A National, Longitudinal Study of the Effects of

Concentrated Hog Production on Ambient Air Pollution

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Abstract

The Environmental Protection Agency (EPA) is currently collecting air pollutant emissions data from large-scale livestock producers in order to regulate these operations under the Clean Air Act. Despite impending federal regulation, little is understood about livestock's effects on ambient air quality at the national level or geographic heterogeneity of effects. Further, current water quality regulation of livestock operations may exacerbate air pollution. In this article I use the geographic concentration of the hog industry between 1980 and 2002 to identify the changes in ambient air pollution, controlling for a number of covariates on production inputs, location features, environmental amenities, as well as emissions from other sources. Using a national, longitudinal dataset, I find that doubling the number of hogs per square mile yields a 10% increase in sulfur-based ambient air pollution. For counties with increases in hog density, reductions in air pollution were on average 20% less than would have occurred in the absence of these changes. While associations between sulfur-based air pollutants and hog production can be found at the national level, those for ammonia-related pollutants are region-specific. Additionally, states with active water quality regulation of hog operations exhibit 8% more ammonia-related pollution, suggesting that regulations of this industry must consider both air and water pollution. Externality costs are estimated to be three times as much per hog as possible regulatory requirements, suggesting significant societal gains from regulation.

JEL Classification: Q5

Keywords: Pollution, livestock, externalities, regulation, public health

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The author would like to thank Jane Zhou for excellent research assistance. All mistakes are solely my own.

Hog production has seen large changes in scale and technology over the past several decades, leading to spatial concentration and thousands of animals per operation. Simultaneous to these changes grows a heightened interest in hog production's contribution to air pollution in the form of hydrogen sulfide (H2S) and ammonia (NH4), as well as other pollutants. Recognizing the extent of the problem, the Environmental Protection Agency (EPA) is currently taking action to regulate large-scale livestock production under the federal Clean Air Act (CAA). This legislation may impose significant costs on the industry and exacerbate other pollution types if multiple pollutants are not jointly considered.

Despite impending federal regulation, current knowledge on air pollution from livestock facilities mostly arises from small, region- or farm-specific studies. Researchers bemoan the lack of understanding of the scope of national-level externality costs, particularly when considering future regulation. In this article I estimate the effects of concentrated hog production and water quality regulation of hog operations on ambient air pollution at the national level using the geographic changes in hog density and the variation in water quality regulation in the U.S. between 1980 and 2002. Because the factors implicated in hog production location are arguably orthogonal to air pollution, and because the industry has been unregulated for air pollution even at state and local levels, estimates of changes in air pollution accompanying geographic changes in production provide a method to measure externalities of the industry.[2] Using a national, longitudinal data set with over 55,000 measured ambient air quality observations and county-level data on hogs per square mile, I find the growth of hog concentrations causes a significant increase in air pollution that is robust with respect to covariates on production inputs, environmental regulation, climate, local economic characteristics, emissions from other sources, as well as unchanging characteristics

[2] In this article I refer to "air pollution" in the sense of air pollution regulation. While odors are certainly a concern, the thrust of upcoming air pollution regulations do not account for odor themselves, but rather the gases associated with odors.

of counties and nationally uniform changes in each year. The results show that doubling hog concentrations in an area increases sulfur dioxide (S02), a product of hydrogen sulfide oxidization, by 10%. For counties with increases in hog density, reductions in air pollution were 20% less than would have occurred otherwise. The use of measured, ambient air quality avoids problems with modeled pollutant levels and also reflects public health exposure.

Effects on particulate matter, a product of ammonia, are only evident at the regional level. This finding is expected due to regional variation in particulate matter composition. Southern and Northern states exhibit the strongest effects, despite the fact that production is most concentrated in the Midwestern region. The production practices employed in different regions may therefore play a significant role in air quality, and provide direction as to which practices should be encouraged through regulation.

Active water quality regulation is correlated with significantly greater particulate matter, but not with sulfur-based pollution. Adopting National Pollution Discharge Elimination System (NPDES) permits for hog operations leads to an 8% *increase* in particulate matter. Water quality regulation of livestock production has long encouraged the volatilization of ammonia, which is associated with particulate matter. The lack of a strong relationship between water quality regulation and sulfur-based pollution argues against reverse causality in which states pursue hog facility water regulation based on generally higher levels of air pollution.

To craft rational policy by weighing the costs of regulatory action with the benefits of reduced pollution first requires understanding the size of the externality. In this article I estimate that externality costs associated with sulfur-based air pollution are three times as much per hog as impermeable lagoon covers that mitigate emissions. This suggests substantial societal gains from air pollution regulation of the hog industry.

Livestock Production and Air Pollution

A combination of new technologies in hog raising, new business arrangements, and the desire to capture economies of scale have led to the current style of hog production (Key and McBride, 2007). Swine production now largely occurs in industrial-style settings with several thousand animals per operation and 87% of hogs at operations with more than 1,000 head (USDA, 2002). No longer strictly coupled with cropping, livestock production has been able to locate based more strongly on market forces (Hubbell and Welsh 1998; Abdalla, Lanyon, and Hallberg, 1995). Vertical integration of different portions of the pork manufacturing process encourages numerous growers locating around a central producer (Kliebenstein and Lawrence 1995; Martin and Zering, 1997), leading to geographic concentration (Kellogg et al., 2000). Historical experience with contract marketing of other livestock types has enabled certain regions to grow faster in this vein. Figure 1 shows changes in hog production by county between 1980 and 2002, revealing heterogeneous changes across the country.

A concentration in the byproducts of hog production accompanies the geographic shifts in livestock farming. A large number of hogs located in a relatively small area leads to a vast amount of excrement per unit of land. While manure was once used as fertilizer, spatial disaggregation from crop production and preference for chemical fertilizers has substantially reduced this practice. To handle the large amounts of byproduct, many hog facilities adopted liquid manure management (USDA, 1996). Hogs are now generally raised indoors on slatted planks above pits. The pits are periodically flushed into open-air "lagoons" which can extend to several acres in size. From the lagoons, workers pump a portion of the manure and spray it onto cover crops (Mallin, 2000). Without proper management, manure can lead to a host of pollution issues.

The switch in manure's role from a soil amendment to a less-useful byproduct has come with increasing regulatory scrutiny (Sullivan, Vasavada, and Smith, 2000; Meyer and Mullinax, 1999). Livestock production has been federally recognized as a source of water pollution since the

1974 Clean Water Act. This regulation designates large-scale livestock farms as "point sources" of pollution and requires them to file National Pollution Discharge Elimination System (NPDES) permits.[3] Getting a permit usually requires operations to fulfill certain waste management criteria, and to limit the amount of manure applied to land to avoid nutrient run-off. Individual states enforce and grant these permits. As such, there is significant variation by state in environmental regulation of hog production (Metcalfe, 2000), leading to the possibility of hog pollution havens. Changes in hog location correlated with regulatory stringency suggest compliance costs are significant (Herath, Weersink, Carpentier, 2005; Roe, Irwin, and Sharpe, 2002; Metcalfe, 2001).[4]

Recognizing the "non-point source" pollution associated with manure run-off, in 2003 the EPA enacted further federal regulation requiring large-scale livestock operations to develop "Comprehensive Nutrient Management Plans" (CNMPs) (EPA, 2003). These plans encourage the dispersion of manure by limiting the amount applied to each unit of land. To comply, operations may need to rent or purchase land, or otherwise locate in areas with few similar operations.

Accompanying changes in production methods and geographic concentration, hog operations have been increasingly implicated as a source of air pollution. As the measurement of odor has proven difficult, the focus for upcoming air pollution regulation instead is on gases.[5] The research on air emissions from livestock operations has been summarized in at least two major studies, one by members of Iowa State University and The University of Iowa (2002) and the other by the National Research Council Ad Hoc Committee on Air Emissions from Animal Feeding Operations (2003). Air pollutants arise from livestock farms via lagoons, spray application of manure, drying fecal matter, and from the animals themselves. Two gases of major concern to public health are hydrogen sulfide (H2S) and ammonia (NH3). Hydrogen sulfide and ammonia are

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[3] "Point sources" are easily-identifiable sources of pollution that can be "plugged."

[4] Evidence from Canada (Weersink and Eveland, 2006) suggests that in that country, siting of livestock facilities is based more strongly on agglomeration economies than on environmental regulations.

[5] See Lacey et al. (2004) for a discussion of the difficulties in measuring odor from livestock operations.

toxic pollutants that have been implicated in human and swine health problems (see Carson, Osweiler, and Thorne, 2002; Holland, Carson, and Donham, 2002; Merchant et al., 2002; Donham, 2002). In addition to these, large-scale livestock farms have been connected to a number of other air pollutants.[6]

Rather than creating a minor nuisance, the amount of air pollution from livestock operations is increasingly shown to be significant. If the current EPA emissions factor is used, the hog facilities in North Carolina are estimated to emit more hydrogen sulfide than the fertilizer producers and paper mills in the state (Schliesser, 2003).[7] Livestock are also the primary emitter of ammonia in the country (EPA, 2000; Gay and Knowlton, 2005). Other indications of hog production's role in air pollution arise from individual incident reports and public health findings. For example, multiple fatalities from hydrogen sulfide poisoning periodically occur when swine operation workers enter manure pits for maintenance (NIOSH, 1993; Madgery, Parker, and Shutske, 1993). This is coupled with myriad newspaper reports on neighbors of hog farms experiencing nausea, vomiting, dizziness, and other symptoms (see, for example, Lee, 2003; Teitz, 2006). Research in peer-reviewed journals has also found connections between proximity to hog facilities and public health effects (Sneeringer, 2008; Thu et al., 1997; Wing and Wolfe, 2000; Cole, Todd, and Wing, 2000).

The concerns surrounding air pollution from livestock production have prompted new federal action. In 2006, the EPA asked large-scale livestock operations to self-monitor emissions in exchange for clemency for past air pollution violations. Recognizing a lack of data with which to construct rational policy, the EPA took this first step toward regulating livestock operations under the Clean Air Act (EPA, 2006). Livestock production can also be regulated for air pollution under

[6] These other air pollutants include both lower-atmospheric ones like volatile organic compounds (VOCs) and upper-atmospheric ones like methane (FAO, 2006).
[7] However, Schliesser suggests that North Carolina hog facilities emit less H2S than the "model farm" operation on which the EPA's emission factors are based.

other legislative auspices, although no action has occurred in this vein yet.[8]

Despite the move to federal regulation, little research has examined the scope of air pollution from hog operations on a national basis. While the EPA (2001) attempted to develop emissions factors for national policy-making using the model farm method,[9] it expresses concern for numerous gaps in knowledge. Further, the National Research Council (2003) critiqued the model farm method, saying it does not account for a number of variables potentially affecting emissions. Other authors have criticized attempts to establish uniform emissions factors based on regional differences (for example, see Schliesser, 2003).[10]

As the industry moves toward air pollution regulation, it faces further rules for water quality either by extending current regulations to smaller farms or by increasing state-level stringency. Without consideration of both pollution media, regulating one pollutant may exacerbate the other (Aillery et al., 2005; Key and Kaplan, 2007). This result has already been found in the manufacturing sector (Greenstone, 2003); in agricultural sectors it is predicted but has not been documented. To reduce the nutrient content in manure and avoid water-based nutrient run-off, hog operations may allow manure to remain in lagoons longer, yielding more air-borne ammonia emissions. The problem lies with the fact that nitrogen pollutes both air and water; policies to reduce ammonia emissions can lead to more nitrogen water run-off, while policies to reduce nitrogen run-off can lead to more ammonia emissions.

Other practices used less frequently to mitigate one type of pollutant also have the potential to aggravate another. Burning manure, a practice that may lessen water pollution, may exacerbate air pollution. Different feeds are being tested to reduce nutrient and sulfur levels in manure,

[8] The Comprehensive Environmental Response, Compensation, and Liability Act (CERCLA) and the Emergency Planning and Community Right-to-Know Act (EPCRA) both require reporting of toxic releases (National Research Council, 2003). Hydrogen sulfide is one such toxic.

[9] The model farm is a model on paper; there is no physical farm at which to estimate emissions.

[10] For example, Schliesser notes that Southern swine lagoon contain "purple sulfur bacteria," which enables less emission of sulfur-based compounds. Further, different regions of the country employ different manure management and land application systems due to temperature and soil properties. These may also impact emissions.

although it is unclear whether these will have an effect on air pollution. Further, reduction of one type of air pollutant may exacerbate another. Lagoon aeration may reduce hydrogen sulfide (and odor) but may yield more ammonia emissions (Powers, 2004a). Likewise, reduction of ammonia by lowering the pH of manure through feed additives may encourage more hydrogen sulfide emissions (Powers, 2004b).

Empirical Strategy

The empirical strategy focuses on providing an consistent estimate of the effect of hog density on air pollution. Begin by considering two equations, one describing the relationship between location decision factors and the level of hog production in an area (h), and one describing the inputs to air pollution in the area (A). Assuming linear additivity, the two equations are:

(1) $$h_i = a_0 + J_i' a_1 + X_i' a_2 + e_i$$

(2) $$A_i = b_0 + d h_i + X_i' b_2 + M_i' b_3 + u_i$$

where i indexes the county. Equations (1) and (2) elucidate which variables need to be included in estimation of the effect of hog production on air pollution. J is a vector of factors correlated with hog production but uncorrelated with air pollution, such as prices of pork products. X is a vector describing factors correlated with hog production and air pollution, including but not limited to precipitation, temperature, land prices, and stringency of general environmental regulation. When identifying effects of hog density on air pollution, endogeneity between h and X will not bias results. M is a vector of variables that determine the level of air pollution but do not determine the level of hog production, such as regulations governing industrial air pollution.

The most basic econometric approach is to estimate Equation (2) with a cross-section of data. Because X will affect A both directly as well as indirectly through h, consistent estimation of d requires the inclusion of X. However, M does not need to be included in the regression model if the goal is unbiased estimation of d. Because M is uncorrelated with h, its exclusion will not produce omitted variable bias in the estimation of d. One primary concern is therefore to be certain of inclusion of the factors in X that affect both h and A. A second primary concern is endogeneity, which occurs if livestock operations specifically locate based on air quality.

To address both of these concerns, consider the factors that impact hog production location. Hog location decisions are arguably made according to factors other than air pollution policy. Hog production has not been regulated for air pollution, and therefore environmental stringency of *air* pollution regulation is arguably not a decision factor in location. The environmental amenities that are choice variables in producer decisions include water supply, precipitation, and temperature, not air quality. This further suggests an exogenous relationship between hog production and air pollution.

The three primary reasons for hog location decisions as expressed in the literature are historical setting, agglomeration economies, and environmental regulation of water pollution. While none of these is directly associated with air pollution, each may be correlated either positively or negatively with it. If so, then any associations between hog production and air pollution could be due to this third factor. If these variables are not controlled for, this could result in omitted variable bias in the coefficient of interest. The first solution to this is to actually include the confounding variable. I therefore include confounders on inputs, technological efficiency, features related to agglomeration, local economic characteristics, environmental regulation stringency, climate, and emissions.

Barring data on specific confounders, a solution is to use panel data to non-parametrically control for fixed characteristics of counties and time periods, in addition to adding time- and county-varying confounders. Three types of variation in hog production changes allow one to non-parametrically control for potentially confounding but unobserved factors. Consider Figure 1, showing percent changes in hog density by county for the entire U.S. The map shows that counties vary over time in their level of hog production, allowing one to factor out features of counties that are unchanging. These include historical setting, environmental amenities such as slope, and non-time-varying preferences of community members for hog production and air pollution. Because these characteristics are fixed over time or before the start of the time period in question, they will be captured in the fixed effect for the county. To the extent that annual wind patterns are static over time, the fixed effect will capture these. Further, it is unlikely that other polluting industries are systematically upwind of hog farms.

A second source of variation from which to identify effects are differences in changes between counties. Because multiple counties are witnessed in multiple time periods, any covariate that affects all counties in a certain year can be factored out. Examples include economy-wide shocks to prices or demand, such as a national recession that lowers pork consumption as well as air pollution.

Finally, Fig. 1 reveals that changes differ even within states. This suggests that something other than state policies has affected location decisions. This within-state variation allows one to control for state-level confounders while still using the variation between counties to identify effects.

Using panel data, controlling for fixed factors non-parametrically yields a regression of the form

(3) $$A_{ist} = a + d h_{ist} + X1'_{ist} b1 + X2'_{st} b2 + g_{is} + g_t + u_{ist}$$

Here, t denotes time period while s denotes state. g_{is} represents fixed effects for county i in state s, and g_t denotes fixed effects of time period t. Fixed characteristics of counties that are correlated with hog production and also effect air pollution will be captured in g_{is}. A set of dummies for time period (g_t) will capture characteristics of individual years that occur for all counties in all states.

$X1_{ist}$ denotes county- and time-varying confounders that are correlated with both air pollution and hog production. $X2_{st}$ denotes state- and time-varying confounders. Because their omission will not impact the estimate of d, the factors in M (from Equation (2)) are excluded. The coefficient d will provide an estimate of how changes in hog density affect changes in ambient air pollution.

Finally, the standard errors in estimation need to be considered. Hog production and air pollution in an area may be correlated over time, leading to heteroscedasticity. Further, error terms may be spatially correlated. In order to adjust the standard errors for both of these possibilities, I cluster them on the level of the state (see Bertrand, Duflo, and Mullainathan, 2004, for the reasoning and structure behind clustering). Such clustering will adjust for unspecified heteroscedasticity.

Data

I gather data from a variety of sources for the period 1980 to 2002.[11] In order to count differentially-sized counties equally, all variables are scaled according to state or county size, or put in terms not directly correlated with county size.

Ambient Air Quality

Before describing the variables of interest it is important to understand the difference between ambient air quality and emissions. Ambient air quality is the level of pollution to which the general population is exposed. The EPA measures ambient air quality via a series of fixed monitors. Emissions, on the other hand, are what are produced from individual sources. If one were considering water quality, emissions would be the amount of pollution emptied into a water body from a pipe, while ambient water quality would be the average level of the pollution in the water

[11] I use this period because most data are available for it. Results using the period 1980 to 2005 yield very similar findings. However, I choose the end year of 2002 for two reasons. First, the emissions data only cover 1990 to 2002, and I hope to avoid confusion by eliminating the extra three years between 2002 and 2005. Second, direct regulation of air pollution from livestock operations in terms of emissions began in 2004. Although this regulation was locally based and for dairies in Southern California, restricting the time period to earlier than first regulatory adoption mitigates concerns of endogeneity.

body. Emissions arise from point or non-point sources; point sources can be identified and "plugged," while non-point sources cannot. I use ambient air quality as my dependent variable, but control for emissions from other sources in certain specifications.

While H2S and NH3 are two of the primary emissions under scrutiny, the EPA at present only collects ambient measures for six "criteria air pollutants" on a nationwide basis. It is therefore necessary to use these measures to explore ambient air pollution from livestock farming on a national basis. These criteria pollutants include sulfur dioxide (SO2), nitrogen dioxide, carbon monoxide, ozone, lead, and particulate matter (PM). SO2 and PM are the only criteria pollutants that are both directly implicated in research on air pollutants from livestock facilities, and can serve as proxies for measuring changes in the primary gases of interest.[12]

Hydrogen sulfide oxidizes to sulfur dioxide in the atmosphere, meaning that in the presence of oxygen, H2S will convert to SO2 (ATSDR, 2006).[13] Livestock facilities have not been widely monitored for SO2 emissions, although SO2 is directly emitted at these facilities (Lim et al., 2003; Okoli et al., 2006; Thorne, 2002). However, the EPA suggests that livestock facilities themselves are not major emitters of this pollutant (EPA, 2002). The changes in SO2 associated with hog production found in this article most likely reflect hydrogen sulfide or other sulfur-based emissions, rather than changes in direct SO2 emissions.[14]

Particulate matter is formed directly by animals as dust, and is created when ammonia binds to air particles. As noted above, livestock operations are the primary emitter of ammonia in the U.S., and as such ambient PM levels may vary with hog production. However, the strategy of estimating changes in PM using changes in hog production is complicated by the fact that many substances lead to the creation of PM, not just ammonia. Further, ammonia is associated with

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[12] While carbon monoxide is associated with "silo gas," it is generally not mentioned in relationship to ambient pollutants associated with livestock.
[13] The exact chemical formula is 2H2S(g) + 3O2(g) → 2SO2(g) + 2H20(g).
[14] The use of SO2 to reflect changes in H2S has also been used by at least one other study (ATSDR, 1997).

particulate matter of 2.5 microns in size (known as PM2.5); while the EPA has begun monitoring of PM2.5, it predominantly monitored particulate matter of 10 microns in diameter (PM10) during this article's period of study. All of these features suggest that estimating ambient air quality effects on PM10 will be more nuanced than examination of SO2 as a proxy for H2S.

Annual ambient air quality data comes from the EPA's AirData System. This provides mean annual ambient air quality measures at 1,221 monitoring stations across the U.S. Not all counties have air pollution data in all years; monitors have generally been established in more populated places. Zero values are not recorded for SO2; the lowest value is 0.0005ppm. Likewise, the lowest value of PM10 recorded is 2µg/m^3. For the SO2 observations, I use what is recorded as the annual mean for the monitor. For the PM10 observations, I use what is recorded as the annual mean of the 24-hour recordings. In both of these instances, the choice is made to accord with the units of the National Ambient Air Quality Standards.[15] To each of these air quality observations, I attach county-year level data on hogs per square mile as well as a number of county-year and state-year controls.

The availability of air pollution measures limits the sample's coverage of the U.S. Monitors are generally placed in more populated areas, meaning that the places with higher hog densities may not be represented. Results should be interpreted to be representative of hog farms in closer proximity to higher population areas.

Hog Production

County-level hog data comes from the USDA's National Agricultural Statistics Service (NASS). The number of hog operations per county is not available on an annual basis, so to create a measure of concentration, I divide the number of hogs by the county's land area in square miles.[16] Not every

[15] The NAAQS for annual SO2 is 0.03ppm, while the annual mean 24-hour PM10 standard is 150µg/m^3.

[16] Number of hog operations by county is available in the Census of Agriculture, which occurs every 5 years. Using this data would severely restrict the same to 5 years, rather than the available 23, so I use the county-level annual data.

county has hog data in an individual year due to confidentiality restrictions. When identification of a specific operation is possible, (due, for example, to all hogs in the county being at a single operation), NASS groups the county with several others to create a "combined county." In order to use these "combined counties," I discern which counties are included in them each year and distribute the number of hogs in the combined county equally to each county in the group.[17]

Water Quality Regulation

As mentioned above, the Clean Water Act designates large-scale livestock operations as point sources of water pollution and requires them to obtain permits to operate. States have individual discretion in interpreting the federal guidelines, however, and so two identical operations in different states may not both be required to file permits. I use whether a state has NPDES permits in the year as an indicator of state-level annual environmental stringency.

The EPA's EnviroFacts database contains information on numerous regulatory activities. Using the Permit Compliance System (PCS) portion of this database, I find all permits listed for hog operations (Standard Industrial Classification System code 0413), the states in which they were issued, and their dates of issuance and expiration. In cases where expiration dates are not listed, I assume they are 5 years after issuance. Likewise, where date of issue is not listed, I assume it is 5 years prior to date of expiry. Because only large operations are required to obtain permits, I do not use the number of permits in a state, as it may dilute estimation of effects from hog density.

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[17] In order to discern which individual counties are in the "combined counties" each year, I do the following. I first find which counties have missing data for every year between 1980 and 2005. I assume that these counties have zero hogs and remove them for comparability with potentially-zero counties that are grouped with heavy production counties. NASS divides states in agricultural statistical districts (ASDs), which are grouping of counties. When a county has either zero hogs or must be censored for confidentiality purposes, it is grouped with other counties in the district into a combined county. According to Bruce Boess, the commodity specialist for hogs at NASS, "In most cases if a county is not published, it means that there is a disclosure problem (meaning one individual owns more than 60% of the hogs in that county or less than 3 producers in the county) or no hogs" (personal communication). If only one county in an ASD must be censored, it is unclear why the other counties with which it is grouped are chosen. County combinations change each year. Assignments of counties to districts also change over time, so I use the current listing consistently over time. For each year, I discern which counties in each ASD have missing hog data (excluding those presumed to be always zero). I then distribute the number of hogs in each combined county equally to the individual counties. In some years, there were no "combined counties" for an ASD, even though there were missing individual counties. These are also discarded. This leaves no zero observations in the sample.

Using this state indicator allows identification of the effect of water quality regulation on air pollution while controlling for hog production level. It is unlikely that air pollution related to livestock operations will lead directly to heightened water quality regulation, as air quality concerns have not been a focus until relatively recently. To test this assumption, I regress whether the state has active NPDES permits in the year on whether the country does not meet Clean Air Act standards (see below for description of this variable), including county and year fixed effects and other confounders (results shown in Appendix Table A.1).[18] Results show no statistically significant effects of air pollution regulation on whether or not a state uses NPDES permits. Further, analysis of two types of air pollution allow for a check of this type of reverse causality. If higher air pollution leads to more environmental regulation in general, then effects of water pollution regulation on air pollution should affect both pollutants; if this isn't the case, it allows for a stronger case against reverse causality.

Emissions from Other Sources

The EPA estimates total county-level emissions from a variety of sources and reports these in the National Emissions Inventory (NEI). Total emissions are calculated using production levels and emissions factors. An emissions factor is generally a multiplier chosen after numerous studies of individual production facilities and then applied uniformly to all facilities in the industry. If an industry is not deemed to be a contributor to emissions of a certain pollutant, then it is not included in the estimated totals.

The NEI contains county-level data for 1990 and 1996 to 2002. I use total emissions for SO2 from both point and non-point sources as a dependent variable in regressions with ambient SO2 as the dependent variable. Since there is no emission factor for SO2 for livestock operations,

[18] This linear probability model is chosen over probit or logit specifications due to the inclusion of the fixed effects. As Lancaster (2000) points out, the incidental parameters problem of bivariate outcome variables with many fixed effects is minimized in linear probability models.

this type of facility is not included in emissions totals and the variable will not be correlated with hog production. While estimated emissions from agriculture are available for ammonia, I do not use these as a dependent variable because doing so would only recover the multiplicative formula used to create them.

Table 1 provides summary statistics for the outcome variables and the explanatory variables of interest over time. The average number of hogs per county is generally declining over time, an artifact of having a larger portion of counties with very few hogs. The Midwestern states exhibit high but declining hog densities, while those for the Southern and Northern states are lower but increasing.[19] Ambient SO2, measured in parts-per-million (ppm), and ambient PM10, measured in micrograms per cubic meter (μg/m^3), are also declining. Estimated SO2 emissions are declining, and the portion of counties in states with NPDES permits is rising.

Inputs and local economic characteristics

A number of inputs to hog production may also be correlated with air pollution. Many of these could also be characterized as local economic characteristics, including per capita income, unemployment rate, poverty rate, and percent of the population over 65. A characteristic of the built environment potentially correlated with livestock farming and air pollution is land cost. The number of new building permits per square mile proxies for this factor. Energy prices for a state may not only impact where livestock operations choose to operate, but also air pollution. A state-level control is therefore industrial sector electricity price (in 2005 dollars per million BTUs). Availability of land for manure disposal may impact both location decisions and average air pollution. I therefore control for the percentage of the state that is in agricultural land.

[19] Regions are defined according to U.S. Census categories. Western states include Washington, Oregon, California, Montana, Idaho, Wyoming, Nevada, Utah, Colorado, Arizona, and New Mexico. The Midwest includes North Dakota, South Dakota, Nebraska, Kansas, Minnesota, Wisconsin, Iowa, Missouri, Illinois, Indiana, Ohio, and Michigan. The South includes Texas, Oklahoma, Arkansas, Louisiana, Mississippi, Alabama, Tennessee, Kentucky, West Virginia, Virginia, Maryland, Delaware, North Carolina, South Carolina, Georgia, and Florida. The North includes Pennsylvania, New Jersey, New York, Massachusetts, Rhode Island, New Hampshire, Vermont, Maine, and Connecticut.

Technological efficiency variables

More technologically advanced operations may have both more hogs and be better at controlling air pollution. At the county level I control the amount spent on feed purchases divided by the amount spent on livestock purchases (in 2005$). At the state level I control for the number of farms (of any type) per square mile. Larger farms are expected to be more technologically efficient and therefore may better control air pollution.

Agglomeration variables

Agglomeration economies for hog production could be correlated with more dense populations, and therefore yield higher air pollution. Densely populated places may have more human waste per square mile of land and more air pollution. Hence, a population density variable is included. Agglomeration could also be associated with changes in vehicle use. In order to control for this, I include a state-level variable on highway fuel usage per square mile of state land.

In the event that livestock operation movement is systematically correlated with another industry's movement, and this other industry affects air pollution, then the coefficient on livestock may be capturing the effects of the other industry. While the literature makes no suggestion of a link between hog farming and any other specific industry, I control for the number of establishments per square mile in 6 other industries. These industries are manufacturing, utilities, wholesale trade, construction, mining, and transportation.

Climate

A number of geologic and weather variables may affect the concentrations of pollution from animal feedlots in the ambient air, and also may be choice variables in location decisions. While many of these will be captured in the fixed effects, I control for time-varying confounders. Certain pollutants react with water in the atmosphere to form acidic compounds, so I control for precipitation and temperature.

Air Pollution Regulation

To control for air pollution regulation that may be correlated with hog production, I include an indicator for whether or not the county has failed to achieve any ambient air quality standard set under the Clean Air Act. Under Title I of the CAA, individual counties that do not attain a specific level of ambient air quality face increased regulatory action (see Greenstone, 2002, for a fuller description). While regulatory action appears relatively consistent in relation to certain air pollutants (see examples for ozone in Henderson, 1996, and for particulate matter in Chay and Greenstone, 2005), the same is not the case for others (see Greenstone, 2004, for specifics on uncertain regulatory activity surrounding SO2). County-level air quality regulation under the CAA is a concern if it is coupled with more intense scrutiny of all potentially polluting industry in the area. However, the first direct regulation of air pollution from livestock operations did not occur until 2004 (South Coast Air Quality Management District, 2004) and thus it is unlikely that hog operations would be scrutinized under ambient air quality standards.[20]

Table 2 shows means, standard deviations, and sources for the time-, county-, and state-varying controls. For these variables, I garner data from the U.S. Census, Bureau of Economic Activity, Bureau of Labor Statistics, National Climactic Data Center, and various editions of the Area Resource File. The table provides descriptions of sources and construction of variables.

Results

Table 3 provides results for models employing different sets of confounders in order to test for robustness. The results for SO2 are presented in Models I-V, while those for PM10 are found in Models VI-VII. Models I and VI show results with just the fixed effects, Models II and VII include all time-varying confounders except for the measures of other industries, and Models III and VIII include the other industry variables. Models V and VI show results for 1990 to 2002 to show the

[20] This 2004 regulation was for dairies in Southern California (South Coast Air Quality Management District, 2004).

effect of inclusion of the emissions variable. All models weight observations by square miles in the county.[21]

The results for SO2 show a strongly significant relationship to hog density; with all covariates, an increase of 100 hogs per square mile yields a 0.00087ppm increase in sulfur dioxide for 1980 to 2002. Inclusion of any non-fixed confounders raises the estimate, which remains robust for inclusion of further confounders for 1980-2002. In order to show the effect of inclusion of SO2 emissions separate from the effect of a different time period, I first show results for 1990 to 2002 (Model V). The coefficient for SO2 is much smaller although still strongly significant, suggesting that effects of hog density on sulfur-based air pollution have been declining. The inclusion of the SO2 emissions variable in Model VI does not affect the coefficient on hog density, suggesting that variables necessary to identify the effects of swine production on air pollution have been included already. Because hog production is not included in emissions totals, this variable is uncorrelated with hog density and, as expected, inclusion of the emissions variable does not change the estimated coefficient on hog density.

While coefficients on hog density are not precisely estimated at the national level for prediction of ambient PM10, the striking aspect of Models VI-VII is the positive and significant coefficient on whether or not the state has active NPDES permits in the year. Active water quality regulation of this form is estimated to raise PM10 level by 2.1$\mu g/m^3$ (an 0.08 elasticity). However, this regulation does not have a clear effect on SO2. This is suggestive of water quality regulations encouraging ammonia volatilization. Alternatively, increased water regulation may be coupled with heightened regulation of odor. Lagoon aeration to reduce sulfur-related odor may increase ammonia pollution, hence the effects related to water pollution regulation may reflect heighted odor regulation. The finding of effects on ammonia-related but not sulfur-related pollution also suggests

[21] Results without weighting by square miles produce substantively the same effects.

that reverse causality is not at play. If such was the case, then both pollutants would be affected.

Much debate on estimating emissions from livestock operations surrounds regional heterogeneity of effects. Table 4 shows results by region, covering the same set of models as in Table 3. For SO2, the effects are most precisely estimated for the South; further, this result is consistent over time and robust when controlling for SO2 emissions. As expected, the PM10 results by region are more precisely estimated than at the national level. Further, these results are only precisely estimated after controlling for confounders, another feature expected due to the many gases that can constitute PM10. The South and North display positive effects, while those for the Midwestern and Western regions are not precisely estimated. The results show that an increase of 100 hogs per square mile yields a 6.7μg/m^3 increase in the North and a 2.0μg/m^3 increase in the South.

While many of the factors that affect both hog production and air pollution are controlled for in the estimation strategy, further consideration of agglomeration economies is necessary. Increased production concentration could be correlated with increased vehicle traffic. If such is the case, the parameter on hog density may actually reflect effects from mobile sources rather than any pollution arising from the hog operations themselves.[22] While the many of the models control for highway fuel use, this may not be perfectly predictive of non-point source air pollution. I therefore control for non-point source emissions of carbon monoxide in subsequent regressions (Appendix Table A.2). Non-point source carbon monoxide emissions represent pollution not only from highway vehicles, but also from farm equipment. The coefficient on hog density does not change, suggesting that effects are not due to increased diesel equipment or vehicular use.

Coupling the regional heterogeneity of effects with the mean densities by region suggests

[22] Alternatively, agglomeration could lead to shorter distances between growers, producers, and markets. This would suggest lower air pollution related to vehicular traffic, and could result in a downward bias in the effect of hogs on sulfur-based pollution.

that the relationship between hog production and air pollution may be non-linear, and that densities in the middle of the distribution exhibit more positive effects than densities at the top of the distribution. Tests for a linear-log functional forms show that hog density's effect on on sulfur-based pollution exhibits "economies of scale" (Table 5, Model IV); increases in density at higher levels do not produce as much pollution as increases at lower densities. The effects on particulate matter do not reveal such concavity. This suggests that larger operations may be able to better control sulfur-based pollution. This could occur if larger operations have the capital to employ lagoon aeration equipment, which reduces hydrogen sulfide but not ammonia. The lack of convexity in the functional form of the relationship between hog density and air pollution suggests that saturation is not occurring at present production levels. The log-log functional form allows for estimation of the elasticity and provides a further robustness check; in Model I of Table 5, a doubling of production causes a 6% increase in sulfur-related air pollution.

One goal of this article is to examine the effect of water quality regulation on air pollution, and therefore I include a time-varying state-level variable. Inclusion of state-time fixed effects is therefore not possible; however, inclusion of such indicators may provide an understanding if unobserved state-level variation is creating bias in the coefficient of interest. I therefore perform the analyses excluding state-level variables but including state-year fixed effects. The concavity of effects on SO2 is more marked in this empirical design which identifies outcomes only using within-state variation. Results (Table 5) show that for SO2, coefficients on hog density are larger when state-year dummy variables are included. This suggests that the coefficient on hog density in Tables 3 and 4 are underestimates, and that unobserved state-level confounders bias downward the effect of hog density on air pollution. This would occur if the unobserved state-level variable is negatively (positively) correlated with air pollution but positively (negatively) correlated with hog production. Unobserved state-level regulations that lower both air pollution and hog production would lead to smaller, not larger, coefficients on hog density in the model with state-year fixed effects. This finding implies that state-level environmental regulations unaccounted for in the main estimation strategy are not responsible for the effects of hog production on air pollution. After controlling for unobserved state-level changes in a year, the elasticity between hog density and SO2 air pollution in the log-log functional form is estimated to be 0.10 (Model II); a doubling of hogs in a county leads to a 10% increase in sulfur-related air pollution.[23]

Magnitude and distribution of effects

While the results show statistically significant relationships between air pollution and hog production, interpretation of results is necessary to estimate externality costs. Since portions of the country have seen large increases in production while others have seen declines, consideration of the distribution of effects also sheds light on effects of future concentration. Table 6 presents estimates of the magnitude and distribution of SO2 air pollution effects in counties that saw increases versus decreases in hog density. The 20% of counties that saw increasing production have gains in hog density nearly four times as large as the losses of the 80% of counties that saw declining production. Because the changes in hog density were greater in counties that saw increases than counties that saw decreases, the predicted changes in air pollution were also more marked in these counties. In counties with increases, air pollution is predicted to be 20% higher than it would have been without these increases, while in counties with decreases, it is 4% lower.

Consideration of the population densities provides further insight as to whether increased concentration helped or hurt more individual people. If increased hog density occurred in more densely populated areas, the effects per person overall may increase with concentration. The lower panel of Table 6 shows population density and estimated effects on air pollution weighted by

[23] Tests for whether results are driven by the high-density states of North Carolina and Iowa are found in Appendix Table A.3. For this I use the most restrictive regressions in Table 5 with the state-year fixed effects. Results are consistent when removing North Carolina or Iowa.

population density. Both types of counties have similar population densities, so weighting does not substantially alter predictions.

The size of the effects can also be compared to the estimates in Greenstone (2003) and Chay and Greenstone (2005) of the effects of CAA "attainment" status. For SO2, an estimated effect of the CAA is 0.0052ppm,[24] and for particulate matter the effect is $10\mu g/m^3$.[25] To "undo" these effects would require 750,000 hogs (for SO2) in an average-sized county. For PM10, the positive effects of the CAA could be reversed through 661,000 hogs in the South or 187,000 hogs in the North.[26] Only four counties attain at least one of these levels, suggesting that this "undoing" is unlikely but possible.[27] This exercise points out that hog operations may have policy-relevant impacts on ambient air pollution, particularly with the trends toward more concentrated production.

To put dollar values on the externality costs requires making several strong assumptions, but the exercise is useful in establishing potential benefits. Externality effects associated with air pollution include loss of property value, deterioration in human health, damage to crops, and loss of worker productivity. To consider all of these factors, I use benefit estimations from the reductions in air pollution attained through the Clean Air Act. This yields externality costs per county per year of $33 per hog.[28]

Multiple methods exist to reduce air pollution from swine facilities, including biofilters,

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[24] Greenstone (2003) finds an effect of the CAA on SO2 between 0.0014 and 0.009ppm for the 1987-1992 period (p. 605). If a county is in "nonattainment" for SO2 under the CAA, the decrease in SO2 is estimated to be between 0.0014 and 0.009ppm. While Greenstone offers estimates from other time periods, I choose this one to better reflect that of this article (1980-2000). I use the mean of these two estimates for comparison. Greenstone strongly points out that the coefficients estimated are largely not statistically significant.

[25] Chay and Greenstone (2005) provide estimates for total suspended particulates (TSPs) rather than PM10. PM10 is a non-constant subset of TSPs.

[26] The average size of a county is 1,265 square miles. To "undo" CAA regulations would require 598 hogs per square mile for SO2, and 526 hogs per square mile in the South or 149 hogs per square mile in the North for PM.

[27] The three counties (with years) with greater than 878,000 hogs are Bladen (2001 onward), Duplin (1992 onward), and Sampson (1992 onward) Counties in North Carolina. These counties also exceed 661,000 for the years listed. Lancaster County, Pennsylvania, exceeds the 167,000 hogs between 1980 and 2002 and is in the North. None of these counties were in "nonattainment" for any pollutant between 1980 and 2005.

[28] The EPA (1999) estimates total annual benefits of the Clean Air Act to be $77,500M (inflated to 2005$); with 3,143 counties in the U.S., this yields $24.7M per county. If we allow that it takes 750,000 hogs in a county to "undo" the CAA, then this yields a per hog externality cost of $33 per hog.

changes in feed, landscaping, and lagoon covers (Powers, 2004a and 2004b). However, not all of these strategies are useful in reducing both hydrogen sulfide and ammonia, or in simultaneously reducing water pollution. In the case of liquid manure management, the strategy that appears best at reducing both gases (as well as odors) is the impermeable lagoon cover. The cost of an impermeable lagoon cover per hog is estimated to be between $2 and $11.[29] Comparing the externality costs per hog to the cost of the lagoon cover suggests that substantial societal gains could be had by requiring impermeable lagoon covers.

Lagoon covers may limit air emissions but will require that more land be used for nitrogen application. Reducing air-based nitrogen (ammonia) means that more nitrogen must be applied to soil (Aillery et al., 2005). How much more land required will depend on how much ammonia is currently emitted. Lagoon covers as well as land application limits would need to be adopted to avoid excessive pollution in all media.

Discussion and Conclusions

The results provide the first evidence (to the author's knowledge) on a national, longitudinal scale that hog production is correlated with ambient air pollution. The results show that a doubling of production in a county yields a 10% increase in sulfur-related pollution. Production at levels high enough to undo the positive effects of the Clean Air Act are already present in certain North Carolina counties, and may become more prevalent as the industry becomes more concentrated. Counties that saw increases in hog production between 1980 and 2002 saw pollution levels that were 20% higher than would have been realized in the absence of increased production.

Externality costs per hog per year are estimated to be $33. This is three times the size of the cost of an impermeable lagoon cover, which could be used to limit hydrogen sulfide, ammonia, and

[29] Massey et al. (2003) estimate that an impermeable lagoon cover costs $.72 to $3.41 per hundredweight. Assuming that an average-sized hog is 300 lbs., and updating to 2005 dollars, this yields a per hog cost of $2.30 to $10.80.

odor emissions. This does not, however, account for additional expenses associated with further land costs needed for the larger amount of nitrogen in the manure.

Examination of results by region show significant differences in effects of hog production on air pollution, suggesting that regional production techniques have heterogeneous effects. Further, non-linear effects suggest that areas with the highest concentrations of hogs may be better at limiting air pollution.

Increased water quality regulation of hog production is positively associated with air pollution for ammonia-related, but not sulfur-related, pollution. Water regulations encourage producers to leave manure in lagoons so that more nitrogen is volatized, thereby leaving less nitrogen to run off fields. This will increase ammonia pollution but not sulfur pollution.

The results presented here document that hog production significantly contributes to ambient air pollution and therefore should be regulated in the same manner as similar industrial polluters. Further, the findings lend themselves to debates on the scale of the issue from a national perspective. However, more detailed exploration is necessary to evaluate emissions from different production processes and manure management techniques. In light of these results, the EPA's current use of resources to gather emissions data on livestock facilities is certainly warranted. The pointed efforts to establish emissions amounts from livestock production reflect the fulfillment of much-needed research. The differential findings by pollutant and the interactions with water pollution regulation suggest that air pollution regulations of swine production need to be written carefully and should take into consideration multiple pollutants.

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Table 1: Summary Statistics for Hog Density and Air Pollution Measures

	Time period					
	1980-2002	**1980-1984**	**1985-1989**	**1990-1994**	**1995-1999**	**2000-2002**
Average hogs per square mile	33.8	39.4	37.3	31.1	29.8	27.3
	(81.2)	(70.7)	(70.6)	(68.3)	(98.9)	(106.7)
Average hogs per square mile -- Western states	1.4	2.0	1.4	1.2	0.9	1.1
	(2.7)	(3.6)	(2.6)	(2.4)	(2.0)	(2.1)
Average hogs per square mile -- Midwestern states	62.8	76.8	74.7	57.9	47.7	40.2
	(86.6)	(93.8)	(93.0)	(76.5)	(78.8)	(76.7)
Average hogs per square mile -- Southern states	18.1	16.5	14.4	16.8	22.4	22.6
	(79.7)	(30.8)	(33.8)	(62.4)	(120.4)	(129.4)
Average hogs per square mile -- Northern states	16.2	18.6	15.0	14.9	15.1	20.9
	(42.5)	(40.7)	(37.5)	(41.9)	(43.6)	(52.8)
Average SO2 (ppm)	0.0068	0.0080	0.0076	0.0067	0.0051	0.0045
	(0.0044)	(0.0053)	(0.0047)	(0.0040)	(0.0027)	(0.0026)
Average PM10 (µg/m^3)	26.8	35.1	35.3	26.2	22.9	22.1
	(9.9)	(12.8)	(12.7)	(7.6)	(6.3)	(5.8)
SO2 emissions per square mile (short tons)	14.1	--	--	15.9	13.0	12.5
	(61.4)	--	--	(71.0)	(55.5)	(49.5)
Percentage of counties in states with any NPDES permits	0.14	0.08	0.09	0.13	0.18	0.32
	(0.34)	(0.27)	(0.28)	(0.34)	(0.38)	(0.47)

Notes: Standard deviations shown in parentheses. There are no PM10 observations before 1982, so the mean for 1980-1984 shows data for just 1982-1984. Data exclude missing observations for hogs which may potentially be zero values. See text for description. Data on average emissions of SO2 only available between 1990 and 2002.

Table 2: Means, Standard Deviations, and Sources of County- and State-Level Confounders that Vary Over Time, 1980-2002

	Mean	Standard deviation	Source and Description
County- and time-varying confounders			
Per capita income (2005$)	$22,390	4,964	Bureau of Economic Analysis Regional Economic Accounts Local Personal Income Table CA1-3. http://www.bea.gov/regional/reis/
Population density (people per square mile)	110.8	279.3	Constructed from variables from the U.S. Census Bureau and the 2006 Area Resource File. Population size comes from the U.S. Census Bureau's Age-Sex-Race files for 1980 to 2002. http://www.census.gov/popest/estimates.php. Land area in square miles comes from the Area Resource File.
Unemployment rate	6.8	3.3	Bureau of Labor Statistics Local Area Unemployment Rates. http://www.bls.gov/LAU/
Poverty rate	15.8	6.9	From the Area Resource File, a data set compiled by the U.S. Dept. of Health and Human Services. The original source is the U.S. Census Small Area Income and Poverty Estimates.
% Population over 65	14.7%	4.0%	Constructed from U.S. Census Bureau Age-Sex-Race files. See above.
Number of building permits per square mile	0.67	2.00	U.S. Bureau of the Census. http://censtats.census.gov/bldg/bldgprmt.shtml. Data for 1990-2002 downloaded; data for 1980-1989 obtained via U.S. Census Bureau.
Annual precipitation (inches)	39.2	14.1	U.S. Historical Climate Network. http://cdiac.ornl.gov/epubs/ndp019/ndp019.html. Individual month and monitor data were averaged by county and year. When data were not available for specific county, the county was assigned the values for the state climate division.
Mean annual temperature (^{0}F)	54.8	7.3	
Construction establishments per square mile	0.25	0.61	1980 to 2002 Annual County Business Patterns. Data for years 1986 to 2002 downloaded from http://www.census.gov/epcd/cbp/index.html. Data prior to 1986 were obtained through the National Archives. County Business Pattern data switches from a Standard Industrial Classification (SIC) system to the North American Industrial Classification System (NAICS) in 1998. To convert data for 1998 to 2002 to SIC codes, I use the "crosswalk" at http://www.census.gov/epcd/ec97brdg/index.html.
Manufacturing establishments per square mile	0.15	0.46	
Utilities establishments per square mile	0.02	0.05	

Wholesale trade establishments per square mile	0.18	0.61	
Transportation and warehousing establishments per square mile	0.05	0.13	
Mining establishments per square mile	0.02	0.05	
Feed efficiency (2005$)	$1.79	$1.49	Dollar amount spent on feed purchases divided by dollar amount spent on livestock purchases. Disaggregation by animal type is not possible. Both variables come from the Bureau of Economic Analysis Regional Economic Accounts, Local Area Personal Income, Farm Income and Expenses, Table CA35.
Not in attainment of Clean Air Act for at least one criteria pollutant	11.8%	32.2%	1980 to 2000 Green Book. The Green Book lists all counties in "nonattainment" for the criteria pollutants. The Green Book each year is published in the Code of Federal Regulations (Title 40, pt. 81, subsection C).
State - and time-varying confounders			
Percentage of land in state in farms	0.06%	0.03%	Number of farm acres divided by number of acres of land in state. Does not distinguish between types of farms. Constructed from state-level measures from the U.S. Dept. of Agriculture's National Agricultural Statistics Service.
Number of farms per square mile	145	110	From state-level data from the U.S. Dept. of Agriculture's National Agricultural Statistics Service.
Electricity price (2005$) ($/million BTU)	$20.16	$5.79	Energy Information Administration. http://www.eia.doe.gov/emeu/states/_seds.html. Energy price is for industry.
Highway fuel use per square mile (1,000s of gallons)	5,854	4,949	U.S. Dept. of Transportation Federal Highway Administration. http://www.fhwa.dot.gov/policy/ohpi/hss/index.cfm. Data for 1980-1995 are from Highway Statistics Summary to 1995 Table MF-226. Data for 1995-2002 are from Highway Statistics Section I: Motor Fuel Table MF-21.

Note: All statistics exclude Hawaii, Alaska, and D.C. and observations with zero values for hogs.

Table 3: Effects of Hog Density and Water Pollution Region on Ambient Air Pollution

	I	II	III	IV	V	VI	VII	VIII
	Dependent Variable							
	SO2 (ppb)	SO2 (ppb)	SO2 (ppb)	SO2 (ppb)	SO2 (ppb)	PM10 (µg/m^3)	PM10 (µg/m^3)	PM10 (µg/m^3)
	Years							
	1980-2002	1980-2002	1980-2002	1990-2002	1990-2002	1980-2002	1980-2002	1980-2002
Hogs/Square Mile	0.00745***	0.00821**	0.00871**	0.00297*	0.00335**	0.0000535	0.00732	0.0105
	(0.0023)	(0.0036)	(0.0038)	(0.0016)	(0.0016)	(0.010)	(0.0096)	(0.012)
Percentage of state land in farms		-22.79	-29.78	-686.0*	-93.14		-504.5	-597.4
		(77.4)	(86.5)	(349)	(190)		(585)	(466)
Farms per square mile		-0.0320	-0.0428	-0.0152	-0.00507		0.0839	0.0748
		(0.021)	(0.025)	(0.027)	(0.022)		(0.075)	(0.072)
Any NPDES permits listed in state (Yes = 1)		-1.526***	-1.509***	0.850*	0.589		2.503**	2.180**
		(0.52)	(0.55)	(0.43)	(0.40)		(0.96)	(0.95)
Not in attainment under Clean Air Act		-1.850	-1.758	-3.821	-4.146*		-4.988***	-4.533**
		(1.80)	(1.97)	(2.54)	(2.18)		(1.79)	(2.02)
SO2 emissions per square mile (short tons)					0.0120**			
					(0.0047)			
Other industry levels?[a]	N	N	Y	Y	Y	N	N	Y
Other county covariates?[b]	N	Y	Y	Y	Y	N	Y	Y
Other state covariates?[c]	N	Y	Y	Y	Y	N	Y	Y
County and year fixed effects?	Y	Y	Y	Y	Y	Y	Y	Y
Adjusted R-squared	0.668	0.687	0.69	0.728	0.741	0.739	0.735	0.74
Observations	31,659	25,527	24,624	10,123	7,731	25,513	21,760	20,964

Notes: Robust standard errors shown in parentheses. Standard errors clustered by state. Observations weighted by number of square miles in county. * refers to significance at the 10% level. ** refers to significance at the 5% level. *** refers to significance at the 1% level. SO2 is in part-per-billion instead of the usual parts-per-million in order to show the coefficients.

[a]Refers to the number of establishments per square mile for 6 different industries; for listing see Table 2.

[b]County covariates refers to mean temperature, precipitation, ln(per capita income), poverty rate, population density, number of building permits per square mile, percentage of population over 65, feed efficiency, and unemployment rate.

[c]Refers to gallons of highway fuel per square mile and industrial electricity cost.

Table 4: Effects of Regional Hog Density and Water Pollution Regulation on Ambient Air Pollution

	I	II	III	IV	V	VI	VII	VIII
	Dependent Variable							
	SO2 (ppb)	SO2 (ppb)	SO2 (ppb)	SO2 (ppb)	SO2 (ppb)	PM10 ($\mu g/m^3$)	PM10 ($\mu g/m^3$)	PM10 ($\mu g/m^3$)
	Years							
	1980-2002	1980-2002	1980-2002	1990-2002	1990-2002	1980-2002	1980-2002	1980-2002
(West = 1)*(Hogs/Square Mile)	0.806***	1.066**	1.139*	-0.901	-0.263	0.235	0.206	0.210
	(0.26)	(0.49)	(0.58)	(0.65)	(0.91)	(0.26)	(0.15)	(0.15)
(Midwestern = 1)*(Hogs/Square Mile)	0.0102	0.0238**	0.0255**	-0.0218	-0.0326	-0.0327	-0.0405	-0.0419
	(0.0079)	(0.011)	(0.012)	(0.014)	(0.019)	(0.029)	(0.031)	(0.028)
(South = 1)*(Hogs/Square Mile)	0.00625***	0.00468**	0.00480***	0.00387***	0.00433***	0.00656	0.0150	0.0199**
	(0.0020)	(0.0017)	(0.0015)	(0.0012)	(0.0013)	(0.011)	(0.010)	(0.0088)
(North = 1)*(Hogs/Square Mile)	0.0123	0.0112	0.0118	0.0108**	0.0113*	0.0361	0.0682**	0.0673**
	(0.018)	(0.016)	(0.017)	(0.0053)	(0.0058)	(0.033)	(0.029)	(0.031)
Any NPDES permits in state		-1.846***	-1.829***	1.050**	0.667		2.396**	2.073**
		(0.63)	(0.65)	(0.42)	(0.44)		(0.94)	(0.93)
SO2 emissions per square mile (short tons)					0.0117**			
					(0.0048)			
Other industry levels?[a]	N	N	Y	Y	Y	N	N	Y
Other county covariates?[b]	N	Y	Y	Y	Y	N	Y	Y
Other state covariates?[c]	N	Y	Y	Y	Y	N	Y	Y
County and year fixed effects?	Y	Y	Y	Y	Y	Y	Y	Y
Adjusted R-squared	0.669	0.69	0.693	0.73	0.742	0.739	0.735	0.74
Observations	31,659	25,527	24,624	10,123	7,731	25,513	21,760	20,964

Notes: Robust standard errors shown in parentheses. Standard errors clustered by state. Observations weighted by number of square miles in county. * refers to significance at the 10% level. ** refers to significance at the 5% level. *** refers to significance at the 1% level. SO2 is in part-per-billion instead of the usual parts-per-million in order to show the coefficients.

[a]Refers to the number of establishments per square mile for 6 different industries; for listing see Table 2.

[b]County covariates refers to attainment status under Clean Air Act, mean temperature, precipitation, ln(per capita income), poverty rate, population density, number of building permits per square mile, percentage of population over 65, feed efficiency, and unemployment rate.

[c]Refers to number of farms per square mile, percent of state land in farms, gallons of highway fuel per square mile, and industrial electricity cost.

Table 5: Non-Linear and Within-State Effects of Regional Hog Density on Ambient Air Pollution, 1980-2002

	I	II	III	IV	V	VI	VII	VIII
	Dependent Variable							
	ln(SO2)	ln(SO2)	SO2 (ppb)	SO2 (ppb)	ln(PM10)	ln(PM10)	PM10 (μg/m^3)	PM10 (μg/m^3)
ln(Hogs/Square Mile)	0.0617**	0.102***	0.369**	0.611***	0.000286	0.00620	-0.332	0.0347
	(0.027)	(0.027)	(0.16)	(0.14)	(0.011)	(0.012)	(0.46)	(0.45)
Any NPDES permits in state	-0.499**		-1.741***		0.0289*		2.333***	
	(0.19)		(0.53)		(0.017)		(0.81)	
Other industry levels?[a]	Y	Y	Y	Y	Y	Y	Y	Y
County covariates?[b]	Y	Y	Y	Y	Y	Y	Y	Y
State covariates?[c]	Y	N	Y	N	Y	N	Y	N
State*time fixed effects?	N	Y	N	Y	N	Y	N	Y
County and year fixed effects?	Y	Y	Y	Y	Y	Y	Y	Y
Adjusted R-squared	0.762	0.770	0.691	0.839	0.781	0.810	0.740	0.777
Observations	24,624	24,624	24,624	24,624	20,964	20,964	20,964	20,964

Notes: Robust standard errors shown in parentheses. Standard errors clustered by state. * refers to significance at the 10% level. ** refers to significance at the 5% level. *** refers to significance at the 1% level. SO2 is in part-per-billion instead of the usual parts-per-million in order to show the coefficients.

[a]Refers to the number of establishments per square mile for 6 different industries; for listing see text.

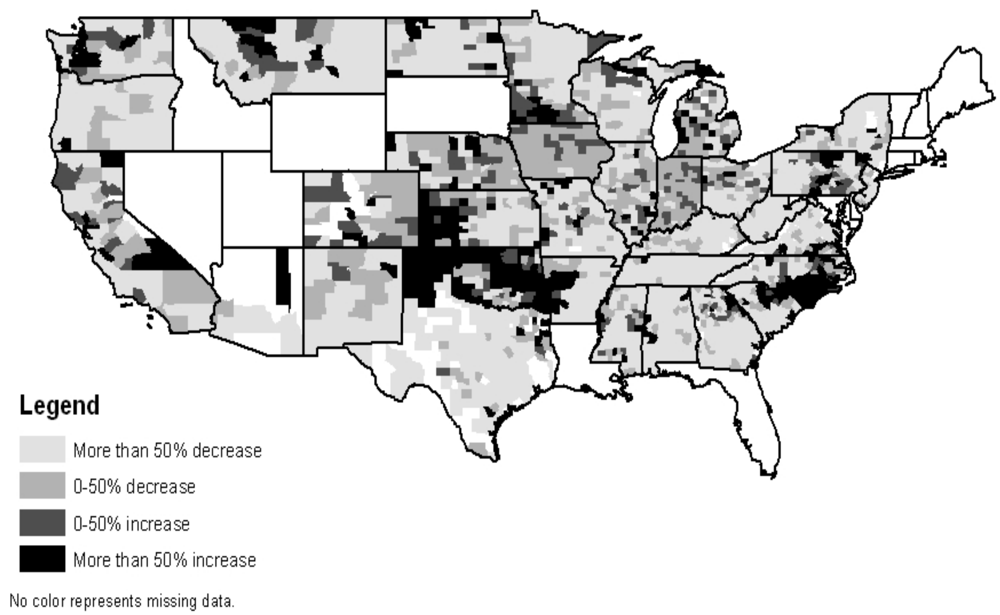
[b]County covariates refers to nonattainment status under Clean Air Act, mean temperature, precipitation, ln(per capita income), poverty rate, population density, number of building permits per square mile, percentage of population over 65, feed efficiency, and unemployment rate.

[c]Refers to percent of state land in farms, number of farms per square mile, gallons of highway fuel per square mile, and industrial electricity cost.

Table 6: Magnitude and Distribution of Effects

	Counties with increasing hog density, 1980-2002	Counties with decreasing hog density, 1980-2002
Percentage of counties	20%	80%
Percentage of square miles	19%	81%
Average change in hog density (hogs/sq.mile), weighted by square miles	41.21	-12.74
Actual average change in SO2 (ppm)	-0.0021	-0.0026
Change in SO2 predicted due to change in hog density (ppm)	0.0004	-0.0001
Change in SO2 without change in hog density (ppm)	-0.0025	-0.0025
Alternative as percentage of actual	120%	96%
Average population density, 1980-2002	103	113
Predicted change in SO2 (ppm), weighted by population density	0.0003	-0.0001

Figure 1: Percentage Change in Number of Hogs by County, 1980-2002



Appendix Table A.1: Effects of Air Pollution Variables on Adoption of Water Pollution Regulation, 1980-2002

	I	II	III	IV	V	VI
			Dependent Variable			
	NPDES Enforced	NPDES Enforced	NPDES Enforced	NPDES Enforced	NPDES Enforced	NPDES Enforced
Not in attainment of at least one criteria air pollutant standard	-0.00852	0.00861				
	(0.0347)	(0.0323)				
Not in attainment of SO2 standard			0.0104	0.00481		
			(0.0988)	(0.0885)		
Not in attainment of PM10 standard					-0.00964	-0.00928
					(0.0323)	(0.0351)
Other industry levels?[a]	N	Y	N	Y	N	Y
Other county covariates?[b]	N	Y	N	Y	N	Y
Other state covariates?[c]	N	Y	N	Y	N	Y
County and year fixed effects?	Y	Y	Y	Y	Y	Y
Adjusted R-squared	0.668	0.696	0.669	0.696	0.669	0.696
Observations	51,862	40,044	51,862	40,044	51,862	40,044

Notes: Robust standard errors shown in parentheses. Standard errors clustered by state. Unit of observation is the county-year. * refers to significance at the 10% level. ** refers to significance at the 5% level. *** refers to significance at the 1% level. SO2 is in part-per-billion instead of the usual parts-per-million in order to show the coefficients.

[a]Refers to the number of establishments per square mile for 6 different industries; for listing see Table 2.

[b]County covariates refers to mean temperature, precipitation, ln(per capita income), poverty rate, population density, number of building permits per square mile, percentage of population over 65, feed efficiency, and unemployment rate.

[c]Refers to number of farms, land in farms, gallons of highway fuel per square mile, and industrial electricity cost.

Appendix Table A.2: Effects of Regional Hog Density and Water Pollution Regulation on Ambient Air Pollution, 1990-2002, Controlling for Non-Poinst Source Carbon Monoxide Emissions

	I	II	III	IV
	Dependent Variable			
	SO2 (ppb)	SO2 (ppb)	SO2 (ppb)	SO2 (ppb)
Hogs/Square Mile	0.00335**	0.00366**		
	(0.0016)	(0.0015)		
Any NPDES permits in state	0.589	0.578	0.667	0.650
	(0.40)	(0.40)	(0.44)	(0.44)
(West = 1)*(Hogs/Square Mile)			-0.263	-0.236
			(0.91)	(0.90)
(Central = 1)*(Hogs/Square Mile)			-0.0326	-0.0292
			(0.019)	(0.018)
(South = 1)*(Hogs/Square Mile)			0.00433***	0.00452***
			(0.0013)	(0.0013)
(North = 1)*(Hogs/Square Mile)			0.0113*	0.0112*
			(0.0058)	(0.0060)
SO2 emissions (short tons) per square mile	0.0120**	0.0128***	0.0117**	0.0125***
	(0.0047)	(0.0044)	(0.0048)	(0.0045)
Non-point source carbon monoxide emissions (short tons) per square mile		-0.00536		-0.00492
		(0.0038)		(0.0036)
Other industry levels?[a]	Y	Y	Y	Y
Other county covariates?[b]	Y	Y	Y	Y
Other state covariates?[c]	Y	Y	Y	Y
County and year fixed effects?	Y	Y	Y	Y
Adjusted R-squared	0.741	0.742	0.742	0.743
Observations	7,731	7,731	7,731	7,731

Notes: Robust standard errors shown in parentheses. Standard errors clustered by state. Observations weighted by number of square miles in county. * refers to significance at the 10% level. ** refers to significance at the 5% level. *** refers to significance at the 1% level. SO2 is in part-per-billion instead of the usual parts-per-million in order to show the coefficients.

[a]Refers to the number of establishments per square mile for 6 different industries; for listing see Table 2.

[b]County covariates refers to mean temperature, precipitation, ln(per capita income), poverty rate, population density, number of building permits per square mile, percentage of population over 65, feed efficiency, and unemployment rate.

[c]Refers to number of farms, land in farms, gallons of highway fuel per square mile, and industrial electricity cost.

Appendix Table A.3: Non-Linear and Within-State Effects of Hog Density on Sulfur Dioxide, Excluding North Carolina and Iowa, 1980-2002

	I	II	III	IV	V	VI
	Sample					
	Full Sample	Exclude North Carolina	Exclude Iowa	Full Sample	Exclude North Carolina	Exclude Iowa
	Dependent Variable					
	ln(SO2)	ln(SO2)	ln(SO2)	SO2 (ppb)	SO2 (ppb)	SO2 (ppb)
ln(Hogs/Square Mile)	0.102***	0.0998***	0.102***	0.611***	0.578***	0.611***
	(0.0271)	(0.0278)	(0.0272)	(0.138)	(0.169)	(0.138)
Other industry levels?[a]	Y	Y	Y	Y	Y	Y
County covariates?[b]	Y	Y	Y	Y	Y	Y
State*time fixed effects?	Y	Y	Y	Y	Y	Y
County and year fixed effects?	Y	Y	Y	Y	Y	Y
Adjusted R-squared	0.839	0.842	0.839	0.770	0.774	0.770
Observations	24,624	23,572	24,402	24,624	23,572	24,402

Notes: Robust standard errors shown in parentheses. Standard errors clustered by state. * refers to significance at the 10% level. ** refers to significance at the 5% level. *** refers to significance at the 1% level. SO2 is in part-per-billion instead of the usual parts-per-million in order to show the coefficients.

[a]Refers to the number of establishments per square mile for 6 different industries; for listing see text.

[b]County covariates refers to nonattainment status under Clean Air Act, mean temperature, precipitation, ln(per capita income), poverty rate, population density, number of building permits per square mile, percentage of population over 65, feed efficiency, and unemployment rate.