestock farms to obtain permits for discharging nutrient wastes similar to permits obtained by municipal waste water treatment plants and industrial entities. To obtain a permit, large-livestock operations had to agree to undertake actions like manure and nutrient management planning, soil testing, building enough waste storage so they did not have to apply manure before rainstorms, and avoiding the application of manure to farm fields when the fields are frozen. While these programs were regulatory in nature, they were also heavily subsidized by the Farm Bill, which required that the USDA spend at least 60% of EQIP funds on livestock management aimed at meeting these regulations.

Alternative Models of Phosphorus Emissions

Phosphorus can be emitted as attached to soil particles or as dissolved in water. Most efforts to control phosphorus have focused indirectly on controlling sediment emissions instead of controlling phosphorus emissions directly. With our data, we can measure attached phosphorus, but trends in this variable could be related either to changes in the amount of phosphorus used by farmers or to adoption of conservation programs, both of which should be pushing attached phosphorus concentrations down. To decompose the effects of conservation programs that have focused on reducing soil erosion from reductions in input use, we estimate a model with attached phosphorus per unit of sediment on the left hand side and a model with pure units of sediment on the left hand side.

We also consider the concentration of soluble reactive phosphorus on the left hand side. Soluble reactive phosphorus is the phosphorus that is in the water solution in soluble form. Given the reductions in industrial sources of soluble phosphorus, the decline in phosphorus usage by farmers, and the increase in crop yields in the past 30 years, the annual fixed effects should trend downward. Recent literature has suggested that conservation tillage could increase in the emission of soluble phosphorus in watersheds (Zhao et al., 2001; Gilley, Eghball, & Marx, 2007a, 2007b). Given that soluble phosphorus is affected both by industrial and agricultural sources, we are unable to specifically identify the contributing factors in our soluble phosphorus model.

Monthly Fixed Effects

Another way to identify the effects conservation is by examining whether there have been changes in the seasonality of emissions over time. The EQIP program, for instance, subsidized manure lagoons in order to provide enough storage so that farmers could apply manure in spring or summer rather than winter. Nutrient management plans encourage farmers to apply nutrients closer to the growing season, e.g., in spring, rather than in fall. Alternatively, conservation tillage and cover crops are intended to hold attached phosphorus in fields during the winter months when crops are not growing. If conservation programs have been effective, the seasonality of nutrient outflows should be changing in predictable ways over time.

To test this, we include monthly dummy variables, m^d . Because environmental variables, such as flow, temperature, and precipitation, are included separately in the model, the monthly dummy variables capture the added influence of changes in conservation programs and farm management on attached or soluble phosphorus concentrations. To test whether federal conservation programs have had an impact on farm management and water quality, we include interaction terms that allow us to assess whether the monthly effects have been stable over time, $(mmid^d\ , mpost^d)$. The two interaction terms included in the model are for what we call the "mid" and "post" periods. The "mid" period is 1980-1995 and the "post" period is 1996-2011. The "early" period before 1980 can be deduced from these interaction effects.

Because conservation tillage holds soil on farm fields during the winter months when crops are not growing, we expect that attached phosphorus concentrations will decline in the late fall, winter, and early spring (December – March) from the initial time period to the post time period. We also expect that we will see a large reduction in soluble phosphorus in all months between the early period and the mid period, following regulation of waste water treatment plants in the 1970s, although the largest impacts should occur in summer given that summer is when waste water treatment plants are a more important part of the water cycle. In recent years, farmers have been urged to push their nutrient applications, via either chemical means, or via manure fertilizer, closer to the time when the nutrients will be used in the spring, we also expect to see reduction in soluble phosphorus in fall and winter from the mid to the post time period.

Empirical Model

The specific model that we estimate is:

$$lnQ_t^W = \alpha^0 + \alpha^1 \ln(temp)_t + \alpha^2\, ln(precp)_t + \alpha^3\, ln(flow)_t + \beta^1\, ln(dapp3m)_t + \beta^2\, ln(corn3m)_t + \beta^W\, ln(corn3m)_t S_w + \beta^{SP}\, ln(corn3m)_t S_{sp} + \beta^F\, ln(corn3m)_t S_F + \sum_{d=1}^{11} \Upsilon^{1,d}\, m_t^d + \sum_{d=1}^{11} \Upsilon^{2,d}\, mmid_t^d + \sum_{d=1}^{11} \Upsilon^{3,d}\, mpost_t^d + \sum_{i=1976}^{2011} \Upsilon^{4,i}\, dd_t^i + \epsilon_t. \quad (6)$$

Since the data used in this analysis is time series data, we need to conduct additional analysis to ensure that the underlying data is stationary, and check whether our errors are correlated. We begin by assessing whether the individual time series that make up the dataset are stationary. Stationarity in time series means probability distributions of time series process are constant or stable over time. We test for non-stationarity using the Augmented Dickey-Fuller (ADF) test. A first step to use the ADF test is to determine whether the data is best tested under a zero mean (no drift, no time trend), single mean (drift, no trend), or trend (drift and time trend) assumption. We find that our data series do not have a zero mean, so the zero mean type model is ruled out

(Table A2 in appendix A). The trend type is also ruled out because none of the data series indicates consistent trend up or down (Figure A1 in appendix A) Therefore, we use single mean type AR(1) in ADF test. To account for potential auto-correlation and heteroskedasticity, we use Newey-West (NW) standard errors (Newey & West, 1987; Andrews, 1991) as reported in our results.

RESULTS

The results of ADF tests for stationarity are shown in Table B1 in appendix B. For all series of both Maumee and Sandusky, the null hypothesis of unit root non-stationarity is rejected at 0.01 level except for corn price series of Maumee and Sandusky which reject non-stationarity at 0.05 and 0.10 level respectively. Based on this analysis, we conclude that the data series used in our regression are stationary and we proceed to use the data without differencing it.

The full set of regression results for the model specified in equation (6) above are reported in Tables B2-B5 in appendix B. Selected parameter estimates on prices, water flow, and the climate variables are shown in Table 1 for each of the models. The price of phosphorus has a negative and significant effect in the Maumee watershed for all models except suspended sediments. Economically, there is no reason why there should be a relationship between phosphorus prices and sediments. The size of the effect varies by regression, with the largest effect for soluble phosphorus. The effect is smaller for attached phosphorus and attached phosphorus per unit sediment, which makes sense, given the less direct link between the price of phosphorus and the movement of attached phosphorus than in the case of soluble phosphorus. The results are similar for the Sandusky watershed.

For this analysis, we have assumed a three month lag on phosphorus prices, however, the three month lag may or may not be indicative of actual farmer decisions. We assume that after farmers make decisions about nutrient applications, the excess nutrients flush out of the system in about 3 months. This "flush" however could take more or less time. In particular with attached phosphorus one might anticipate that a longer lag time would be more appropriate, and in fact, attached phosphorus may be unrelated to price since so much attached phosphorus was attached over many years past. We test for lags of different time length by using lags of 1, 2, and 6 months and find that while the size of the parameters changes, the sign does not.[2]

In general, we expect that an increase in corn prices will lead to more land in corn, an increase in plowing, more soil movement and more attached phosphorus emission. The effect of corn prices on phosphorus concentrations varies by season, as expected, and by pollutant type. For attached phosphorus, the parameters on corn prices are positive for each season, and are significant, in the Maumee. The effects of corn prices on attached phosphorus per unit sediment and suspended sediment are also positive across the seasons (except for one parameter that is negative, but insignificant). These make sense, given that higher corn prices induce more corn planting, more tillage, and more phosphorus applications. The effects are greatest in fall and winter when farmers have the most time to respond to price signals, but they are positive in spring when farmers still have the opportunity to make changes. For the Sandusky watershed, the effects are less significant overall, and only the corn price in winter is positive and significant for attached phosphorus. This appears to be driven mainly by the effect of corn prices on tillage and sediments.

[2] Results available upon request.

For soluble phosphorus, the parameters on spring and fall corn prices are negative and significant in the Maumee, while the parameters on winter and spring corn prices are positive and significant in the Sandusky. The different responses to corn prices in the two watersheds can be explained by two competing forces. First, additional plowing to plant corn will increase attached phosphorus emissions, but will reduce emissions of soluble phosphorus as long as phosphorus applications do not increase (Zhao et al., 2001; Gilley, Eghball, & Marx, 2007a, 2007b). Second, phosphorus applications likely increase with additional corn planting because it displaces other crops (e.g., soybeans) in the region that do not require phosphorus. We cannot state with certainty in advance which of these effects will dominate. In the larger Maumee watershed, it appears that the additional plowing associated with additional acres of corn production tends to reduce soluble phosphorus outflows, while in the Sandusky watershed, the opposite occurs. We also estimate a model for the total concentration of phosphorus (attached plus soluble), and these results indicate that the aggregate effect of corn price changes is dominated by the impacts on attached phosphorus in both watersheds.[3]

Higher temperatures increase attached phosphorus and reduce soluble phosphorus in both watersheds (Table 1). On the other hand, greater precipitation increases soluble phosphorus runoff and reduces attached phosphorus runoff in both watersheds. This appears 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.[4] We find that higher

[3] Available upon request.

[4] Given that the watersheds are fairly large, there could be temporal lags in the effect of temperature and precipitation on our measures of water quality. To account for this, we also estimate models that use temperature

flow increases nutrient concentrations in general, but interestingly, higher flow reduces the amount of attached phosphorus per unit of sediment. The effect of flow is larger in the Sandusky watershed, which is expected because it is a smaller watershed.

To assess whether environmental policies have had an effect on phosphorus concentrations, we examine the annual incremental effects, which are shown in tabular and graphical form in appendix B. If the trend of the incremental effects is above 0 (Figures B1-B2), then the emission of the pollutants is increasing, and vice-versa. Further if the trend is sloped upward or downward, it means the cumulative effect is strengthening. In both the Maumee and the Sandusky, attached phosphorus was fairly stable prior to 1995, and has declined since 1996. The decline is strengthening in both watersheds, given the downward slope in the trend. This overall reduction is clearly driven in both watersheds by the reduction in sediment emissions since 1996. In contrast, attached phosphorus emissions per unit of sediment, which were trending downward before 1995, have been trending upward ever since. This mirrors soluble phosphorus emissions which have also been trending upward since 1996.

The cumulative predicted changes for 1976-1995, 1996-2011, and 1976-2011 are shown Table 2. These estimates are the sum of the fixed effect parameters over the given time period. The statistical tests assess whether the cumulative effect is different from 0. The trend in

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and precipitation in preceding 10 day intervals for up to 90 days. We then test each 10 day period independently for both temperature and precipitation. Including these alternative measures of temperature and precipitation does not measurably change the other results in our analysis. With a 95% confidence interval, only three of our parameter estimates are statistically different. These 10 day interval fixed effects also confirm that the largest effects of temperature and precipitation occur in the 30 days immediately preceding our water quality observations. Beyond 30 days, temperature and precipitation have no discernible impact on the results.

attached phosphorus has been down over the entire time period, and the strongest reductions occurred after 1996. The reductions in attached phosphorus are driven by changes in suspended sediment, which have declined 70% since 1976. Attached phosphorus per unit sediment rose from 1976 to 1995 in the Maumee, but then declined modestly from 1996-2011. There was not a significant change in attached phosphorus per unit sediment in the Sandusky watershed.

The largest reduction in soluble phosphorus occurred prior to 1995, but soluble phosphorus has been increasing ever since. The earlier reductions result from reductions in point source loadings that occurred in the 1970s and continue today. Based on data from Dolan and Chapra (2012), point source loadings above the monitoring stations used for our analysis fell 1.5% per year from 1976 to 1995 in the Maumee river basin and 2.5% per year over the same time period in the Sandusky river basin. We find a statistically significant and large increase in soluble phosphorus concentrations in both watersheds over the period 1996-2011, which can only be attributed to agriculture.

These results confirm a sizable reduction in point source loads of soluble phosphorus, and a 70% reduction in suspended sediment. The reduction in suspended sediments have driven attached phosphorus loads downward. The amount of phosphorus per unit sediment has actually increased over the time period although most of this increase occurred before 1996. The results suggest that conservation programs have reduced sediment pollution in watersheds, but they have not reduced phosphorus. Despite falling nutrient inputs, rising crop yields, and increasing incentives to install more conservation practices, trends in phosphorus emissions, including both attached phosphorus per unit sediment and soluble phosphorus, have been increasing.

Testing differences in the fixed effects for various months over time allows us to assess how changes in industrial or agricultural management activities within the watershed have affected nutrient concentrations. We cannot completely identify the agricultural effects separately from industrial effects; however, the signature of the two types of activities is evident in different ways. First, waste water treatment plants contribute to soluble phosphorus, and not to attached phosphorus. This means that we can interpret changes to the monthly parameters in the attached phosphorus as being caused by agriculture. Second, the effects of reductions in industrial loadings will be evident mainly before 1981 (see Figure 1). Third, waste water treatment plants have their most important effects on phosphorus concentrations in summer, when natural water flows are lowest, and the waste water plants contribute a larger share of the total water flow.

For the Maumee River, our model detects very large, and statistically significant, reductions in soluble phosphorus concentrations in all months from the period before 1981 to the most recent period (Figure 2). The effect is not as pronounced in the Sandusky river basin because point sources make up a smaller proportion of the flow in that watershed (Dolan and Chapra, 2012). The reduction is largest in summer in both watersheds, as expected.

Agriculture should also have an effect on soluble phosphorus concentrations. For instance, agriculture may also contribute to the reduction in soluble phosphorus concentrations in summer because increasing crop yields have led to increasing export of phosphorus from watersheds. Admittedly, however, we cannot distinguish agricultural from industrial activities here. It is surprising though that there is not a sustained reduction in soluble phosphorus in winter from the 1981-1995 period to the 1996-2011 period, given that conservation programs have strongly encouraged farmers to shift their phosphorus applications from fall and winter to spring; to plant cover crops in late summer or fall to “soak” up excess phosphorus and hold it in soils over winter; to install grass waterways that intercept phosphorus as it leaves farms; and to incorporate manure into soils so that it cannot run off directly into streams, particularly in winter. Given the investments documented above in these activities since 1996, and their primary focus on reducing fall emissions, it is surprising that we do not detect a larger reduction in soluble phosphorus in winter.

Identification is easier for suspended sediments, attached phosphorus, and attached phosphorus per unit sediment since agricultural management is the dominant contributor to sediment and attached phosphorus. If the increase in conservation activities over the past 20 years, like conservation tillage and the Conservation Reserve Program, have had any effect, they should have reduced sediments, with a larger effect in winter than in summer because they cover the soil during a time of year when the soil was bare historically. The change in summer should be smaller because crops do the work of providing cover, but this has not changed over time. The results do indicate a statistically significant reduction in suspended sediments in fall and winter in both watersheds (Figure 2). The reduction in fall and winter, however, has been partially offset with a statistically significant increase in suspended sediment concentrations in spring. This likely results from spring tillage: As farmers have reduced their fall and winter tillage in order to maintain cover on their fields over winter, they appear to have shifted some tillage operations to spring.

We also see evidence that conservation practices have trapped more phosphorus in soils – attached phosphorus per unit sediment was uniformly higher across the months in the period 1996-2011 relative to the two earlier periods (Figure 2). The primary role of conservation practices is to store phosphorus in soils rather than allow it to go downstream so it makes sense that this would increase over time. The net effect of conservation on attached phosphorus concentration differs across the seasons (Figure 2). The reduction in suspended sediments is large enough in fall and winter to drive the overall effect on attached phosphorus downward, but attached phosphorus has actually increased in spring.

POLICY ANALYSIS

The results in this analysis suggest that the enormous efforts of the conservation community to reduce pollution from agriculture have reduced attached phosphorus through conservation tillage, while soluble phosphorus concentrations have increased. It is unclear whether these changes in phosphorus concentrations have had a net negative or positive effect on actual water quality. To determine the water quality effect, we need to calculate actual emissions, or phosphorus loadings, which are determined by multiplying the daily concentration with the daily flow. For this analysis we use the model to predict phosphorus loadings in these watersheds under the business as usual (baseline) and a counterfactual. The baseline is calculated using the estimated parameters in the model. The counterfactual assumes that there have been no policy changes since 1996 by imposing the fixed effect parameters for the 1980-1995 period on the 1996-2011 period. For the counterfactual case we set the annual fixed effects in the 1996-2011 period equal to their average level in the 1980-1995 period. For the monthly fixed effects, we use the parameter estimates for 1980-1995 level to predict concentrations in 1996- 2011.

The results of our comparison of the baseline, which assumes policy changes have occurred between the 1980-1995 period and the 1996-2011 period, and the counterfactual, which assumes that no policy changes have occurred, are shown in table 3. Both watersheds experienced a sizable increase in flow between the 1980-1995 period and the 1996-2011 period. For soluble phosphorus, the counterfactual implies that there would have been less soluble phosphorus loading under the policy conditions of 1980-1995 period. This result is consistent in both watersheds. In contrast, attached phosphorus loading would have been greater if not for the policy changes that occurred from the 1980s to 1990s. These results confirm that widespread adoption of conservation tillage potentially reduced attached phosphorus emissions.

Looking at the combined outputs from the watersheds, however, our results show that the increases in soluble phosphorus have exceeded the reductions in attached phosphorus. Attached phosphorus was smaller by around 176 metric tons per year in the baseline as compared to the counterfactual, but soluble phosphorus increased by 322 metric tons. As a consequence, Lake Erie experienced a gain in total phosphorus emissions of 146 metric tons per year, or 7.5%, between the earlier and later periods. Despite our efforts at trapping phosphorus, which have been successful in reducing sediment flows, soluble phosphorus emissions are increasing. These results confirm a number of scientific studies (Zhao et al., 2001 and Gilley, Eghball, & Marx, 2007a, b).

These results should give policy makers pause as they consider implementing new policies to reduce nutrients, particularly if the new policies simply do more or the same. Ohio's Phosphorus Task Force calls for a 40% reduction in nutrient loading in Lake Erie watersheds using the same methods as have been used in the past. Nothing in our model suggests that a change of this scale is plausible using techniques used in the past. An alternative approach to reduce nutrient loads, however, is to target phosphorus inputs directly with a phosphorus input tax. Based on the elasticity of phosphorus outputs in watersheds with respect to phosphorus price that we calculate, a 10% increase in the price of phosphorus will reduce soluble phosphorus concentrations by 3.3 to 4.3%. For policy purposes, we examine the effect of a 25% tax on phosphorus inputs (table B6). From just these two watersheds, this phosphorus tax can reduce soluble phosphorus concentrations by around 72 metric tons per year. This represents about an

8% reduction in soluble phosphorus loading. Obviously to achieve a 40% reduction in nutrients would require significantly higher costs.

CONCLUSION

This paper develops a model of nutrient emissions in agricultural watersheds. Nutrient emissions are modeled as a function of ecological, economic, and policy variables. The model is estimated with data from two watersheds that are dominated by agricultural uses in Ohio over a 37 year period. Ecological variables like water flow, temperature, and precipitation have strong influences on the emissions of nutrients, as expected. Economic variables, like nutrient prices and crop prices, also have important implications for nutrient emissions. Specifically, higher prices for nutrient inputs lead to lower emissions of nutrients in watersheds, suggesting that farmers respond to higher prices by reducing nutrient inputs. The effect of prices on soluble phosphorus is larger than the effect on attached phosphorus, which makes sense given that soluble phosphorus is associated with contemporaneous emissions and attached phosphorus is a function of historical emissions.

The results on crop prices indicate that higher winter corn prices have a positive effect on attached phosphorus concentrations, while they have an uncertain effect on soluble phosphorus concentrations. The attached phosphorus 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 causes more sediment and more attached phosphorus to move into streams. Soluble phosphorus, on the other hand, could increase or decrease when farmers switch to corn. Plowing will reduce soluble phosphorus, but shifting from soybeans to corn will increase phosphorus inputs onto farm fields.

We identify the effects of various management and environmental policy changes over the past 37 years using several approaches. First, we use observational data to show that phosphorus inputs have been declining, and conservation funding for voluntary phosphorus emission reductions in farming has been increasing. In light of this, phosphorus pollution should be trending downward. We argue that if phosphorus concentrations are increasing, the implication is that conservation is failing. Second, the timing of efforts in industry and agriculture should be observable since industry started reducing pollution in the 1970s and appears to have been successful by the early 1980s, while agriculture began investing in voluntary efforts heavily in the 1990s Third, we analyze several measures of pollution because the measures undertaken by point sources to reduce pollution will have different effects than those undertaken in agriculture, and the activities undertaken in agriculture are not uniform in their effects on pollution.

We show that there has been a large reduction in suspended sediments over time, and that this is attributed to the expansion of voluntary, but subsidized, agricultural conservation programs. We also show that there was a large reduction in soluble phosphorus before 1981, and that this was largely attributed to reductions in pollution from industrial sources. While the reductions in sediments appear to be gaining strength, owing to deepening efforts by farmers to do conservation tillage, the reductions in soluble phosphorus gained before 1995 have almost been reversed since 1996. There is no remaining large source for phosphorus other than agriculture, so we attribute this recent increase to agriculture. In fact, recent literature suggests that conservation tillage could increase in the emission of soluble phosphorus in watersheds (Zhao et al., 2001; Gilley, Eghball, & Marx, 2007a, 2007b).

A set of monthly fixed effects further illustrate the complexities of conservation programs vis-à-vis traditional regulation. There is clear evidence that industrial regulation in the 1970s reduced soluble phosphorus, as those regulations were intended to do. There is also clear evidence that conservation programs have reduced suspended sediments, particularly in fall and winter. While farmers have reduced plowing in fall, they appear to have increased it in spring, negating some of the benefits of conservation tillage. Further, by emphasizing trapping of phosphorus in farm fields, conservation programs have inadvertently increased the phosphorus attached to sediments. This means that the net effects of conservation programs on attached phosphorus concentrations is mixed, with a reduction in fall and winter, and an increase in spring.

These results suggest that agricultural pollution abatement programs have provided a reduction in sediments with some reduction in attached phosphorus, however, they have very little beneficial effect on overall phosphorus concentrations. In fact, total emissions have increased 12% from the period 1996-2011 compared to the period 1981-1995. The traditional programs that try to trap nutrients within the watershed are leaky and appear to have very little long-term impact despite the effort. We do find that there is hope for policy success however, if economic instruments are used. Our parameters on nutrient input prices suggest a modest nutrient input tax of 25% would reduce phosphorus loads by around 8%, and in particular soluble phosphorus. Soluble phosphorus it turns out is the most important contributor to harmful algal blooms.

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TABLE 1.—EFFECTS OF PRICE AND WEATHER VARIABLES

	Soluble Phosphorus	Attached Phosphorus	Attached P per unit SS	Suspended Sediment(SS)
Panel 1A: Maumee				
Phosphorus Price	–0.425**	–0.141**	-0.111*	-0.027
	(0.084)	(0.053)	(0.046)	(0.071)
Corn Price Winter	–0.188	0.51**	0.295**	0.241**
	(0.140)	(0.073)	(0.065)	(0.094)
Corn Price Spring	–0.409*	0.211**	0.205**	0.011
	(0.160)	(0.058)	(0.052)	(0.076)
Corn Price Summer	–0.035	0.106*	-0.081	0.193**
	(0.150)	(0.051)	(0.047)	(0.070)
Corn Price Fall	–0.257*	0.394**	0.104*	0.308**
	(0.114)	(0.051)	(0.047)	(0.068)
Temperature	–1.559**	0.535**	-0.919**	1.462**
	(0.067)	(0.037)	(0.036)	(0.050)
Precipitation	0.364**	–0.092**	-0.052**	-0.041**
	(0.026)	(0.010)	(0.010)	(0.014)
Flow	0.320**	0.344**	-0.229**	0.572**
	(0.012)	(0.005)	(0.004)	(0.007)
Panel 1B: Sandusky				
Phosphorus Price	–0.331**	0.031	-0.166**	0.201
	(0.089)	(0.086)	(0.063)	(0.108)
Corn Price Winter	0.394**	0.306**	0.031	0.281*
	(0.137)	(0.094)	(0.075)	(0.115)
Corn Price Spring	0.393**	–0.006	-0.091	0.063
	(0.152)	(0.086)	(0.068)	(0.107)
Corn Price Summer	0.128	–0.058	-0.235**	0.154
	(0.140)	(0.074)	(0.061)	(0.092)
Corn Price Fall	–0.089	0.118	0.305**	-0.171
	(0.131)	(0.077)	(0.064)	(0.097)
Temperature	–0.569**	0.747**	-0.800**	1.543**
	(0.069)	(0.051)	(0.046)	(0.065)
Precipitation	0.219**	–0.039**	-0.028**	-0.012
	(0.023)	(0.013)	(0.010)	(0.017)
Flow	0.458**	0.491**	-0.245**	0.735**
	(0.009)	(0.006)	(0.004)	(0.007)

Newey–West Standard Errors are shown in parentheses. Noting that the regression equation is “log-log” form, the percent change in each phosphorus (Soluble, Attached) from a one percent increase in independent variables is shown. The effects of corn price for 4 seasons are calculated from the coefficients of dummy variables associated with corn price (Ln(corn3m)* S^W, Ln(corn3m)* S^{SP}, Ln(corn3m)* S^F). ** p <0.01,* p <0.05.

TABLE 2.—CUMULATIVE PROPORTIONAL CHANGE IN POLLUTANT VARIABLE

	Soluble Phosphorus	Attached Phosphorus	Attached P Per unit SS	Suspended Sediment(SS)
Panel A: Maumee				
1976–1995	–1.274***	–0.142	0.402***	–0.561***
	(0.154)	(0.088)	(0.073)	(0.117)
1996–2011	1.037***	–0.246***	–0.145***	–0.117
	(0.126)	(0.054)	(0.048)	(0.077)
1976–2011	–0.237**	–0.388***	0.257***	–0.678***
	(0.111)	(0.077)	(0.062)	(0.099)
Panel B: Sandusky				
1976–1995	–1.241***	–0.242**	0.140	–0.332**
	(0.165)	(0.122)	(0.121)	(0.160)
1996–2011	0.968***	–0.411***	–0.058	–0.385***
	(0.129)	(0.084)	(0.066)	(0.110)
1976–2011	–0.273**	–0.652***	0.082	–0.717***
	(0.112)	(0.096)	(0.092)	(0.123)

Newey–West Standard Errors are shown in parentheses. Noting that the regression equation is "log–log" form, the percent change in each phosphorus (Soluble, Attached) from a one percent increase in independent variables is shown. The effects of corn price for 4 seasons are calculated from the coefficients of dummy variables associated with corn price (Ln(corn3m)* S^W, Ln(corn3m)* S^{SP}, Ln(corn3m)* S^F). *** p <0.01, ** p <0.05, * p <0.10.

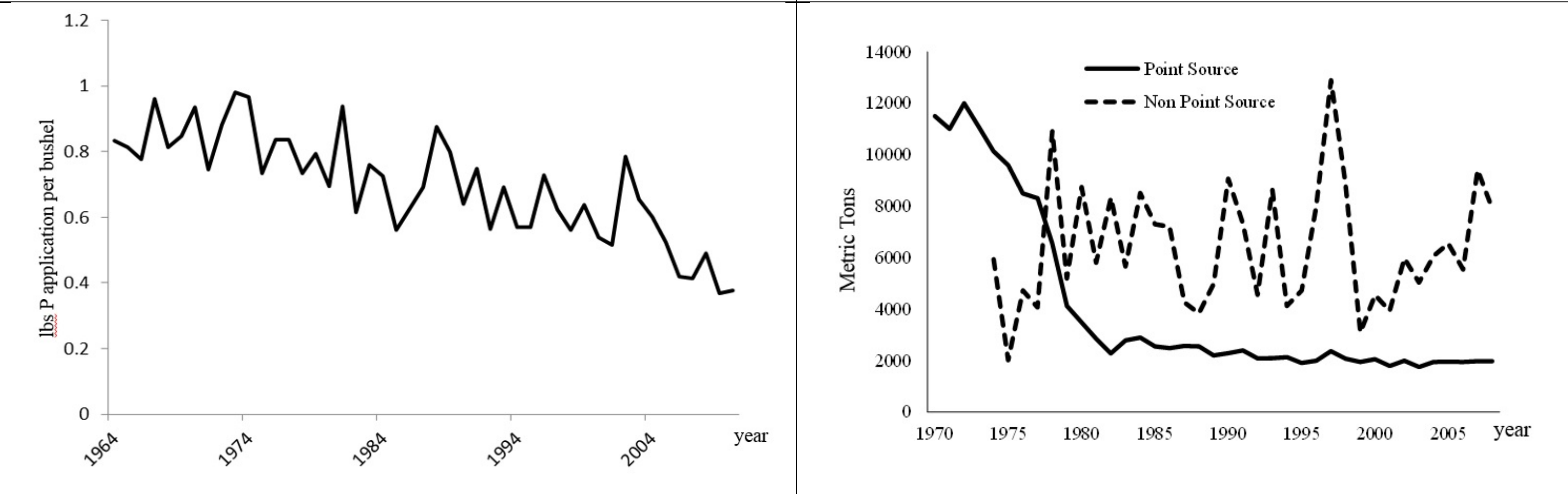
TABLE 3.—COMPARISON OF PREDICTED SOLUBLE, ATTACHED, AND TOTAL PHOSPHORUS LOADINGS IN THE BASELINE AND COUNTERFACTUAL CASES

	Flow	Loadings					
		Soluble Phosphorus		Attached Phosphorus		Total Phosphorus	
		Baseline	Counter-factual	Baseline	Counter-factual	Baseline	Counter-factual
	(Billion Liters per year)	(Metric tons per year)					
Maumee							
1980–1995	4679	348	348	1215	1215	1563	1563
1996–2011	5722	429	176	1312	1392	1740	1569
% Change	22.3%	23.3%	–49.3%	7.9%	14.6%	11.4%	0.4%
Sandusky							
1980–1995	1092	81	81	319	319	400	400
1996–2011	1350	111	40	347	443	458	483
% Change	23.7%	36.9%	–49.9%	8.9%	38.8%	14.5%	20.9%
Total (Maumee + Sandusky)							
1980–1995	5771	429	429	1534	1534	1963	1963
1996–2011	7072	539	217	1659	1835	2198	2052
% Change	22.5%	25.8%	–49.4%	8.1%	19.6%	12.0%	4.5%

For this analysis we use the model to predict phosphorus loadings in these watersheds under the business as usual (baseline) and a counterfactual. Thus, the baseline is calculated using the estimated parameters in the model. The counterfactual assumes that there have been no policy changes since 1996 by imposing the fixed effect parameters for the 1980–1995 period on the 1996-2011 period. For the counterfactual case we set the annual fixed effects in the 1996-2011 period equal to their average level in the 1980-1995 period. For the monthly fixed effects, we use the parameter estimates for 1980-1995 level to predict concentrations in 1996- 2011. Total phosphorus is the summation of Soluble and Attached phosphorus.

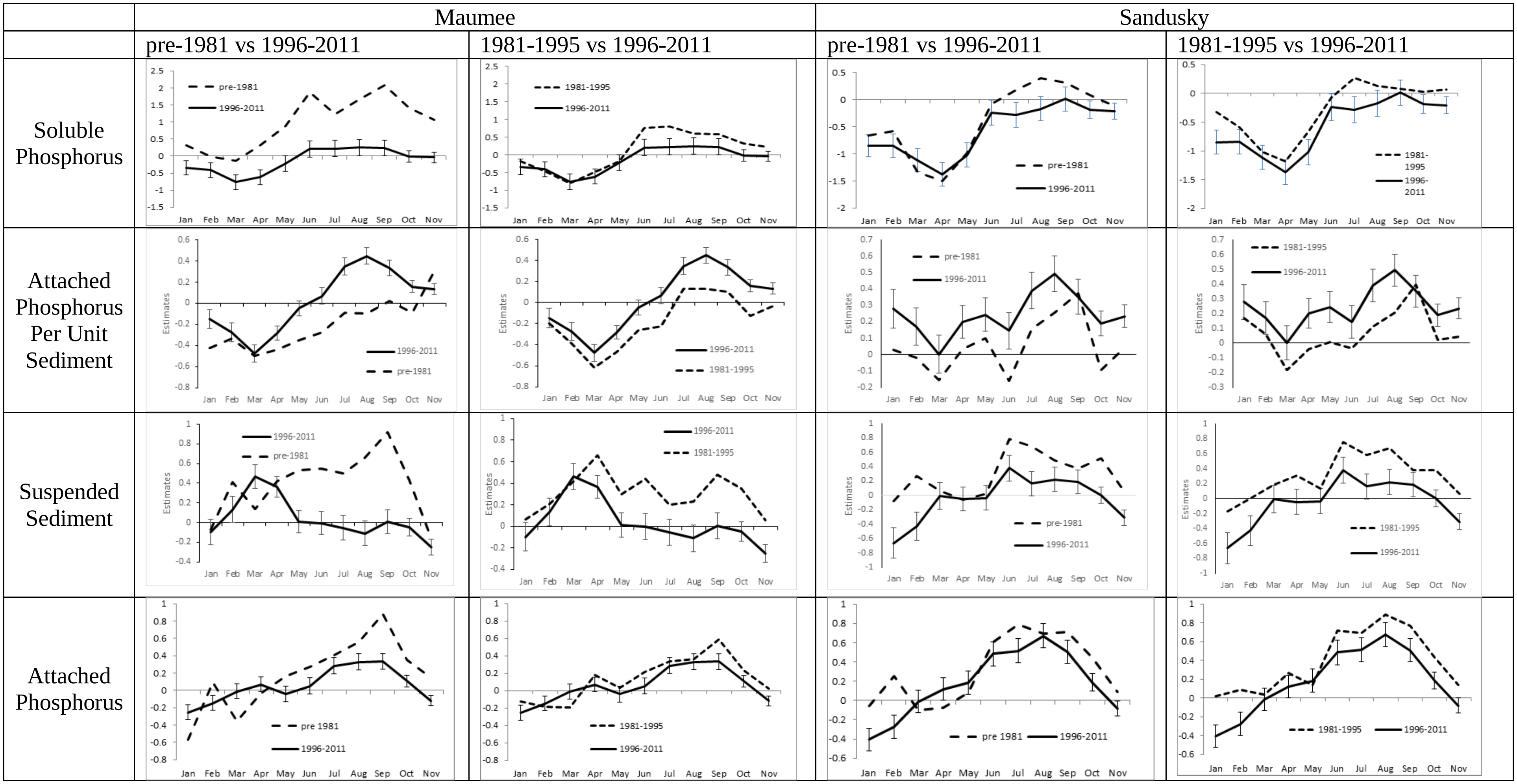
FIGURE 1.— OHIO INTENSITY OF PHOSPHORUS APPLICATION AND POLLUTION LOADS TO LAKE ERIE.

Panel A: Phosphorus Application per Bushel of Corn, Soybean and Wheat Produced in Ohio	Panel B: Point and nonpoint source pollution loads to Lake Erie



Sources: Panel 1A -- Taylor (1994) and USDA-NASS (2014);
Panel 1B – Ohio Phosphorus Task Force (2013), Dolan and Chapra (2012), and DePinto et al. (2006)

FIGURE 2 – MONTHLY FIXED EFFECTS FOR JANUARY – NOVEMBER.



Notes: Error bars represent the 95% confidence interval. The first column of results for each watershed compares the monthly fixed effects for the period before 1981 to the 1996-2011 period. The second column of results for each watershed compares the fixed effects for the period 1981-1995 to the 1996-2011 period.

Appendix A.— Variables Names and Descriptions

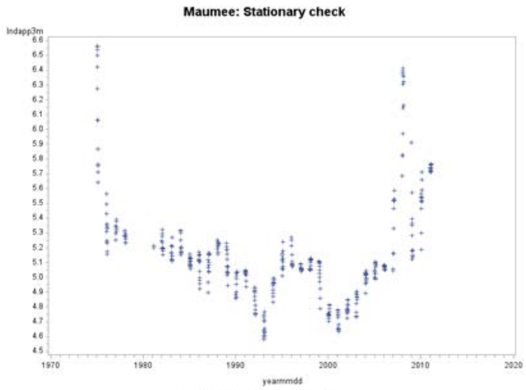
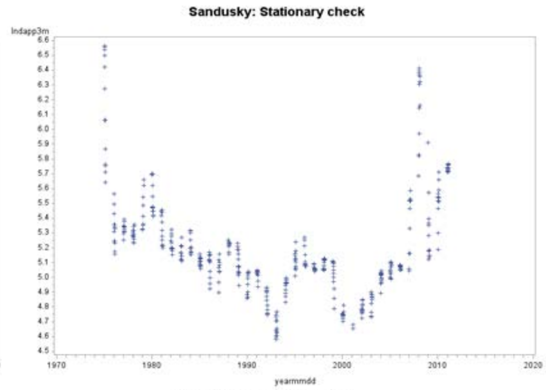
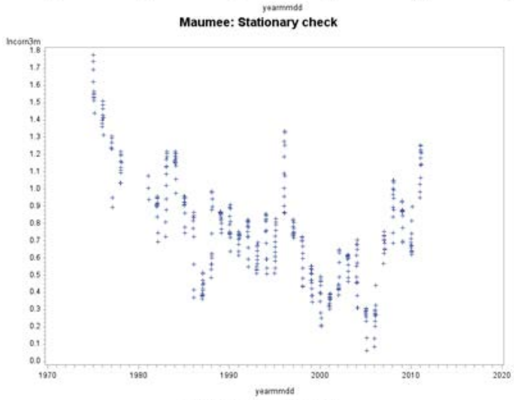
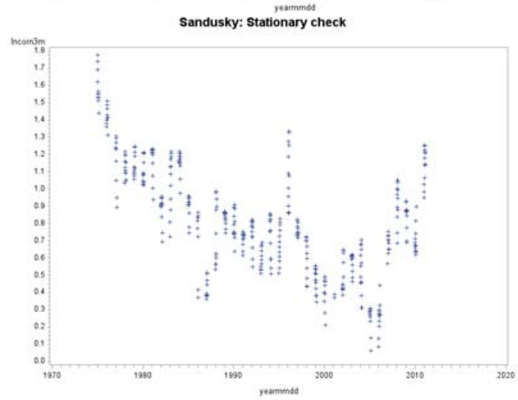
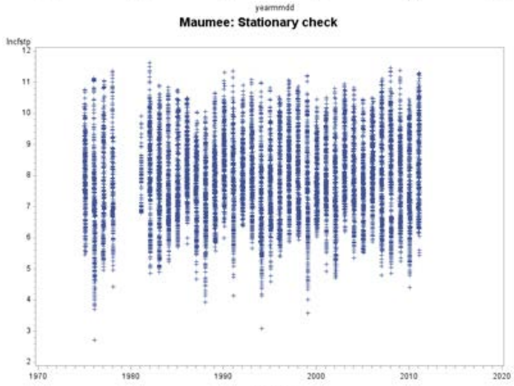
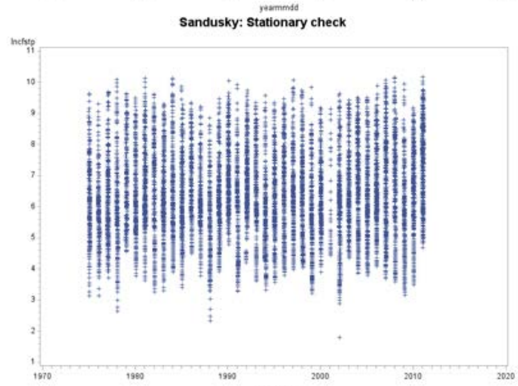
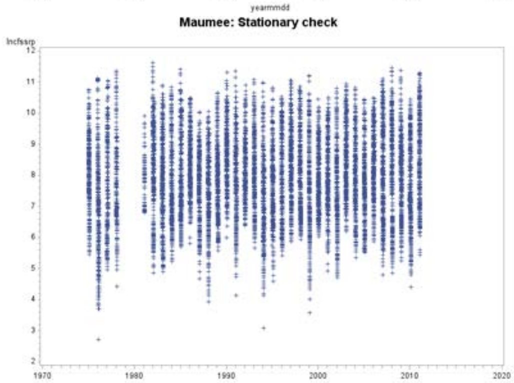
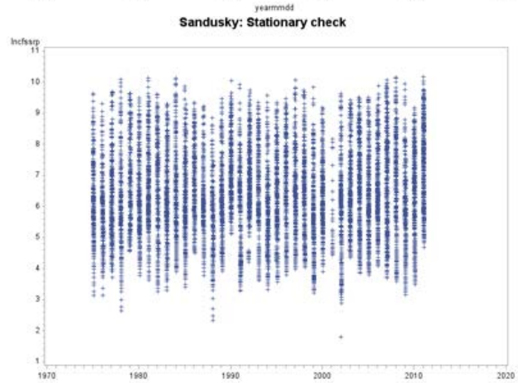
TABLE A1.—DESCRIPTION OF VARIABLES USED IN REGRESSION ANALYSIS

Variable	Description
LnQ^W	
Ln(SRP)	Log of soluble reactive phosphorus concentration (mg/L) Source: Heidelberg University (2012)
Ln(ATTP)	Log of attached phosphorus (TP–SRP) (mg/L) Where TP is total phosphorus concentration (mg/L) collected from Heidelberg University (2012)
Ln(ATTPSS)	Log of attached phosphorus per unit sediment (TP–SRP)/SS (unitless) Source: Heidelberg University (2012)
Ln(SS)	Log of suspended sediments (mg/L) Source: Heidelberg University (2012)
Ln(flow)	Log of flow rate for samples with observations of the appropriate left hand side variable (cubic feet per second). Variable given as Ln(cfsrp), Ln(cfsattp), Ln(cfsattpss), or Ln(SS); Source: Heidelberg University (2012)
Ln(temp)	Log of preceding 30day average temperature for all weather stations Source: National Climate Data Center
Ln(precp)	Log of preceding 30 day average precipitation per day for all weather stations Source: National Climate Data Center
LnQ^F	
Ln(dapp3m)	Log of Diammonium phosphate preceding 3month average price (real 1982 US$) Source: World Bank Data (2013)
Ln(corn3m)	Log of corn 3 preceding month average price (real 1982 US$) Source: US Department of Agriculture, National Agricultural Statistics Service (USDA-NASS, 2014)
*Ln(corn3m)** S^W	Log of corn 3 preceding month average price interacted with winter season Where $S^W = 1$ *if month = Jan, Feb, and Mar,* $= 0$ *otherwise*
*Ln(corn3m)** S^{SP}	Log of corn 3 preceding month average price interacted with spring season Where $S^{SP} = 1$ *if month= Apr, May, and June,* $= 0$ *otherwise*
*Ln(corn3m)** S^F	Log of corn 3 preceding month average price interacted with fall season Where $S^F = 1$ *if month= Oct, Nov, and Dec,* $= 0$ *otherwise*
$Policies_t$	
$m^1 - m^{11}$	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 $dpost = 1\ if\ year > 1995,$ $= 0\ otherwise$
$dd^{1976} - dd^{2011}$	$dd^i = 1\ \ if\ year \geq i,$ $= 0\ \ otherwise$

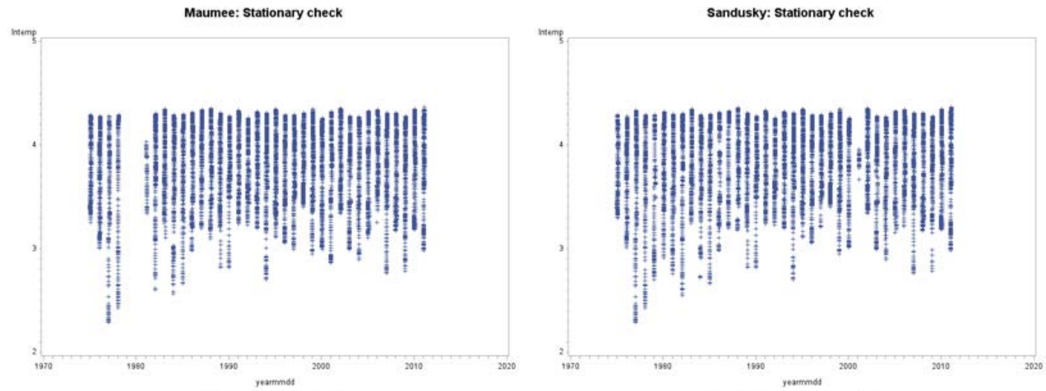
TABLE A2.— DATA AVERAGES

	Maumee			Sandusky		
Variable	N	Mean	Std Dev	N	Mean	Std Dev
Ln(dapp3m)	11575	5.159806	0.350523	11359	5.187445	0.338535
Ln(corn3m)	11575	0.770392	0.315447	11359	0.809991	0.311477
Ln(cfstp)	11509	7.789528	1.368458	11296	6.086492	1.489077
Ln(cfssrp)	11319	7.806891	1.371066	11002	6.110979	1.491581
Ln(temp)	11575	3.851203	0.39198	11359	3.859738	0.39307
Ln(precp)	11575	–2.47727	0.563941	11359	–2.46342	0.554378
Ln(SRP)	10799	–3.33948	1.324374	10249	–3.6935	1.346749
Ln(ATTP)	11504	–1.87417	0.610706	11273	-2.25316	0.871163

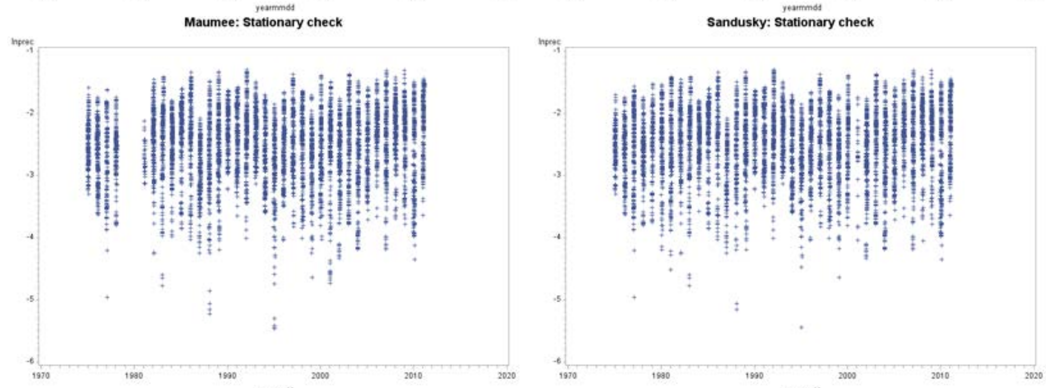
Figure A1. —Trends for Each Data Series

Variable	Maumee	Sandusky
Ln(dapp3m)		
Ln(corn3m)		
Ln(cfstp)		
Ln(cfssrp)		

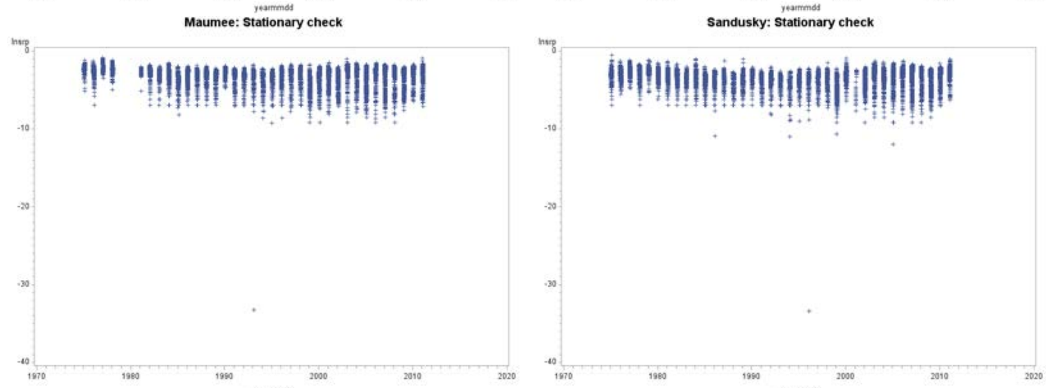
Ln(temp)



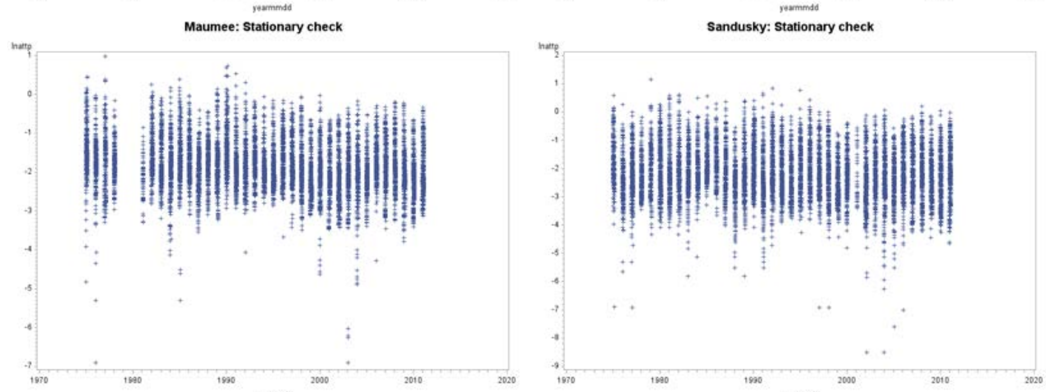
Ln(precp)



Ln(SRP)



Ln(ATTP)



The X–axis is time, and the Y–axis is the value of variables.

APPENDIX B.— RESULTS

TABLE B1.—AUGMENTED DICKEY-FULLER UNIT ROOT TESTS (TYPE: SINGLE MEAN)

	Maumee			Sandusky		
	Lags	Tau	Pr < Tau	Lags	Tau	Pr < Tau
Ln(dapp3m)	1	–3.81	0.003	1	–4.07	0.0012
Ln(corn3m)	1	–3.06	0.0301	1	–2.73	0.0697
Ln(cfstp)	1	–19.59	<.0001	1	–21.89	<.0001
Ln(cfssrp)	1	–19.32	<.0001	1	–21.71	<.0001
Ln(temp)	1	–5.41	<.0001	1	–5.85	<.0001
Ln(precp)	1	–14.05	<.0001	1	–13.07	<.0001
Ln(SRP)	1	–15.89	<.0001	1	–17.32	<.0001
Ln(ATTP)	1	–26.25	<.0001	1	–26.69	<.0001

TABLE B2.—REGRESSION RESULTS FOR MAUMEE FOR SRP, AND ATTACHED P.

	Ln(SRP)		Ln(ATTP)	
Variables	**Estimate**	**t-value**	**Estimate**	**t-value**
intercept	4.1669	7.23	–6.3104	–18.20
m^1	0.3153	1.70	–0.5671	–4.26
m^2	–0.0163	–0.08	0.0958	0.77
m^3	–0.1375	–0.71	–0.3549	–3.12
m^4	0.3157	1.47	–0.0335	–0.33
m^5	0.8742	3.91	0.1664	1.69
m^6	1.8656	8.30	0.2695	2.68
m^7	1.2338	5.60	0.4036	4.04
m^8	1.6587	7.10	0.5626	4.74
m^9	2.0914	9.03	0.8845	9.03
m^{10}	1.4132	9.89	0.3539	4.27
m^{11}	1.0667	8.17	0.1483	1.37
$mmid^1$	–0.5018	–3.76	0.4399	3.66
$mmid^2$	–0.4400	–2.96	–0.2769	–2.58
$mmid^3$	–0.6725	–4.72	0.1586	1.71
$mmid^4$	–0.8020	–5.69	0.2163	2.44
$mmid^5$	–1.0652	–6.83	–0.1343	–1.61
$mmid^6$	–1.1106	–7.85	–0.0566	–0.68
$mmid^7$	–0.4382	–3.05	–0.0687	–0.81
$mmid^8$	–1.0671	–6.63	–0.2008	–1.88
$mmid^9$	–1.5107	–9.60	–0.2985	–3.56
$mmid^{10}$	–1.0951	–6.25	–0.1187	–1.42
$mmid^{11}$	–0.8415	–5.89	–0.1226	–1.11
$mpost^1$	–0.6568	–4.67	0.3138	2.58
$mpost^2$	–0.3929	–2.59	–0.2424	–2.18
$mpost^3$	–0.6266	–4.31	0.3430	3.58
$mpost^4$	–0.9338	–6.05	0.1023	1.15
$mpost^5$	–1.0937	–6.90	–0.2075	–2.46
$mpost^6$	–1.6576	–10.35	–0.2179	–2.61
$mpost^7$	–1.0093	–6.29	–0.1189	–1.38
$mpost^8$	–1.4113	–8.32	–0.2335	–2.19
$mpost^9$	–1.8639	–10.93	–0.5516	–6.58
$mpost^{10}$	–1.4296	–9.51	–0.2468	–2.99
$mpost^{11}$	–1.1076	–7.70	–0.2661	–2.43
Ln(dapp3m)	–0.4246	–5.03	–0.1411	–2.68
Ln(corn3m)	–0.0355	–0.24	0.1057	2.06
Ln(flow)	0.3205	27.58	0.3440	68.51
Ln(temp)	–1.5592	–23.19	0.5351	14.48
Ln(precp)	0.3641	14.30	–0.0923	–9.20
*Ln(corn3m)** S^W	–0.1528	–1.28	0.4047	7.18
*Ln(corn3m)** S^{SP}	–0.3731	–2.70	0.1054	2.58
*Ln(corn3m)** S^F	–0.2218	–1.68	0.2887	7.16
dd^{1976}	–0.4538	–5.12	0.0647	1.08
dd^{1977}	0.3057	5.00	0.1573	2.88
dd^{1978}	–0.3555	–5.95	–0.2767	–5.66
dd^{1981}	0.2480	2.04	–0.5500	–6.69
dd^{1982}	–0.1374	–1.81	0.6018	13.36
dd^{1983}	–0.0295	–0.45	–0.1574	–4.81
dd^{1984}	–0.1641	–2.70	–0.0246	–0.76
dd^{1985}	–1.2682	–15.41	0.2388	6.43
dd^{1986}	0.7607	8.61	–0.1720	–4.99

dd^{1987}	0.2986	3.09	–0.0169	–0.50
dd^{1988}	–0.1449	–1.52	0.3188	8.82
dd^{1989}	–0.4094	–4.71	–0.2383	–7.06
dd^{1990}	0.6700	8.90	0.0504	1.52
dd^{1991}	–0.5983	–8.09	–0.0913	–2.93
dd^{1992}	0.0349	0.43	–0.1928	–6.25
dd^{1993}	–0.4095	–2.80	0.2210	7.29
dd^{1994}	–0.2719	–1.73	0.0821	2.79
dd^{1995}	0.6501	6.24	–0.1572	–5.60
dd^{1996}	0.1619	1.31	0.1302	2.83
dd^{1997}	0.1060	1.06	–0.1399	–3.93
dd^{1998}	0.1659	1.82	–0.0067	–0.20
dd^{1999}	–0.6525	–7.13	0.0022	0.08
dd^{2000}	0.5522	6.25	–0.0619	–1.97
dd^{2001}	–0.0829	–1.04	–0.1033	–3.56
dd^{2002}	0.2170	2.84	0.0559	1.91
dd^{2003}	0.3739	4.67	–0.2019	–6.62
dd^{2004}	–0.1770	–1.99	0.1297	3.55
dd^{2005}	–0.5259	–4.96	0.1906	4.78
dd^{2006}	0.5574	5.78	0.1168	3.73
dd^{2007}	–0.3235	–3.37	–0.1251	–3.08
dd^{2008}	0.6637	6.55	0.1598	3.15
dd^{2009}	–0.5140	–6.08	–0.2924	–4.85
dd^{2010}	0.8898	12.79	0.1038	3.08
dd^{2011}	–0.3747	–4.74	–0.2038	–5.55

TABLE B3.—REGRESSION RESULTS FOR MAUMEE FOR SUSPENDED SEDIMENT AND ATTACHED PHOSPHORUS PER UNIT SEDIMENT.

	Ln(ATTPSS)		Ln(SS)	
Variables	**Estimate**	**t-value**	**Estimate**	**t-value**
intercept	-0.2423	-0.79	-6.1005	-12.97
m^1	-0.4231	-3.39	-0.0735	-0.5
m^2	-0.3317	-2.4	0.4134	2.77
m^3	-0.4956	-5.24	0.1341	0.95
m^4	-0.437	-5.61	0.4185	3.63
m^5	-0.3532	-4.49	0.5358	4.53
m^6	-0.2754	-3.32	0.5512	4.46
m^7	-0.0934	-1.14	0.5039	4.21
m^8	-0.0937	-1.03	0.6626	4.72
m^9	0.0205	0.23	0.9208	7.01
m^{10}	-0.0915	-1.35	0.4315	4.02
m^{11}	0.3066	3.57	-0.1623	-1.39
$mmid^1$	0.2273	2	0.1394	1.09
$mmid^2$	-0.0592	-0.47	-0.2072	-1.65
$mmid^3$	-0.1227	-1.64	0.2819	2.42
$mmid^4$	-0.0325	-0.46	0.2416	2.4
$mmid^5$	0.0904	1.31	-0.2359	-2.36
$mmid^6$	0.0474	0.67	-0.1065	-1.05
$mmid^7$	0.2266	3.21	-0.3008	-3.12
$mmid^8$	0.2261	2.84	-0.4327	-3.58
$mmid^9$	0.0852	1.07	-0.4396	-3.88
$mmid^{10}$	-0.0319	-0.46	-0.0778	-0.72
$mmid^{11}$	-0.34	-3.78	0.2185	1.8
$mpost^1$	0.2734	2.44	-0.0249	-0.19
$mpost^2$	0.0567	0.45	-0.2802	-2.13
$mpost^3$	0.0193	0.25	0.3318	2.81
$mpost^4$	0.1546	2.23	-0.0544	-0.53
$mpost^5$	0.3065	4.55	-0.5246	-5.16
$mpost^6$	0.3421	4.89	-0.5551	-5.34
$mpost^7$	0.4404	6.33	-0.558	-5.62
$mpost^8$	0.5418	6.91	-0.7738	-6.31
$mpost^9$	0.3136	3.98	-0.9152	-8.05
$mpost^{10}$	0.2497	3.65	-0.4805	-4.44
$mpost^{11}$	-0.1724	-1.94	-0.0886	-0.73
Ln(dapp3m)	-0.1113	-2.45	-0.0271	-0.38
Ln(corn3m)	-0.0809	-1.71	0.1932	2.75
Ln(flow)	-0.2291	-54.71	0.5725	82.81
Ln(temp)	-0.9188	-25.84	1.4616	29.23
Ln(precp)	-0.0521	-5.25	-0.0407	-2.83
*Ln(corn3m)** S^W	0.3755	7.36	0.0479	0.65
*Ln(corn3m)** S^{SP}	0.2858	8.72	-0.1821	-3.67
*Ln(corn3m)** S^F	0.1848	5.34	0.1146	2.12
dd^{1976}	0.0593	1.04	-0.0383	-0.51
dd^{1977}	0.061	1.11	0.1043	1.78
dd^{1978}	0.4514	8.14	-0.7286	-12.22
dd^{1981}	-0.4456	-5.59	-0.0823	-0.7
dd^{1982}	0.14	2.61	0.4576	5.49
dd^{1983}	0.0389	1.53	-0.1989	-4.42
dd^{1984}	-0.0105	-0.35	-0.0144	-0.32

dd^{1985}	-0.106	-2.61	0.3472	7.1
dd^{1986}	0.1122	2.95	-0.2809	-6.14
dd^{1987}	-0.1149	-3.57	0.1006	2.31
dd^{1988}	0.1818	5.29	0.1324	3.01
dd^{1989}	-0.1288	-3.62	-0.1103	-2.42
dd^{1990}	-0.1447	-4.94	0.1984	4.09
dd^{1991}	0.0585	2.31	-0.1516	-3.42
dd^{1992}	0.0864	2.66	-0.2781	-6.91
dd^{1993}	0.1407	4.42	0.0821	2.05
dd^{1994}	0.0465	1.62	0.0326	0.77
dd^{1995}	-0.0245	-0.88	-0.1329	-3.21
dd^{1996}	-0.2169	-5.18	0.3359	5.27
dd^{1997}	-0.1214	-3.89	-0.0124	-0.27
dd^{1998}	0.1911	7.43	-0.1973	-4.64
dd^{1999}	-0.0409	-1.62	0.0453	1.09
dd^{2000}	-0.0239	-0.74	-0.0354	-0.78
dd^{2001}	-0.0448	-1.64	-0.0585	-1.49
dd^{2002}	0.0016	0.06	0.0528	1.28
dd^{2003}	0.0743	2.83	-0.2774	-6.53
dd^{2004}	-0.0792	-2.82	0.1997	4.69
dd^{2005}	0.0904	2.85	0.0927	1.94
dd^{2006}	0.079	3.49	0.0578	1.5
dd^{2007}	-0.0051	-0.16	-0.1265	-2.3
dd^{2008}	-0.0802	-1.89	0.2352	3.47
dd^{2009}	-0.0591	-1.24	-0.2341	-2.81
dd^{2010}	0.0983	3.56	0.0067	0.14
dd^{2011}	-0.0082	-0.25	-0.2015	-3.78

TABLE B4.—REGRESSION RESULTS FOR SANDUSKY FOR SRP, AND ATTACHED P.

	Ln(SRP)		Ln(ATTP)	
Variables	**Estimate**	**t-value**	**Estimate**	**t-value**
intercept	–0.9919	–1.63	–8.3914	–15.31
m^1	–0.6611	–3.36	–0.0573	–0.41
m^2	–0.5739	–2.7	0.2570	1.81
m^3	–1.3359	–6.62	–0.1006	–0.76
m^4	–1.5036	–6.87	–0.0762	–0.64
m^5	–0.9813	–4.47	0.0791	0.65
m^6	–0.0745	–0.34	0.6044	4.56
m^7	0.1767	0.83	0.7877	7.24
m^8	0.3911	1.91	0.6944	6.15
m^9	0.3157	1.52	0.7079	6.49
m^{10}	0.0853	0.77	0.4433	5.12
m^{11}	–0.1236	–1.1	0.0860	0.9
$mmid^1$	0.3311	2.78	0.0755	0.68
$mmid^2$	–0.0104	–0.08	–0.1699	–1.53
$mmid^3$	0.3229	2.68	0.1324	1.39
$mmid^4$	0.3257	2.6	0.3448	3.64
$mmid^5$	0.3145	2.39	0.0589	0.61
$mmid^6$	–0.0005	0	0.1135	1.08
$mmid^7$	0.0914	0.67	–0.0972	–1.15
$mmid^8$	–0.2598	–2.03	0.1900	2.08
$mmid^9$	–0.2317	–1.76	0.0603	0.67
$mmid^{10}$	–0.0546	–0.43	–0.0045	–0.05
$mmid^{11}$	0.1848	1.43	0.0488	0.48
$mpost^1$	–0.1919	–1.48	–0.3487	–2.75
$mpost^2$	–0.2731	–1.88	–0.5335	–4.48
$mpost^3$	0.2197	1.65	0.0881	0.87
$mpost^4$	0.1294	0.9	0.1947	1.97
$mpost^5$	–0.0414	–0.29	0.1036	1.02
$mpost^6$	–0.1658	–1.18	–0.1213	–1.11
$mpost^7$	–0.4594	–3.03	–0.2736	–3.05
$mpost^8$	–0.5607	–3.95	–0.0223	–0.24
$mpost^9$	–0.3023	–2.08	–0.2038	–2.2
$mpost^{10}$	–0.2688	–2.15	–0.2572	–2.72
$mpost^{11}$	–0.0851	–0.55	–0.1683	–1.59
Ln(dapp3m)	–0.3315	–3.75	0.0311	0.36
Ln(corn3m)	0.1278	0.91	–0.058	–0.78
Ln(flow)	0.4577	50.37	0.4906	87.83
Ln(temp)	–0.5691	–8.23	0.7473	14.61
Ln(precp)	0.2188	9.42	–0.0390	–3.1
*Ln(corn3m)** S^W	0.2664	2.46	0.3635	5.07
*Ln(corn3m)** S^{SP}	0.2648	2.22	0.0523	1
*Ln(corn3m)** S^F	–0.2163	–1.39	0.1756	2.94
dd^{1976}	–0.1602	–1.55	–0.3031	–3.2
dd^{1977}	0.3954	6.41	0.0656	1.15
dd^{1978}	–0.2974	–5.26	0.1956	4.72
dd^{1979}	–0.0004	–0.01	–0.1175	–2.08
dd^{1980}	–0.1645	–1.62	–0.0481	–0.49
dd^{1981}	–0.4051	–6.58	–0.3896	–8.5
dd^{1982}	–0.04	–0.59	0.3856	8.41
dd^{1983}	0.0188	0.3	–0.2291	–5.31
dd^{1984}	–0.3121	–4.73	0.1126	3.05
dd^{1985}	–0.6831	–8.11	0.3221	8.43
dd^{1986}	0.1402	1.38	–0.1862	–4.92
dd^{1987}	0.8571	7.89	–0.2337	–4.46
dd^{1988}	–0.9405	–9.26	0.0431	0.72

dd^{1989}	–0.0741	–0.84	0.0076	0.15
dd^{1990}	0.4505	6.04	–0.0232	–0.54
dd^{1991}	–0.4987	–6.76	0.0253	0.56
dd^{1992}	0.0539	0.64	–0.1741	–3.68
dd^{1993}	–0.2282	–2.61	0.2362	5.57
dd^{1994}	–0.6785	–5.78	–0.0733	–1.73
dd^{1995}	1.3263	11.14	0.1427	3.88
dd^{1996}	–0.7993	–4.21	0.1679	2.41
dd^{1997}	0.6043	3.78	–0.1546	–3.22
dd^{1998}	0.2099	2.28	–0.0956	–2.43
dd^{1999}	–0.2414	–2.71	0.0902	2.59
dd^{2000}	1.1835	14.91	–0.2109	–4.62
dd^{2001}	–1.4065	–6.35	0.4060	5.88
dd^{2002}	0.9369	4.24	–0.3475	–4.71
dd^{2003}	0.3147	3.67	0.0197	0.41
dd^{2004}	–0.1767	–2.03	–0.1538	–2.68
dd^{2005}	–0.0119	–0.12	–0.0918	–1.38
dd^{2006}	0.4082	4.38	0.3408	6.74
dd^{2007}	–0.5729	–6.31	–0.1742	–2.89
dd^{2008}	0.4280	4.26	0.1547	1.85
dd^{2009}	–0.5159	–5.15	0.2334	2.31
dd^{2010}	0.6066	8.46	–0.3314	–6.44
dd^{2011}	0.0001	0	–0.2638	–4.48

TABLE B5.—REGRESSION RESULTS FOR SANDUSKY FOR SUSPENDED SEDIMENT AND PHOSPHORUS PER UNIT SEDIMENT.

	Ln(ATTPSS)		**Ln(SS)**	
Variables	**Estimate**	**t-value**	**Estimate**	**t-value**
intercept	-0.4701	-1.1	-7.9514	-11.46
m^1	0.0292	0.26	-0.0777	-0.44
m^2	-0.0159	-0.11	0.2663	1.45
m^3	-0.1552	-1.5	0.0647	0.39
m^4	0.0339	0.35	-0.059	-0.41
m^5	0.1018	1.03	0.026	0.17
m^6	-0.1578	-1.46	0.7881	5.1
m^7	0.1576	1.69	0.6825	4.9
m^8	0.2575	2.78	0.4866	3.43
m^9	0.3755	3.86	0.377	2.76
m^{10}	-0.0917	-1.09	0.5191	5.21
m^{11}	0.0424	0.43	0.0527	0.49
$mmid^1$	0.1414	1.4	-0.0895	-0.65
$mmid^2$	0.0757	0.61	-0.2631	-1.83
$mmid^3$	-0.0266	-0.32	0.1243	1.04
$mmid^4$	-0.0735	-0.84	0.3667	3.27
$mmid^5$	-0.0935	-1.09	0.1056	0.85
$mmid^6$	0.124	1.33	-0.0343	-0.29
$mmid^7$	-0.0472	-0.59	-0.0984	-0.89
$mmid^8$	-0.0488	-0.61	0.1921	1.66
$mmid^9$	0.0193	0.22	-0.0016	-0.01
$mmid^{10}$	0.1177	1.32	-0.1404	-1.32
$mmid^{11}$	0.0008	0.01	0.0079	0.07
$mpost^1$	0.251	2.54	-0.5837	-3.73
$mpost^2$	0.1865	1.51	-0.6943	-4.48
$mpost^3$	0.1581	1.97	-0.0701	-0.56
$mpost^4$	0.1663	1.99	0.0157	0.14
$mpost^5$	0.1418	1.71	-0.0593	-0.46
$mpost^6$	0.3032	3.33	-0.4087	-3.33
$mpost^7$	0.2333	3	-0.5173	-4.55
$mpost^8$	0.2359	3.11	-0.2664	-2.26
$mpost^9$	-0.0237	-0.28	-0.1864	-1.63
$mpost^{10}$	0.282	3.25	-0.5175	-4.81
$mpost^{11}$	0.1925	1.84	-0.3609	-3.01
Ln(dapp3m)	-0.1663	-2.66	0.201	1.87
Ln(corn3m)	-0.2346	-3.84	0.1539	1.68
Ln(flow)	-0.2448	-58.35	0.7349	102.53
Ln(temp)	-0.8005	-17.55	1.5434	23.77
Ln(precp)	-0.0275	-2.7	-0.0124	-0.74
*Ln(corn3m)** S^W	0.2651	4.84	0.1275	1.35
*Ln(corn3m)** S^{SP}	0.144	3.8	-0.0909	-1.38
*Ln(corn3m)**S^F	0.5393	11.18	-0.3249	-4.35
dd^{1976}	-0.0262	-0.29	-0.2658	-2.55
dd^{1977}	-0.1227	-2.28	0.1863	3.24
dd^{1978}	0.1615	4.18	0.0363	0.73
dd^{1979}	-0.0717	-1.44	-0.0521	-0.8
dd^{1980}	0.0195	0.23	-0.0088	-0.07
dd^{1981}	0.0345	0.82	-0.4352	-6.93
dd^{1982}	-0.071	-1.89	0.4496	7.65

dd^{1983}	0.1595	4.78	-0.3885	-7.6
dd^{1984}	0.1691	4.87	-0.0564	-1.16
dd^{1985}	-0.0552	-1.3	0.3742	7.35
dd^{1986}	-0.2116	-5.28	0.0274	0.53
dd^{1987}	0.0008	0.02	-0.2317	-3.09
dd^{1988}	0.4206	7.8	-0.3449	-3.99
dd^{1989}	-0.4017	-8.95	0.3788	5.53
dd^{1990}	-0.0457	-1.64	0.0179	0.33
dd^{1991}	-0.0745	-2.26	0.0798	1.57
dd^{1992}	0.0992	2.75	-0.2529	-4.61
dd^{1993}	-0.0135	-0.48	0.2483	4.75
dd^{1994}	0.134	4.35	-0.2071	-3.88
dd^{1995}	0.0355	1.13	0.1124	2.15
dd^{1996}	-0.2267	-4	0.3545	3.99
dd^{1997}	-0.1286	-3.93	-0.0252	-0.4
dd^{1998}	0.1713	6.01	-0.2687	-5.11
dd^{1999}	-0.208	-6.47	0.2967	6.13
dd^{2000}	0.0861	2.2	-0.2989	-4.82
dd^{2001}	0.1425	1.93	0.2782	2.6
dd^{2002}	-0.1448	-1.92	-0.2292	-2.14
dd^{2003}	-0.0022	-0.06	0.0375	0.67
dd^{2004}	-0.0771	-2.49	-0.0943	-1.58
dd^{2005}	0.0248	0.64	-0.1197	-1.68
dd^{2006}	0.0833	2.49	0.2623	4.49
dd^{2007}	0.1795	4.54	-0.3379	-4.54
dd^{2008}	-0.0779	-1.4	0.2304	2.12
dd^{2009}	-0.2597	-3.98	0.4961	3.75
dd^{2010}	0.3057	9.1	-0.6411	-9.32
dd^{2011}	0.0736	1.76	-0.3258	-4.05

TABLE B6.—POLICY EFFECTS OF A 25% TAX ON PHOSPHORUS INPUTS PURCHASED FOR AGRICULTURAL USE ON SOLUBLE PHOSPHORUS EMISSIONS IN THE TWO WATERSHEDS EXAMINED

		Soluble Phosphorus (Metric tons/year)
Maumee		
	Base Annual	641
	25% phosphorus Tax	582
	Change	*(59)*
Sandusky		
	Base Annual	179
	25% phosphorus Tax	166
	Change	*(13)*
Total (Maumee + Sandusky)		
	Base Annual	820
	25% phosphorus Tax	748
	Change	*(72)*

FIGURE B1.— INCREMENTAL ANNUAL FIXED EFFECTS, MAUMEE RIVER BASIN

<table>
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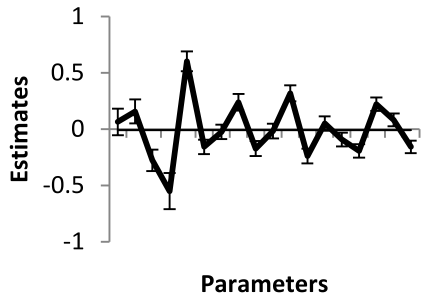
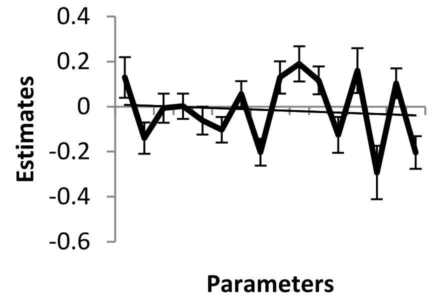
<tr><td>Attached Phosphorus</td><td>
</td><td>
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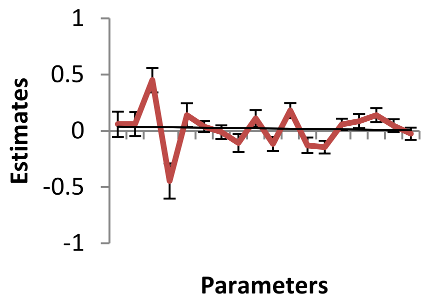
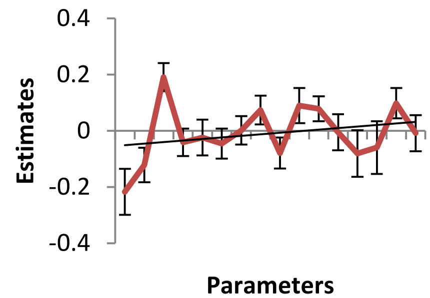
<tr><td>Attached Phosphorus Per unit Sediment</td><td>
</td><td>
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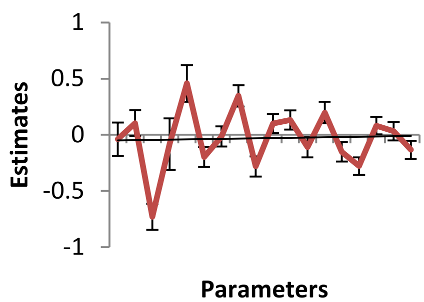
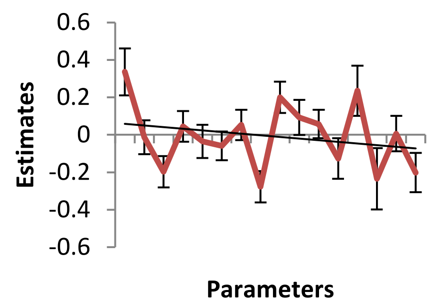
<tr><td>Suspended Sediment</td><td>
</td><td>
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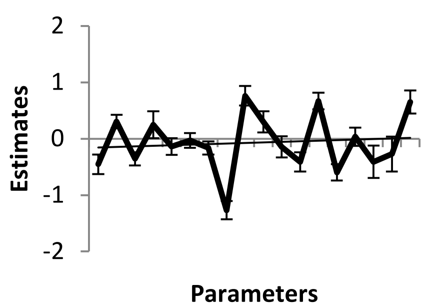
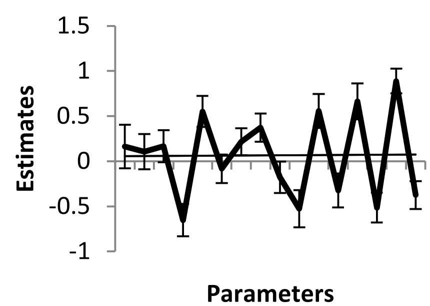
<tr><td>Soluble Phoshorus</td><td>
</td><td>
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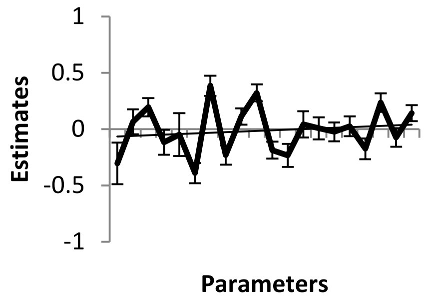
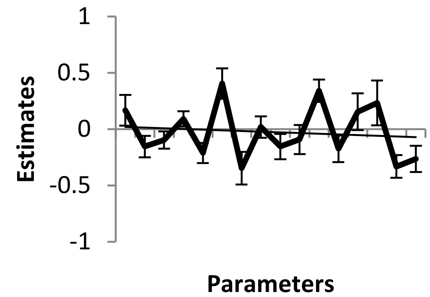
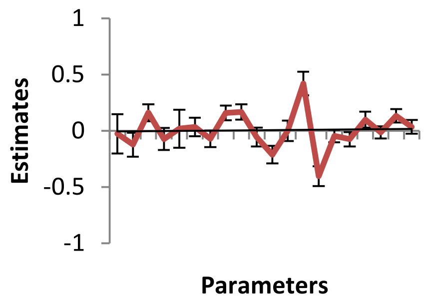
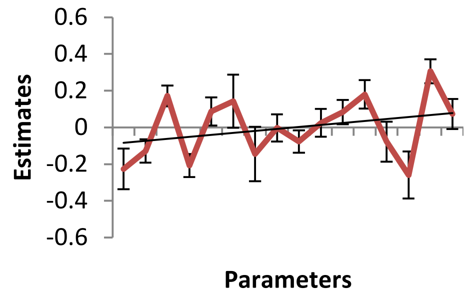
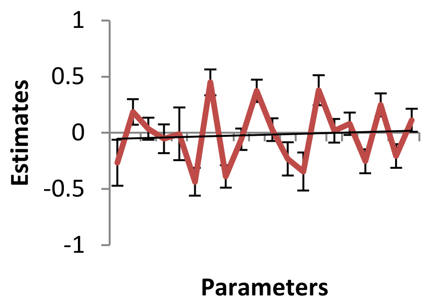
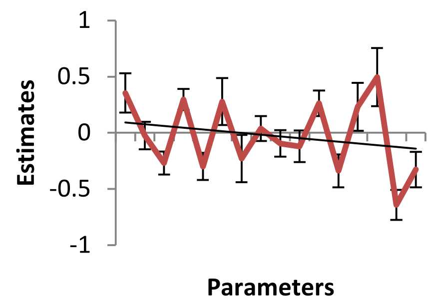
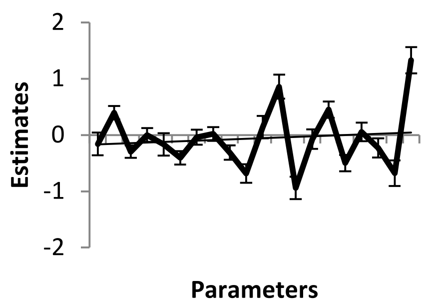
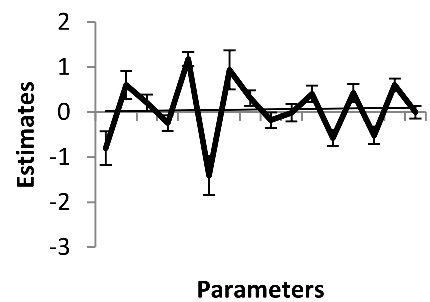
</table>

Error bars indicate 95% confidence interval.

FIGURE *B2*.— INCREMENTAL ANNUAL FIXED EFFECTS, SANDUSKY RIVER BASIN

	1976-1995	1996-2011
Attached Phosphorus		
Attached Phosphorus Per unit Sediment		
Suspended Sediment		
Soluble Phoshorus		

Error bars indicate 95% confidence interval.