THE IMPLICATIONS OF ENVIRONMENTAL POLICY ON NUTRIENT OUTPUTS IN AGRICULTURAL WATERSHEDS

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Abstract—We examine whether federally-sponsored voluntary environmental programs to reduce phosphorus pollution from agriculture have had any impact on water quality outcomes. Using daily observations on nutrient emissions taken over 37 years in two Great Lakes tributaries, we estimate an econometric model of phosphorus emissions. Phosphorus emissions are the most important contributor to harmful algal blooms, which have recently caused significant health concerns. Our results indicate that these voluntary programs have had very little effect on phosphorus outputs. In contrast, we show that an input tax could be very effective at reducing phosphorus pollution, and consequently the likelihood of future harmful algal blooms.

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I. **Introduction**

GOVERNMENT-SPONSORED voluntary pollution reduction programs are an increasingly common feature of environmental protection in the United States. Businesses that self-select into these programs voluntarily pledge to abate emissions that are not addressed by environmental laws or over-comply with emission standards (see e.g., Innes & Sam, 2008; Carrion-Flores, Innes, & Sam, 2013). For example, over 1200 manufacturing firms signed up for the 33/50 program, the US Environmental Protection Agency (EPA)'s first formal effort to achieve voluntary pollution reductions by regulated businesses. 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 (CAFOs) 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.

A number of papers have empirically explored 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; Vidovic & Khanna, 2007; Innes & Sam, 2008; 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 (Dasgupta, Hettige, & Wheeler, 2000; Khanna & Anton, 2002a, 2000b) with mixed evidence of the effectiveness of the non-mandatory approach (see e.g., Koehler, 2007 for a review).

In this paper, we primarily concern ourselves with federal efforts designed to achieve pollution reductions pertaining to water quality improvement. Since the 1980s, more than $1 billion per year has been spent improving water quality through voluntary agricultural conservation programs nationwide. These programs have focused on removing land from production, trapping nutrients in farm fields via practices like conservation tillage, installing manure management structures, shifting the timing of nutrient applications, and other practices. The Conservation Reserve Program (CRP), which began 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. Many of these fields remain out of agricultural production today. In addition to CRP, conservation tillage for 40 years 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 these 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,

[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.

new drainage structures, and on manure and nutrient management practices, particularly from large livestock operations. By law, 60% of the funds in EQIP must be used to assist farmers to reduce the impacts of their manure. In 2000, new regulations on CAFOs were implemented nationwide by the EPA 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 these increasing efforts and given that many of the efforts involve capital investments or changes in land use, 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.

Numerous economic simulation models have been constructed to assess the effects of installing best management practices in agricultural watersheds (e.g., Piper, Huang, & Ribaudo, 1989; Wu & 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 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).

For the analysis in this paper, we focus on the concentration of phosphorus in the two watersheds. Phosphorus 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 analysis develops an empirical model of nutrient pollution in agricultural watersheds. We model the concentration of phosphorus in agricultural streams as a function of economic, ecological, and policy variables. The economic variables include nutrient input prices and crop output prices. The ecological variables focus on weather, water flow, and seasonality. For the policy variables, we use fixed effects to model policy changes over the time period of observations (1975 to 2011). The model is based on daily observations. To our knowledge, this is the first ever attempt to empirically determine the impact of economic, ecological, and policy variables on nutrient pollution in agricultural watersheds.

Briefly, 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. 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.

II. 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 can be given as:

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

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. In relatively 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):

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

All else equal, higher nutrient prices (P^N) will reduce the quantity of nutrient demanded (i.e, an increase in nutrient prices from P^1 to P^2 in figure 1 will cause nutrient quantities to decrease from Q^1 to Q^2). Other factors also will increase or decrease the quantity of nutrient demanded by farms, including crop types and crop yields. Higher corn prices (P^O), for instance, will increase the desire to supply more corn in land for farmers, which in turn will increase the quantity of phosphorus used because corn is a more intensive demander of phosphorus (e.g., a shift from Q^1 to Q^3 in figure 1). While we cannot incorporate Q^F directly into our empirical model, we can incorporate prices for corn and for phosphorus in the model.

Higher crop yields will use up a greater proportion of the nutrient that is applied for crops. All else equal, higher crop yields thus should reduce nutrient outputs in agricultural watersheds (Y^F). Over time, crop yields have continued to rise at 1-2% per year, increasing the quantity of nutrients exported from watersheds as food. Moreover, data indicate that aggregate measures of phosphorus inputs in Midwestern farms have fallen over the past 30 years (Bruuselma et al.2011). In Ohio, in particular, the intensity of phosphorus use on farms has declined since the 1960's (figure 2). These data illustrate not only that the main crops on Ohio have become significantly more efficient at using nutrient inputs, but also that farmers have become more efficient at applying the nutrients to avoid losses during the application process. Given these trends, phosphorus outputs from agricultural watersheds should be declining. In theory, the application of conservation practices, C^F, should reduce phosphorus emissions from watersheds. Conservation practices include conservation tillage, conservation set-asides (particularly on highly erodible land), filter strips/riparian zones, cover crops, and manure and nutrient management planning. The primary purpose of these practices is to intercept nutrients that are not used by plants during the growing season and hold them until the following growing season. Data from Pavelis, Helms, and Stalcup (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 keep land in productive agricultural uses, but apply conservation practices to this "working" land. With rising funding, these programs should have become more and more effective over time, leading to increases in C^F in our model, and reductions in nutrient outputs from watersheds.

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 3). 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 test 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. As shown in table 1, 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 since the 1970s by the

National Center for Water Quality Research at Heidelberg University (Heidelberg University, 2012).

We estimate the following model:

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

The variables used in the regression analysis have been described above and are summarized in table 2. The left hand side variable (Q^W) is the flow weighted average daily concentration of either attached phosphorus or soluble reactive phosphorus, 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.

Two models are estimated for each of the watersheds. One model considers the concentration of attached phosphorus on the left hand side. Attached phosphorus is the phosphorus that is attached to soil particles, and that remains attached as it flows through the river system. A second model uses the concentration of soluble reactive phosphorus on the left hand side, which is the phosphorus that is in the water solution in soluble form. These two components of total phosphorus are modeled separately because the main drivers in the model, agricultural activity and ecosystem variables, are expected to affect them differently.

A. Environmental Variables

The environmental variables (Q^E) modeled here include the flow of water *(flow)*, temperature *(temp)*, and precipitation *(precp)*. 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.

B. Phosphorus Input by Farmers

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:

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

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.

C. Policy Variables

To model the effects of trends in crop yields and policies, we utilize fixed effects. When considered over the alternative models for attached and soluble phosphorus, these fixed effects help identify the influence of time and policy changes in the watersheds. The fixed effects are:

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

First, we include annual dummy variables to capture time trends. For this analysis we create 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. While the parameter of a regular year dummy--which is one for year *i* and zero otherwise--captures the cumulative effect for year *i* from the base year 1975 up to year *i*, the parameter $\Upsilon^{4,i}$ on a dummy variable dd_t^i captures the incremental annual effect of policies on Q_t^W level for year *i* alone, and 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 (see figure 3), we expect to the see a significant downward trend in the 1970s for the soluble phosphorus model.

For a number of reasons, we expect to see an intensifying downward trend in both attached and soluble phosphorus as a result of policy actions and trends in farming. First, Bruuselma et al. (2011) showed that by the 1970s, farmers had built up significant phosphorus in Ohio soils, and they started to draw that down with reduced applications in the 1970s and 1980s (see also figure 2). Since this phosphorus is largely attached to soils, one would expect to see a reduction in attached phosphorus over time. Second, two other policy shifts occurred in the 1980s which should have reinforced a downward trend in nutrients. It was then that the two most important soil conservation programs gained steam: the widespread adoption of conservation tillage and the CRP. 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). While enrollments in CRP declined slightly in the early 2000s, 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).

Third, the 1996 Farm Bill added a new suite of conservation programs that tried new methods to reduce nutrient pollution in farming. It also ushered in a period of rising subsidies for farmers to implement the practices. 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, these changes in 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, water quality improvement efforts in agriculture added regulatory programs 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.

Given these trends, phosphorus concentrations in agricultural watersheds should be declining. For soluble phosphorus concentrations, the dummy variables are expected to be negative in the 1970s due to regulated reductions in point sources, after 1996 due to the increased emphasis on conservation, and again after 2002 with an increase in subsidies and new EPA regulatory programs on large livestock operations. For attached phosphorus concentrations, the dummy variables should decline continuously over our time horizon as attached phosphorus is drawn down by rising crop yields, and as conservation tillage and the CRP were widely adopted.

In addition to overall time trends, farm management and the application of conservation practices will alter the timing of nutrient outflows from watersheds. For instance, subsidized manure lagoons are intended to provide enough storage so that farmers do not need to apply manure in winter when they cannot incorporate it into the soil with tillage. 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 nutrients in fields during the winter months when crops are not growing. If conservation programs are effective, the seasonality of nutrient outflows should change 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 farm management on phosphorus concentrations. In order to test for changes that conservation and policies have had 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.

One expectation is 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. This expectation is based on the role that conservation tillage is supposed to play in holding soil on farm fields during the winter months when crops are not growing. 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. Because 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 should also see a reduction in soluble phosphorus in fall and winter from the mid to the post time period.

D. Empirical Model

The specific model that we estimate is (with the log of nutrient concentrations on the left hand side):

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

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 1 in appendix 2). The trend type is also ruled out because none of the data series indicates consistent trend up or down (figure 1 in appendix 2) 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.

III. Results

The results of ADF tests for stationarity are shown in table 3. 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 nonstationarity 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.

A. Effects of Farmers

The full set of regression results for the model specified in equation (6) above are reported in appendix 1. For reporting, we extract information from the full set of results and present it in the text separately. The select results regarding the effects of price changes, water flow, and the climate variables are shown in table 4. The price of phosphorus has a negative and significant effect in the Maumee watershed in both regressions of soluble and attached phosphorus; however, the size of the effect varies by regression. It is largest for the soluble phosphorus regression and smallest for the attached phosphorus regression. Because phosphorus accumulates in soil by attaching to soil particles, there is a less direct link between the price of phosphorus and the movement of attached phosphorus than is the case of soluble phosphorus. The results are similar for the Sandusky watershed, however for that watershed, the phosphorus price is only significant in the case of the soluble phosphorus regression. In the Sandusky watershed, changes in phosphorus prices have little effect on attached phosphorus concentration.

One potential issue with these results is that the three month lag on phosphorus prices may not be optimal from a farmer decision perspective. That is, we are assuming 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]

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, while only the winter corn price is positive and significant in the Sandusky. It is surprising that summer corn prices have a positive effect on attached phosphorus because it is not clear that price changes at that time of year will lead to significant management changes, but the results on corn prices generally make sense: An increase in corn prices will lead to more land in corn, an increase in plowing, more soil movement and more attached phosphorus emission.

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 will increase with additional corn planting because it displaces other crops (e.g., soybeans) in the region that are less nutrient intensive. We cannot state with certainty in advance which of these effects will dominate. In the larger Maumee

[2] Results available upon request.

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]

B. Effects of Environmental Variables

Table 4 shows that higher temperatures increase attached phosphorus and reduce soluble phosphorus in both watersheds. On the other hand, greater precipitation increases soluble phosphorus runoff and reduces attached phosphorus 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.[4] We find that higher flow increases nutrient concentrations. The effect of flow is larger in the Sandusky watershed, which is expected because it is a smaller watershed.

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[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 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.

C. Effects of Policies

To assess whether environmental policies have had an effect on phosphorus concentrations, we examine the annual incremental effects over two periods, 1976-1995, and 1996-2011 in figures 4 and 5. The period 1976-1995 captures the influence of earlier regulations on point sources. The period 1996-2011 captures the period of intensifying efforts to reduce nonpoint source pollution. Parameters that are less than 0 imply that pollution reductions have occurred relative to the base year period (1975), and vice-versa. Given all the efforts since the 1970s, we expect to see the parameters on these fixed effects trending downward, and in particular we expect to see them trending downward in the post 1996 period due to farm conservation efforts.

For soluble phosphorus, in fact, we see the opposite trend. Pollution reduction was greatest in the period from 1976 to the early 1980s (figure 4). We can sum the incremental fixed effects in figure 4 to determine the cumulative effect of policies. Over the period from 1976 to 1995, our results indicate that there was a large and statistically significant reduction in soluble phosphorus concentrations in both watersheds. This makes sense given the strong reduction in point source loadings from the mid-1970s to the present. 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. Point source loadings have remained fairly constant since the mid-1990s, but the fixed effects in our model suggest a statistically significant and large increase in soluble phosphorus concentrations over the period 1996-2011.

In contrast, attached phosphorus concentrations have decreased over time (figure 5). Our results are consistent with those the results in Richards, Baker, & Crumrine (2009), although this study controls for a range of other factors that could be affecting attached phosphorus as well. The downward trend is expected given the large increase in conservation tillage that occurred over period of analysis. We also find evidence that the downward trend has intensified. From 1976-1995, there was a statistically significant reduction in attached phosphorus in each watershed. The reduction from 1996-2011 was even greater and statistically significant in each watershed.

The monthly fixed effects can also be used to account for the influence of policies, conservation and management, which are expected to have different impacts on soluble and attached phosphorus concentrations over the course of the year. For soluble phosphorus the monthly fixed effects suggest that concentrations are lower in winter and spring, but higher in summer and fall (figure 6). This result contrasts with un-corrected[5] estimates of soluble phosphorus concentrations for these watersheds which show that the peak soluble phosphorus concentrations occur in December-February, coinciding with periods of highest river flow. Our monthly fixed effects, however, hold flow and other variables constant (including prices), and thus account for changes in farm management decisions that influence soluble phosphorus concentration. One reason why the monthly fixed effect parameters peak in July-August is that point sources, which emit a relatively constant amount of phosphorus throughout the year, have their largest effect on concentrations during summer when overall river flows are low. Farming also bears some responsibility for this summer peak. Farmers who manage wheat (10-20% of

[5] The un-corrected estimates are the average daily concentrations calculated directly from the data.

crop acres in the two watersheds) often apply manure to fields after the wheat harvest (indeed this technique is often used by livestock farmers in order to use manure productively), and this manure contributes to soluble phosphorus emissions.

Farms also contribute to increased summertime phosphorus concentrations by emitting soluble phosphorus that has not been used yet by crops. While most phosphorus applications to crops occur right before planting, usually in late March or April, some of the phosphorus used by crops will move into river systems during summertime rainfall events, and some will become attached to soils (Sharpley, 1985; Murdock & Call, 2006). Aside from annual contributions, there is an immense stock of phosphorus that has built up in soils over the years (Bruuselma et al., 2011). Microbial action during the growing season converts this phosphorus into soluble forms that can move into river systems (Sharpley, 1985, 1995; Stewart & Tiessen, 1987). It thus makes sense that farming practices contribute to the relative increase in phosphorus concentrations during the summer. At the same time during the year that phosphorus in soils is declining, namely during the summer months (Sharpley, 1985; Murdock & Call, 2006), our parameter estimates indicate that phosphorus in water is increasing. .

The interaction terms for the periods 1980-1995 and 1996-2011 test whether conservation programs and changes in farming practices have shifted the seasonality of phosphorus concentrations. Most conservation programs in farming have focused on reducing emissions in winter and early spring because that is when most loading occurs. For soluble phosphorus, this involves shifting the timing of the application of phosphorus from winter to spring; planting cover crops in late summer or fall to “soak” up excess phosphorus and hold it in soils; installing grass waterways to intercept phosphorus as it leaves farms; and incorporating manure into soils so that it cannot run off directly into streams. For soluble phosphorus, there is a strong, and statistically significant reduction in soluble phosphorus concentrations in all months between the pre-1980 period and the 1996-2011 period in the Maumee watershed (figure 6, panel A). Most of the change in concentrations in the winter occurred by the 1980-1995 period, although from this middle period to the 1996-2011 time period, there was an additional, statistically significant reduction in soluble concentrations in summer (figure 6, panel B). We observe a similar result in summer and winter months for the Sandusky watershed, although the effect is not as large and it appears to attenuate over time (figure 6, panels C and D).

Two factors drive these seasonal reductions in soluble phosphorus concentrations over time, reductions in point source loads and rising crop yields. The Maumee watershed has more point sources (Dolan & Chapra, 2012), and so the effects are largest there. The reduction in concentrations over time are largest in summer months, which is consistent with a reduction in point source loads. Point sources will have larger implications for nutrient concentrations in the low flow periods of summer because their emissions are constant whereas overall water flows are lower in summer and fall. Farming practices may also contribute to the reduction in soluble phosphorus concentrations in summer because crop yields have increased over time (1-2% per year on average). Another change in farming practices is the shift in phosphorus applications from fall towards spring. As farmers have done this, soluble phosphorus concentrations in late fall and winter (November – February) have fallen while soluble phosphorus concentrations in spring (March – May) have not changed in a statistically significant way.

We make the same comparisons of the monthly fixed effects for the attached phosphorus regressions. The monthly fixed effects for attached phosphorus rise from their lows in January to a peak in late summer (August and September) and then decline through the fall (figure 7). As with soluble phosphorus, this pattern differs from the un-corrected attached phosphorus concentration in these two rivers which shows that attached phosphorus concentrations in these watersheds peak from March to May and then decline through the summer. In our fixed effects (figure 7), there is a late summer/early fall peak in the concentration of phosphorus attached to soils. This late summer increase in the concentration of attached phosphorus in rivers results from an increase in the concentration of phosphorus attached to soils rather than an increase in the flow of soil sediments. The increase in phosphorus attached to soils occurs because the size of the soil particles is smaller during low flow periods, and smaller soil particles hold proportionally more phosphorus than larger soil particles (LimnoTech, 2013).

The growth of conservation tillage and the CRP should cause attached phosphorus concentrations to decrease in late fall and winter because conservation tillage holds soil particles on the landscape, and the CRP traps soil particles in grass waterways, riparian zones, or other set-asides. The results in figure 7 show that there has been a statistically significant reduction in attached phosphorus concentration in the winter months in both watersheds. The results, however, also show an increase in attached phosphorus emissions in spring in both river basins. As farmers have shifted their plowing operations from fall to spring, there has been a release of phosphorus in attached form during the spring months.

IV. 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 at the same time causing an increase in soluble phosphorus concentrations. Since the 1980s, farmers have dramatically expanded the amount of conservation tillage they do, and they have enrolled large areas of land in the government sponsored CRP. In addition, society has increased subsidy payments to implement a whole host of practices that are supposed to reduce nutrient pollution. Currently, these programs cost society $5 billion per year, or $14 per acre of cropland (Pavelis, Helms, & Stalcup, 2011). Since passage of the 1996 Farm Bill, payments for conservation have increased on a per acre basis in real terms by around 3% per year. The EPA also has regulated large livestock operations that are suspected of contributing a large share of pollution to our waterways, and the USDA has diverted money to help farmers meet these regulations. Despite all this work, there has been surprisingly little improvement in water quality.

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. 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.

The goal of this analysis is to assess whether the policies have had an effect on phosphorus loadings. Loadings are the important environmental variable because loadings affect the amount of phosphorus received by Lake Erie. Loadings are the daily concentration multiplied by the daily flow. 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 5. Both watersheds experienced an 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 large increases in soluble phosphorus have far exceeded any modest reductions that might have been made 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 tonnes. As a consequence, Lake Erie experienced a total gain in total phosphorus emissions of 146 metric tons per year, or 7.5%, between the earlier and later periods we analyze. There are a number of reasons for this increase. As we have trapped more and more phosphorus in the ecosystem with conservation programs, it is increasing emitted in soluble form, and there is evidence that conservation tillage itself leads to an increase in soluble phosphorus emissions (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. For instance, 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% (table 4). For policy purposes, we examine the effect of a 25% tax on phosphorus inputs (table 6). 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.

It is useful to note that a phosphorus input tax is likely much easier to administer than the current conservation programs administered by the USDA. The current USDA programs require a large amount of research by universities and government research organizations, many administrators, technicians, book keepers, and others to ensure that practices that are used are actually implemented. This system has built up over the years and is already in place, but it would not be necessary to implement a phosphorus input tax.

V. 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. In particular, the effect of prices on soluble phosphorus is larger than the effect on attached phosphorus. This 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.

To test for the influence of various technology changes and policies that have been enacted over the past 37 years, we introduce a series of fixed effects. Incremental annual fixed effects are used to test whether there has been a long term reduction in nutrients in the watershed. We specify these annual fixed effects to test whether the effects of technologies and policies have been growing and becoming more significant over time, as expected. For instance, there has been a large increase in conservation tillage in these watersheds over the time period, there has been a large expansion of land that has been set-aside for environmental reasons, and the funds used to pay farmers to reduce pollution have increased significantly. We hypothesize that these changes should cause pollution reductions to increase in these watersheds. In addition, we develop separate models for soluble phosphorus and attached phosphorus. Given the large increase in conservation tillage and the expansion of land that is set-aside, we expect to see, and indeed find, a reduction in attached phosphorus. Unfortunately, however, we find that soluble phosphorus concentrations increase, and these increases offset any reductions in attached phosphorus. As a result, the widespread adoption of conservation tillage, the implementation of conservation practices, and direct government regulation, have had very little impact in the watersheds we examine. In fact, because soluble phosphorus causes more damage in the environment than attached phosphorus, damages have increased.

We also include monthly fixed effects to test for the seasonality of various policies that have been implemented. By interacting these monthly fixed effects with specific time periods, we test for their stability over time. For example, the adoption of conservation tillage should reduce attached phosphorus runoff in the fall and winter because it maintains cover on farm fields that holds soil in place. Alternatively, farmers have been paid to apply nutrients in the spring rather than the fall, and they have been paid not to apply manure during the winter, in order to try to reduce emissions during the critical winter period. Regulations also impose limits on the application of manure during winter months. These efforts should reduce nutrient emissions in winter, and they should reduce overall nutrient emission given that this is the period when most nutrient emissions occur.

The results on the monthly fixed effects illustrate important seasonal influences. Farm management leads to larger concentrations of soluble phosphorus in summer and fall. This is perhaps not surprising given that most farming activity occurs during spring and summer. The monthly effects have changed over time, although this has little to do with farm practices. For instance, summer and fall concentrations of soluble phosphorus declined from the 1970s and 1980s to the present due to reductions in phosphorus emissions by waste water treatment plants and other points sources. These sources have been heavily regulated and the impacts of these regulations are readily apparent in the data. We do find some modest evidence that attached phosphorus declined in the winter, a result that is consistent with the theory of conservation tillage. Our results, however, also show that attached phosphorus emissions have increased in spring, which likely results from the shift from fall to spring plowing.

Taken together, the annual and monthly fixed effects do provide evidence that attached phosphorus loads declined from the 1980s to the present due to the increased adoption of conservation tillage over the time period. We estimate that policies and economic forces caused attached phosphorus emissions to fall by around 11% relative to what they otherwise would have been. In contrast, however, soluble phosphorus emissions increased by 75% relative to what they otherwise would have been. Despite efforts to reduce pollution, soluble and attached phosphorus increased in the two watersheds by about 146 metric tons per year, or 7%.

In general, these results suggest that agricultural pollution abatement programs have had very little beneficial effect on water quality. Although attached phosphorus is down modestly, soluble phosphorus has increased substantially, such that the total change in the watershed is towards increased emissions. These results indicate that traditional conservation programs are unlikely to be successful in reducing nutrient emissions from watersheds. 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. In contrast, we find that nutrient input prices are negatively related to nutrient concentrations. A modest nutrient input tax of 25% would reduce phosphorus loads by around 8%, and in particular soluble phosphorus.

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TABLE 1.—WATERSHED CHARACTERISTICS, YEARS FOR SAMPLES, AND FLOW INFORMATION

	Total Area (hectares)	Agricultural Area (hectares)	Years	Average Annual Flow ($m^3 s^{-1}$)	Average Annual Total Phosphorus ($mg L^{-1}$)
Maumee	1,640,162	1,474,506	1975–2011	156	0.40
Sandusky	324,664	273,042	1975–2011	34	0.41

For the Maumee river watershed data for 1979 and 1980 are missing at random.

TABLE 2.—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(flow)	
Ln(cfstp)	Log of flow rate for samples on with ATTP 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(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 $dmid = 1\ if\ 1980 \le year \le 1995,$ $= 0\ otherwise$
$mpost^1 - mpost^{11}$	$mpost^i = m^i * dpost$ Where $dpost = 1\ if\ year > 1995,$ $= 0\ otherwise$
$dd^{1976} - dd^{2011}$	$dd^i = 1\ \ if\ year \ge i,$ $= 0\ \ otherwise$

TABLE 3.—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 4.—EFFECTS OF PRICE AND WEATHER VARIABLES

	Maumee		Sandusky	
	Soluble Phosphorus	Attached Phosphorus	Soluble Phosphorus	Attached Phosphorus
Phosphorus Price	–0.425***	–0.141***	–0.331***	0.031
	(0.084)	(0.053)	(0.089)	(0.086)
Corn price in Winter	–0.188	0.510***	0.394***	0.306***
	(0.140)	(0.073)	(0.137)	(0.094)
Corn price in Spring	–0.409**	0.211***	0.393***	–0.006
	(0.160)	(0.058)	(0.152)	(0.086)
Corn price in Summer	–0.035	0.106**	0.128	–0.058
	(0.150)	(0.051)	(0.140)	(0.074)
Corn price in Fall	–0.257**	0.394***	–0.089	0.118
	(0.114)	(0.051)	(0.131)	(0.077)
Temperature	–1.559***	0.535***	–0.569***	0.747***
	(0.067)	(0.037)	(0.069)	(0.051)
Precipitation	0.364***	–0.092***	0.219***	–0.039***
	(0.026)	(0.010)	(0.023)	(0.013)
Flow	0.320***	0.344***	0.458***	0.491***
	(0.012)	(0.005)	(0.009)	(0.006)

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

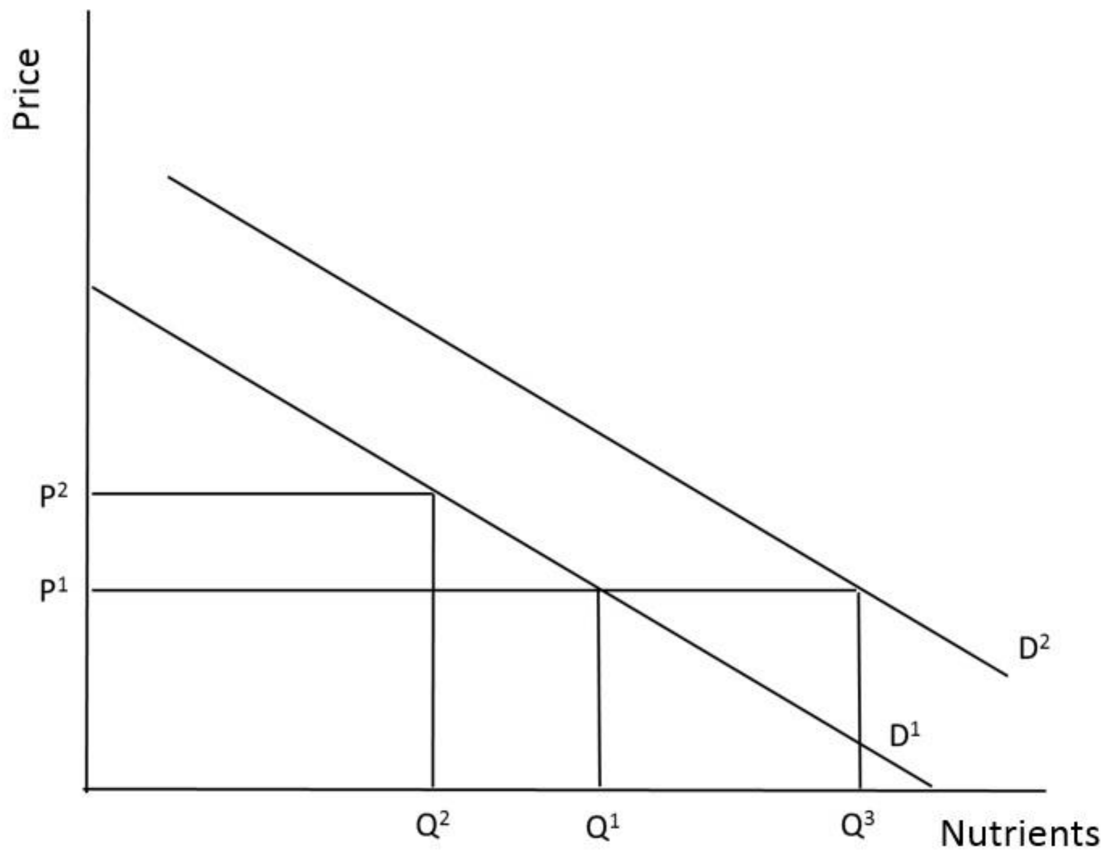
	Flow	Loadings					
		Soluble Phosphorus		Attached Phosphorus		Total Phosphorus	
		Baseline	Counter-factual	Baseline	Counter-factual	Baseline	Counter-factual
	(Billion Liters per year)	(Metric tons per year)					
Maumee							
1980–1995	4679	348	348	1215	1215	1563	1563
1996–2011	5722	429	176	1312	1392	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.

TABLE 6.—POLICY EFFECTS OF A 25% TAX ON PHOSPHORUS INPUTS PURCHASED FOR AGRICULTURAL USE ON SOLUBLE PHOSPHORUS EMISSIONS IN THE TWO WATERSHEDS EXAMINED

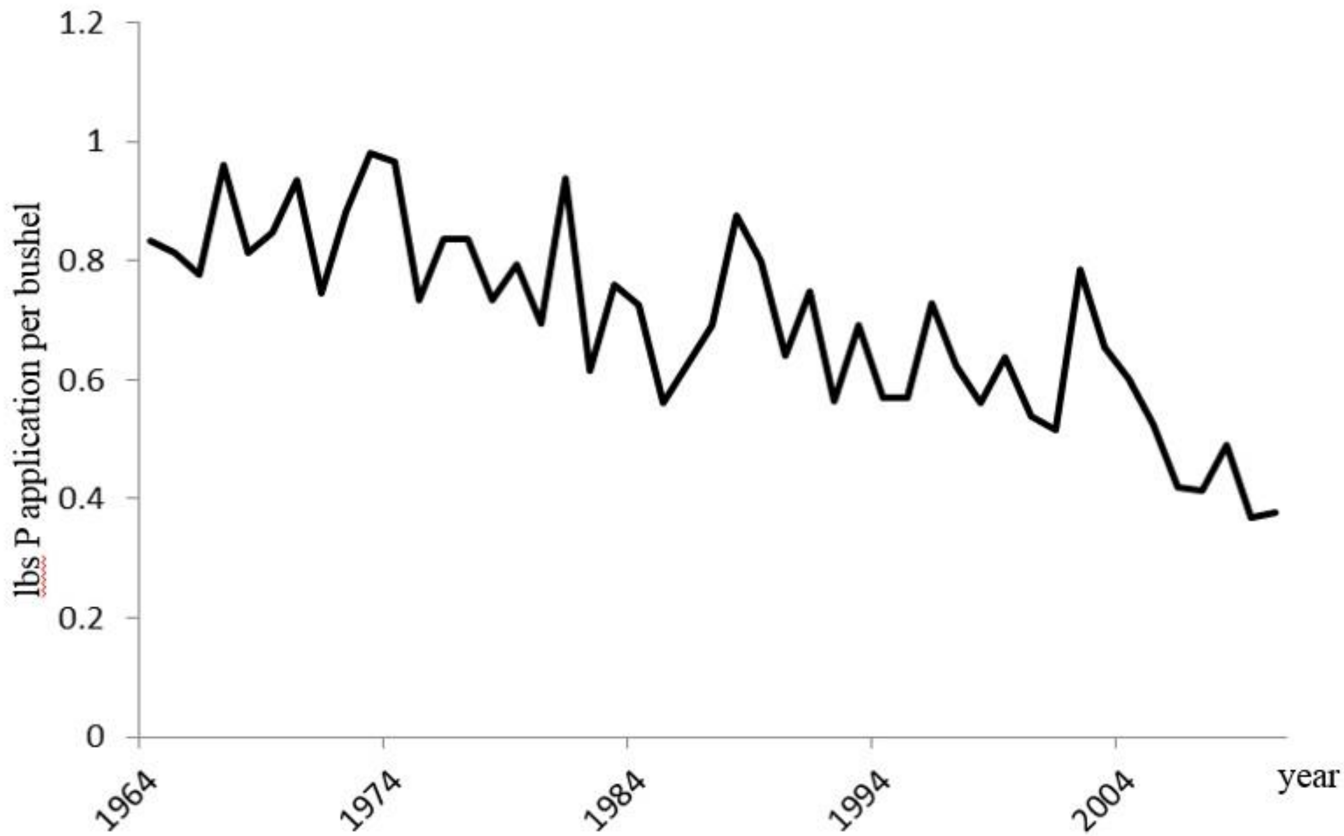
		Soluble Phosphorus (Metric tons/year)
Maumee		
	Base Annual	641
	25% phosphorus Tax	582
	Change	*(59)*
Sandusky		
	Base Annual	179
	25% phosphorus Tax	166
	Change	*(13)*
Total (Maumee + Sandusky)		
	Base Annual	820
	25% phosphorus Tax	748
	Change	*(72)*

FIGURE 1.—REPRESENTATIVE FARMER'S DEMAND FUNCTION FOR NUTRIENTS



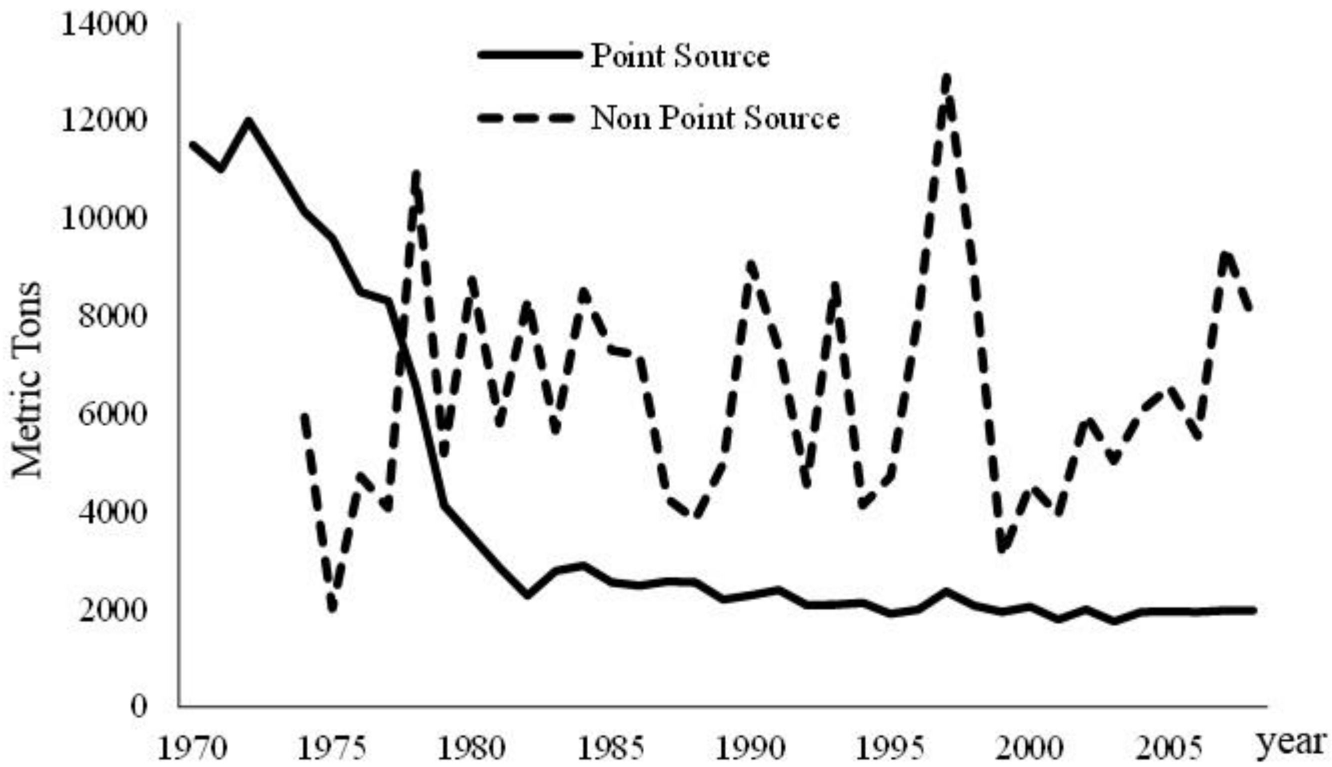
All else equal, higher nutrient prices (from P^1 to P^2) will reduce the quantity of nutrient demanded (from Q^1 to Q^2). Higher corn prices will increase the demand for land in corn, which in turn will increase the quantity of phosphorus used (e.g., a shift from Q^1 to Q^3).

FIGURE 2.—OHIO INTENSITY OF PHOSPHORUS APPLICATION IN LBS OF PHOSPHORUS APPLICATION PER BUSHEL OF CORN, SOYBEAN AND WHEAT PRODUCED



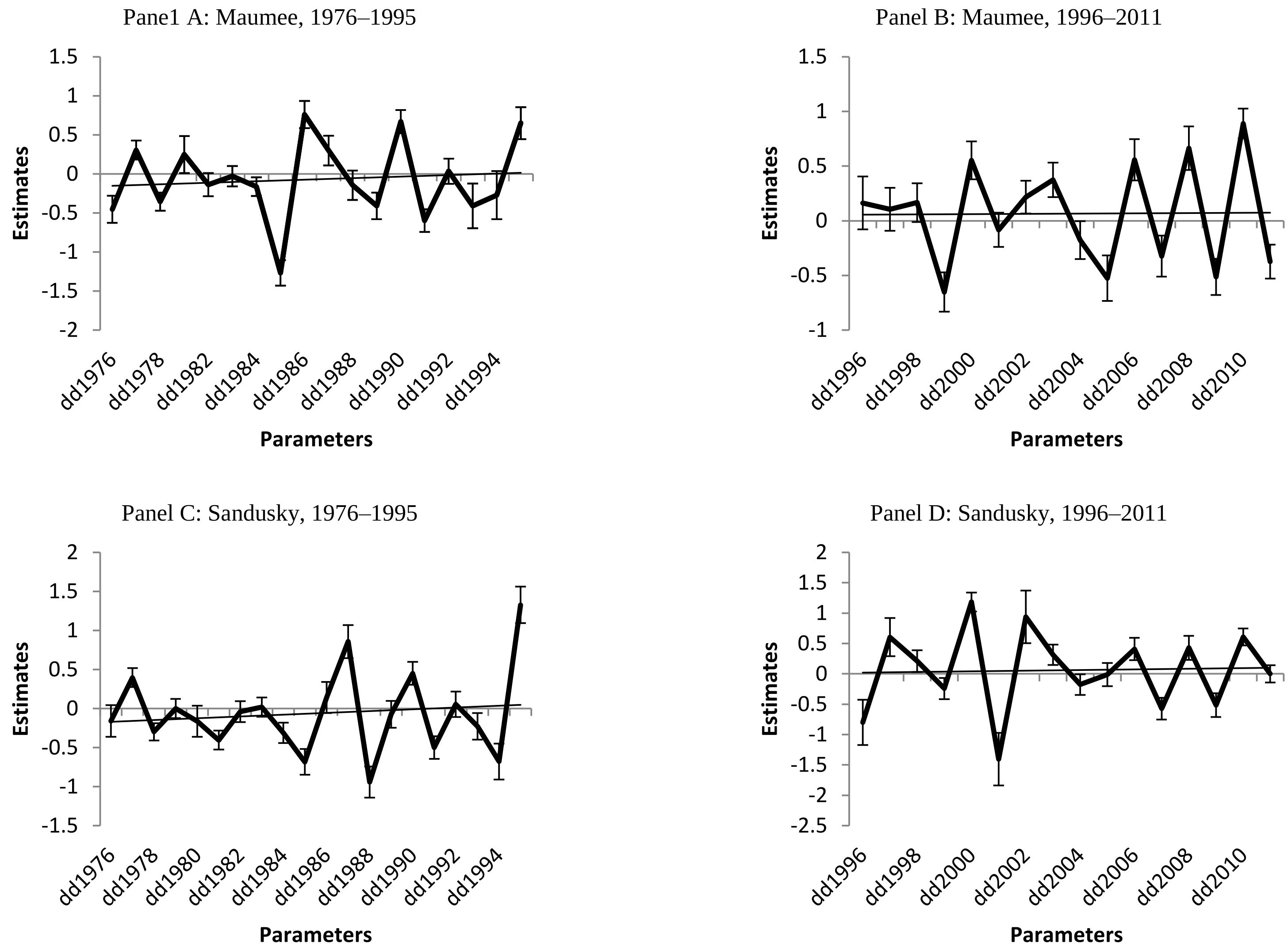
Source: Taylor (1994) and USDA-NASS (2014)

FIGURE 3.—POINT AND NONPOINT SOURCE PHOSPHORUS LOADS TO LAKE ERIE



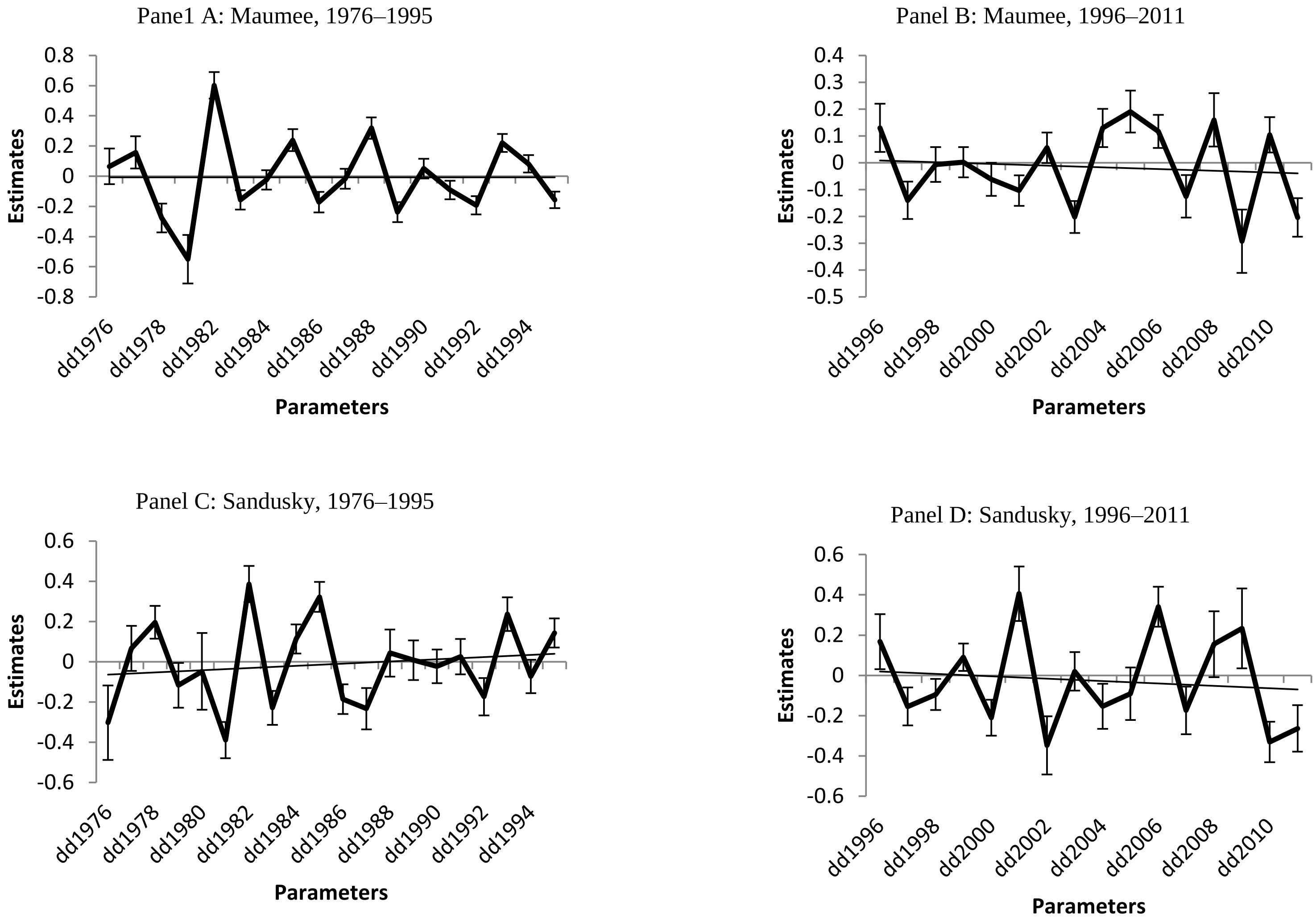
Source: Ohio Phosphorus Task Force (2013), Dolan and Chapra (2012), and DePinto et al. (2006)

FIGURE 4.—INCREMENTAL ANNUAL FIXED EFFECTS FOR THE SOLUBLE PHOSPHORUS CONCENTRATION MODEL



Error bars indicate 95% confidence interval.

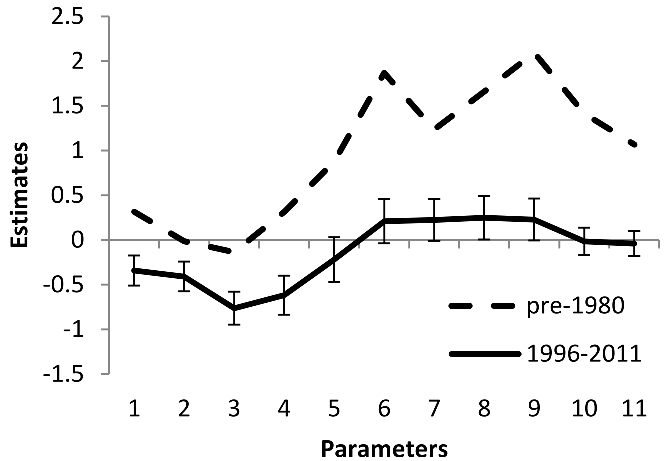
FIGURE 5.— INCREMENTAL ANNUAL FIXED EFFECTS FOR THE ATTACHED PHOSPHORUS CONCENTRATION MODEL



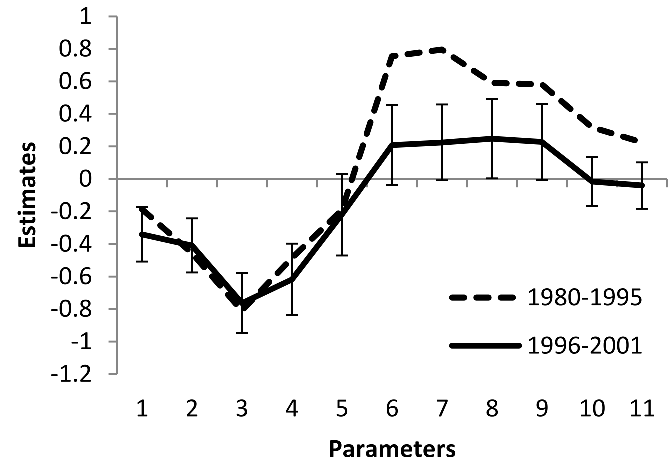
Error bars indicate 95% confidence interval.

FIGURE 6.—MONTHLY FIXED EFFECTS FOR SOLUBLE PHOSPHORUS CONCENTRATION MODEL

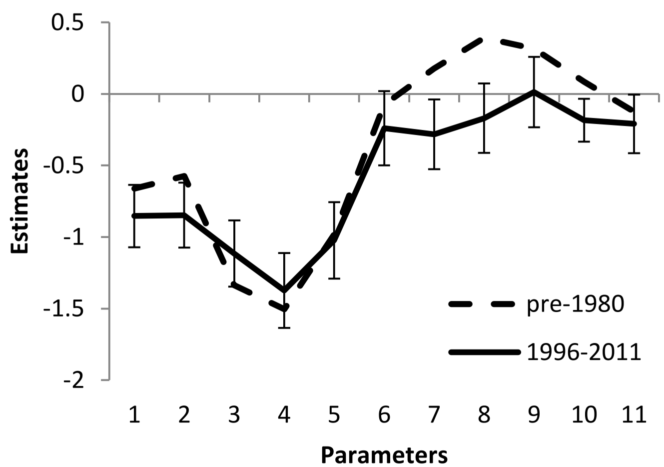
Pane1 A: Maumee, compare pre–1980 to 1996–2011 period.



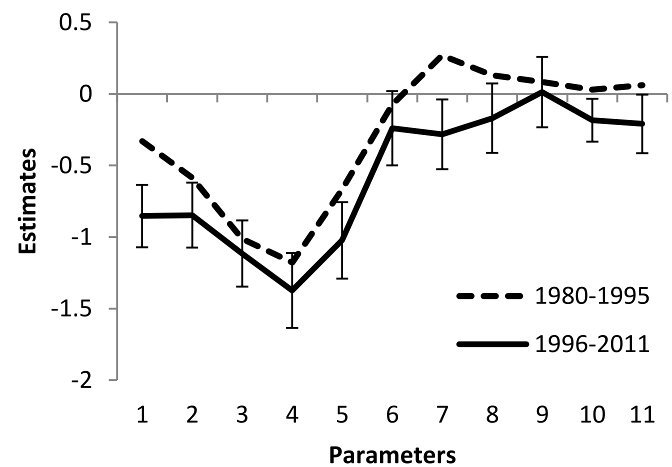
Panel B: Maumee, compare 1980–1995 period to 1996–2011 period.



Panel C: Sandusky, compare pre–1980 to 1996–2011 period.

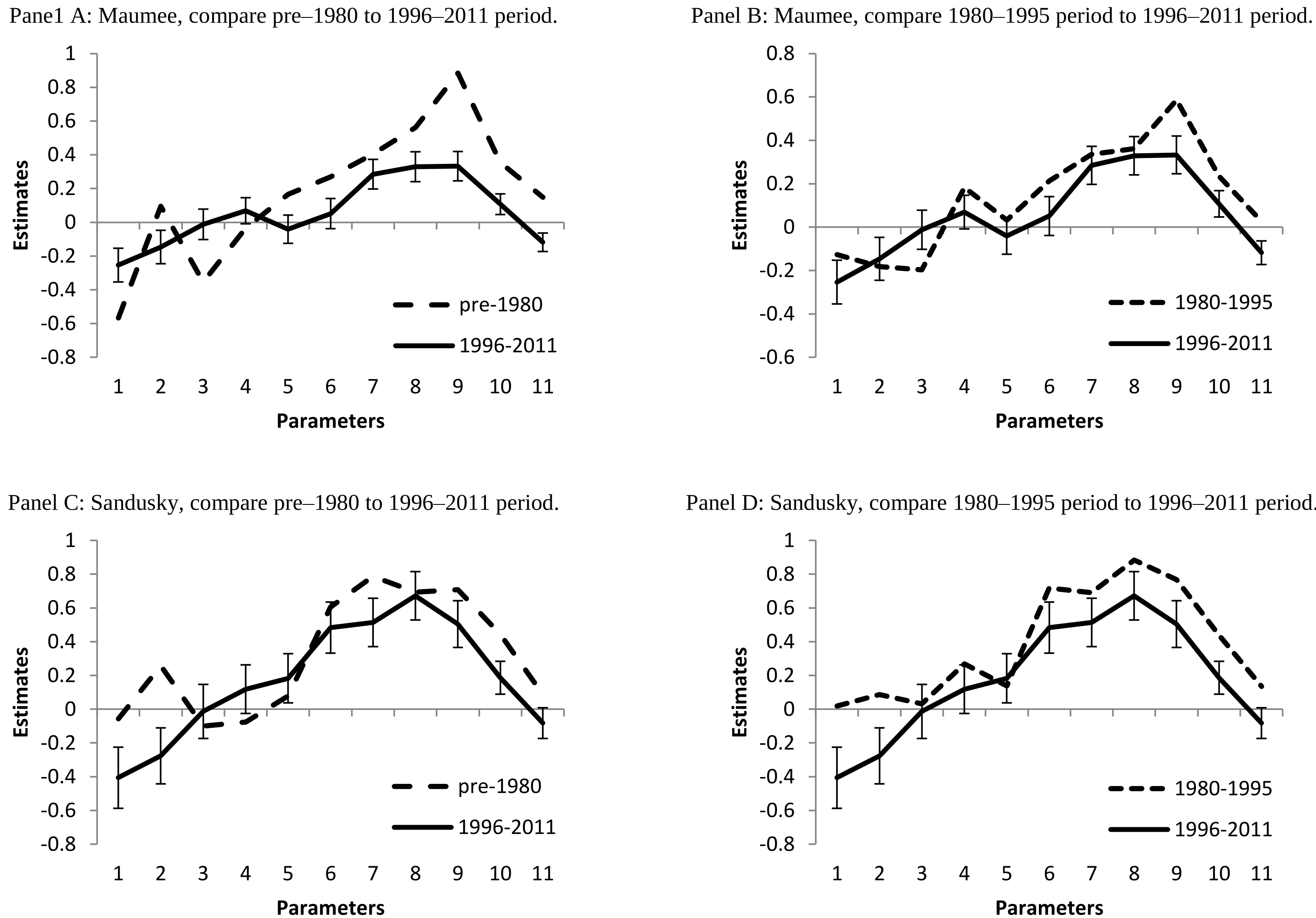


Panel D: Sandusky, compare 1980–1995 period to 1996–2011 period.



The x–axis is months, with 1=Jan and 11 = Nov. Error bars indicate 95% confidence interval.

FIGURE 7.—MONTHLY FIXED EFFECTS FOR ATTACHED PHOSPHORUS CONCENTRATION MODEL



The x–axis is months, with 1=Jan and 11 = Nov. Error bars indicate 95% confidence interval.

APPENDIX 1.—REGRESSION RESULTS

The regression results for Maumee

	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(cfstp), or Ln(cfssrp)	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

Ln(ATTP) are associated with *Ln(cfstp), and Ln(SRP)* is associated with *Ln(cfssrp)*. Note: *** p <0.01, ** p <0.05, * p <0.1

APPENDIX 1.—REGRESSION RESULTS

The regression results for Sandusky

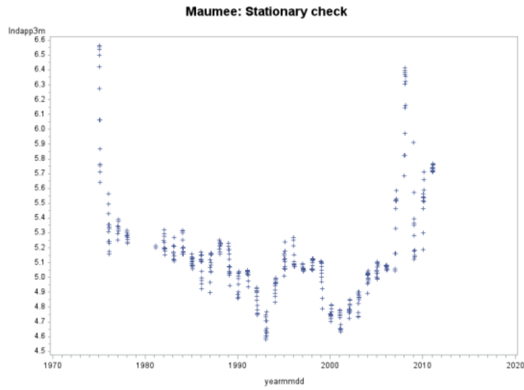
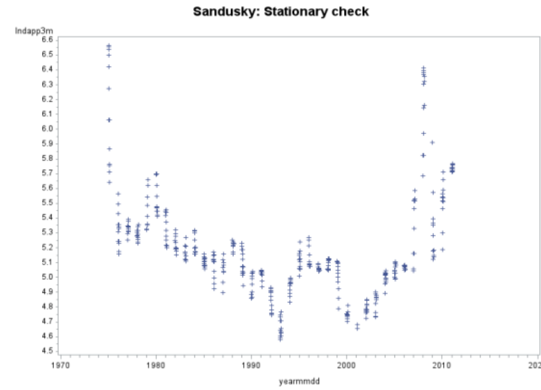
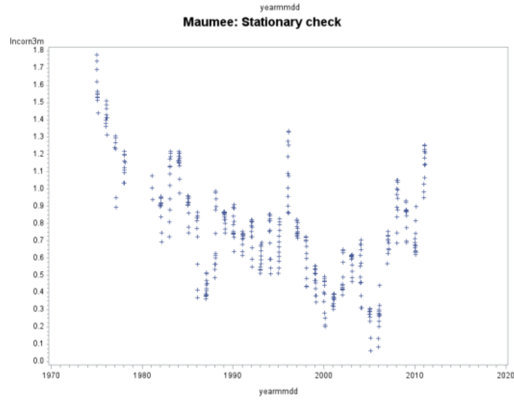
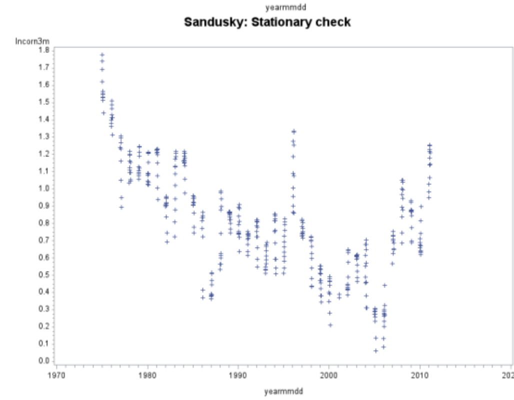
	Ln(SRP)		Ln(ATTP)	
Variables	**Estimate**	**tvalue**	**Estimate**	**t-value**
intercept	–0.9919	–1.63	–8.3914 ***	–15.31
m^1	–0.6611 ***	–3.36	–0.0573	–0.41
m^2	–0.5739 ***	–2.7	0.2570 *	1.81
m^3	–1.3359 ***	–6.62	–0.1006	–0.76
m^4	–1.5036 ***	–6.87	–0.0762	–0.64
m^5	–0.9813 ***	–4.47	0.0791	0.65
m^6	–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(cfstp), or Ln(cfssrp)	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

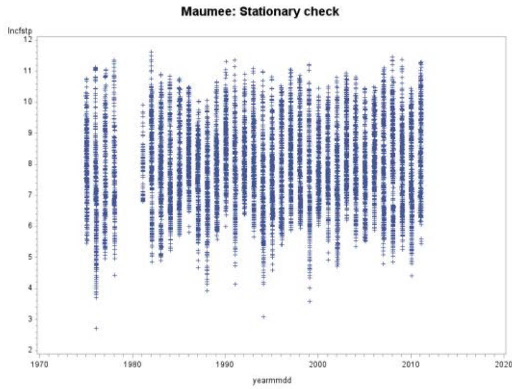
Ln(ATTP) are associated with *Ln(cfstp)*, and *Ln(SRP)* is associated with *Ln(cfssrp)*. Note: *** p <0.01, ** p <0.05, * p <0.1

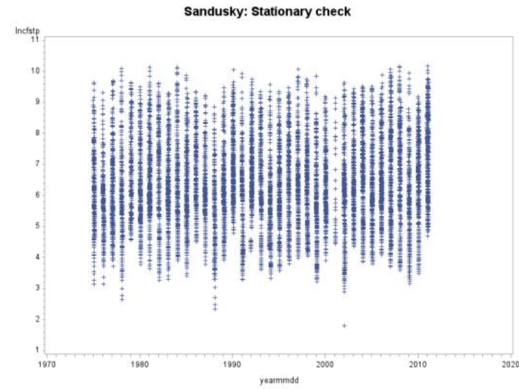
APPENDIX 2.—DATA DESCRIPTIONS

Figure 1. —Trends for Each Data Series

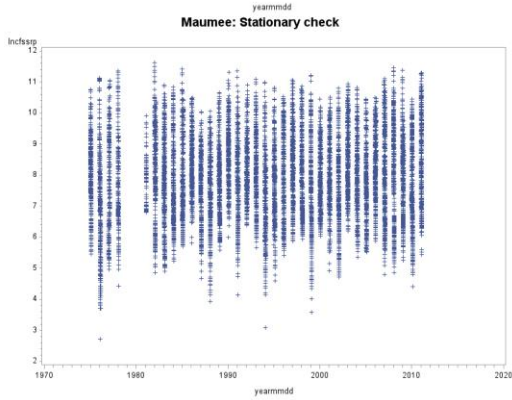
Variable	Maumee	Sandusky
Ln(dapp3m)		
Ln(corn3m)		

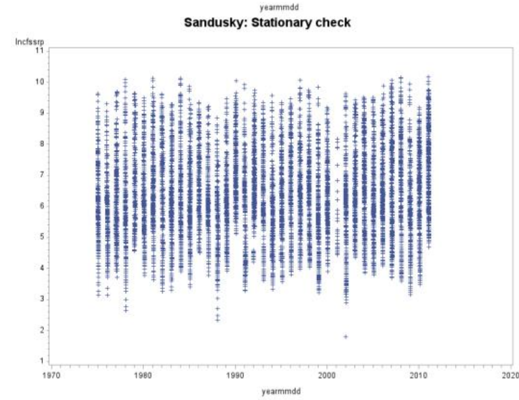
Ln(cfstp)



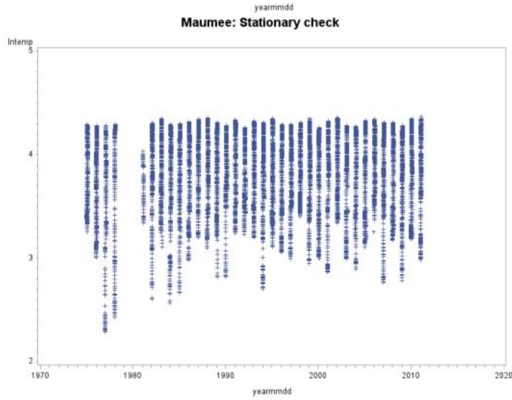


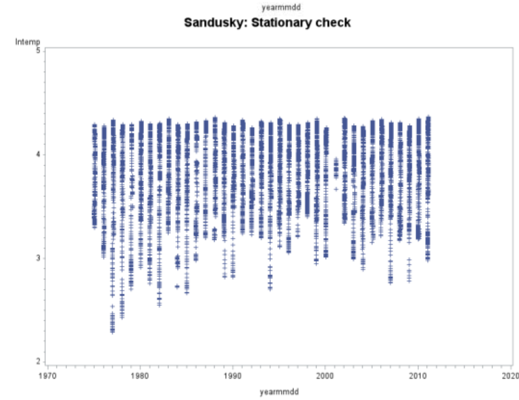
Ln(cfssrp)



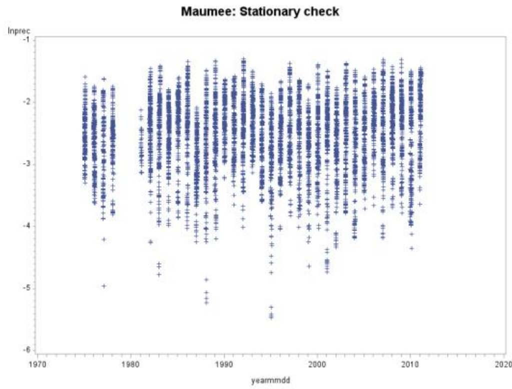


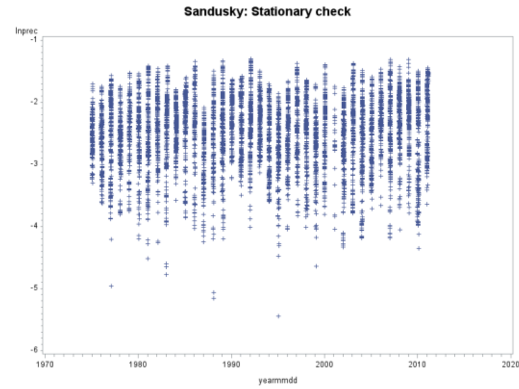
Ln(temp)



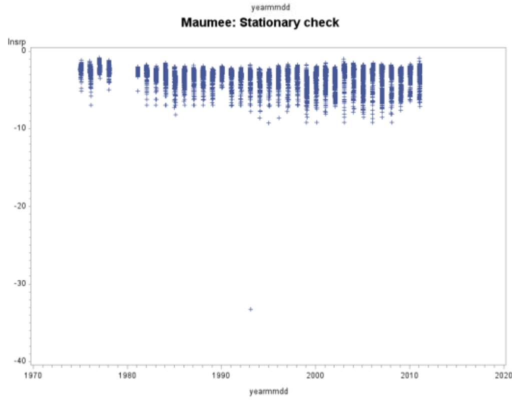


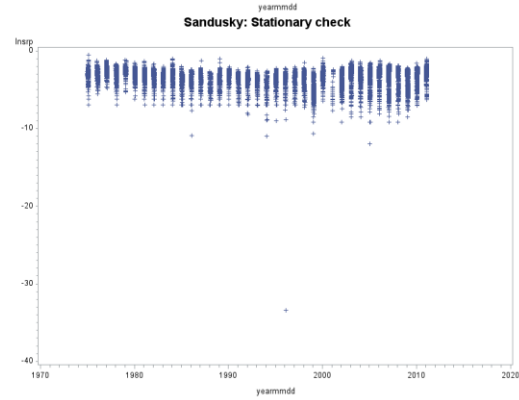
Ln(precp)



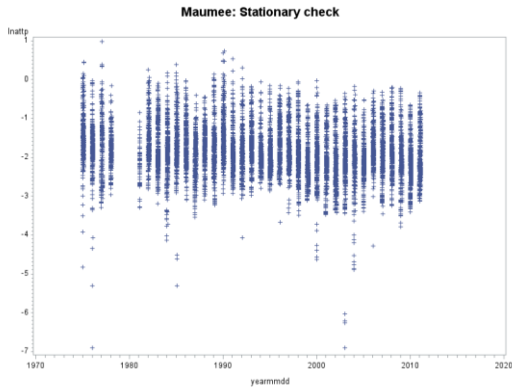


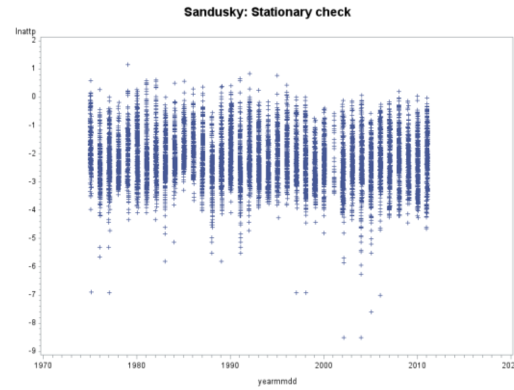
Ln(SRP)





Ln(ATTP)





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

APPENDIX 2.—DATA DESCRIPTIONS

Table 1.—Data Statistics

	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