JOB MARKET PAPER

Concentrated Livestock Farming, Groundwater and Air Pollution, and Infant Health: An Econometric Analysis

Stacy Sneeringer*
University of California at Berkeley

Incomplete; Do not cite.

November 2, 2004

Abstract

The past two decades have witnessed major shifts in the livestock farming industry. Changes in structure, method, and geographic distribution have spurred lower meat prices, but they have also raised concerns about the public health effects of large, concentrated livestock farms. I exploit the geographic shifts in livestock farming between 1980 and 1999 by analyzing a rich dataset of demographic, livestock, pollution, and hydro-geologic variables in a county fixed effects model. Looking at one measure of public health, infant mortality, suggests that a 100,000 animal unit increase in a county corresponds to between 40 and 60 more deaths per 100,000 births, even after controlling for demographic and socio-economic covariates. I estimate that the change in the distribution of livestock between 1980 and 1999 has been associated with 6,784 additional infant deaths. The paper explores whether this correlation arises from groundwater and air pollution by exploring the linkages between livestock farming and pollution, and then those between pollution and infant health. I find that livestock farming is strongly correlated with nitrogen dioxide and ozone, and weakly correlated with sulfur dioxide and groundwater nitrates. A 100,000 animal unit increase corresponds to a .0018ppm increase in nitrogen dioxide and a .0016ppm increase in ozone. Instrumental variable analysis suggests that much of the change in infant mortality related to increased livestock can be attributed to changes in air pollution. Given these results, regulation aimed at reducing the negative health effects of livestock farms needs to include air pollution measures.

---

* Ph.D. Candidate in Economics. Mailing address: Department of Economics, University of California, Berkeley, 549 Evans Hall #3880, Berkeley, CA 94720-3880. E-mail: sneering@econ.berkeley.edu. I would like to thank David Card, Kenneth Y. Chay, Ronald D. Lee, and David Zilberman for valuable advice. I have also received helpful comments from David S. Lee, Francisco Martorell, Willliam Nazaroff, Elizabeth Weber Handwerker, Jane Herr, Sally Kwak, Laura Chioda, Tanguy Brachet, and seminar participants at the UC Berkeley Labor Seminar and Demography Brown Bag. Special thanks to Robert Kellogg of the Natural Resources Conservation Service of the U.S. Department of Agriculture who provided data for this project. Partial funding was provided by a National Institute for Child Health and Human Development training grant. All mistakes are solely my own.

I. Introduction

The past two decades have witnessed major shifts in the livestock farming industry. New technologies, corporate structures, and the desire to capture economies of scale have led to declines in the number of farms and increases in the average size of livestock farms. Figures 1 and 2 show the number of livestock farms and livestock by animal type over the past several decades, reflecting these trends. These shifts in methods have also allowed for changes in the geographic distribution of livestock farms. Decreasing transportation costs have meant that livestock can now be raised in areas distant from where feed is grown. These changes in structure, methods, and geographic distribution have led to lower meat prices, but have also raised public health concerns surrounding large livestock operations.

Numerous groups have expressed anxiety over the impact of livestock farms on surrounding populations. In January, 2004, the American Public Health Association called for a moratorium on new livestock operations until more could be understood about the effects of livestock farming on infant health (Lawrence and Wallinga, 2004). Several states have temporarily banned further construction of large livestock facilities, and vice-presidential candidate John Edwards has called for this ban to be nation-wide and permanent.

A concentration in the byproducts of animal production accompanies the intensification of livestock farming, and it is these by-products that lead to public health worries. It is now common for a livestock operation to house tens of thousands of animals in indoor pens, producing many times the waste of comparable numbers of humans. A large number of livestock concentrated in a small area leads to a vast amount of excrement in that same area. This concentration leads to two key issues: concern over potential spillage from the facilities used to store animal wastes (so-called "lagoons"); and concern over the impact of high concentration of the processed wastes which are periodically emptied from the lagoons and spread on nearby land.

Anxiety over pollution from livestock farms focuses on contamination of groundwater and air. Nitrogen, one of the main byproducts of livestock farming, can pollute groundwater. Ingestion of two forms of nitrogen, nitrate and nitrite,[1] can lead to human health problems, particularly among pregnant women and infants. Certain gases are associated with livestock farming; these gases have been found to be toxic to humans, and to contribute to overall air pollution levels.

Few studies have documented public health impacts of livestock farms; most focus on the *potential* for health consequences, rather than actual correlations between poor outcomes and animal production. This study tries to answer two questions. First, are there measurable negative public health effects associated with livestock farms? This study analyzes whether poor public health is correlated with increased livestock farming in an area as measured by infant mortality and other reproductive health outcomes. I use a national dataset for 1980 to 1990 with a rich set of information on demographics of mothers, livestock per county, socio-economic characteristics, and housing features. A county and time-period fixed-effects model with state controls allows me to measure whether infant health is correlated with livestock farming, even after controlling for possibly changing demographics. This model exploits changes by county within states to identify effects of livestock farms, thereby controlling for state-level regulations. I find that a 100,000 animal unit increase in a county corresponds to between 60 and 78 more deaths per 100,000 births, and a decreased Apgar score of .44 at the median.

The second question that this study endeavors to answer is whether these negative public health effects are related to pollution arising from livestock farms. The paper explores how much pollution contributes to this finding by analyzing the groundwater and air pollution associated with livestock farming, and the health outcomes associated with this pollution. For this I use water and air quality data garnered from the Environmental Protection Agency (EPA) and the United States Geological Survey (USGS), and control for hydro-geologic covariates in a county fixed-effects model. I find that livestock are strongly correlated with nitrogen dioxide and ozone; a 100,000 animal unit increase corresponds to a .0018ppm increase in nitrogen dioxide and a .0016ppm increase in ozone. Livestock are weakly correlated with sulfur dioxide and groundwater nitrates; at the median, a 100,000 animal unit increase

[1] Nitrate and nitrite are both forms of nitrogen; the chemical differences are described later in the paper. For simplicity, “nitrogen”, “nitrate and nitrite”, and “nitrates” all refer to the same thing.

corresponds to a 4.57mg/L increase in groundwater nitrates and a .00045ppm increase in sulfur dioxide. Instrumental variable analysis reveals that a .0018ppm increase in NO_2 due to a 100,000 animal unit increase yields a .246 increase in the IMR. This finding suggests that much of the negative health related to livestock farms is due to air pollution.

These findings are useful for current policy discussions on regulation of livestock farming. Past federal attempts to minimize negative public health impacts of livestock farming have been via Clean Water Act regulations. Recent discussions center on the air quality impacts of feedlots. Thus, this study helps to explore whether regulatory concerns should turn more towards air pollution. The longitudinal, national scope of the paper also lends itself to policy-minded generalizations. The paper finds that much of the negative effects of livestock farming arise from air pollution, suggesting that more attention needs to be paid to air quality regulations of livestock farms if negative public health effects are to be avoided.

The paper is organized in the following manner. Section two provides background on livestock farming, groundwater and air pollution associated with livestock farming, and the accompanying health effects of this pollution. Section three describes the demographic, farming, groundwater, air quality, and land use data. In section four I analyze the correlation between infant mortality and livestock farming, controlling for demographic characteristics. In section five I examine the empirical connections between livestock farming and pollution, and those between livestock-related pollution and health. The final section discusses the results and policy implications.

II. The Shifting Livestock Industry and Pollution

The past two decades have witnessed major changes in the scale and method of livestock production. For the chief livestock types (cows, hogs, and poultry), the number of farms has decreased over the past two decades, even while the number of animals in inventory has increased or remained constant. These trends suggest that livestock production has become spatially more concentrated, an occurrence documented by several authors (for example, see Kellogg, 2000; Meyer and Schwankl, 2000). Maps 1 and 2 show the number of animal units per square mile by county in 1982 and 1997. Map 3 shows the percent change from 1982 to 1997 in animal units by county. Viewed together, these maps reveal that some areas of the country have experienced declines in animal farming, while others have seen increases. Despite these changes, the most concentrated areas of livestock production have remained in the middle of the country. These trends have led to the current style of livestock farming of large operations raising thousands of animals in industrial-style settings. Table 1 shows the average number of animals by facility in 1997, as well as the average size of the largest farms.

Accompanying the concentration of livestock farming described above is intensification of manure production, which can become an extensive problem if not handled appropriately. Animals each produce far more waste than humans. A single feeder pig annually produces about 3.5 times the amount of solid waste as a human, while a single dairy cow produces about 44 times the amount as a human (Fleming and Ford, 2001). This means that with about 300 million humans and 37 million cows in the U.S., cows produce over 5 times as much waste as humans each year. The total amount of manure produced by cows, hogs, and poultry in 1997 was approximately 880 million tons; this number has been increasing over the past 15 years (scorecard.org, 2004).

Earlier research focus concerning pollution from livestock farms was on groundwater, due to the new methods of manure management that have accompanied the concentration of livestock farming. Liquid manure management has become the operation of choice for many large livestock facilities (USDA, 1996). This method varies by animal type, but always includes mixing the manure with water in order to create a liquid form (slurry). This liquid manure is then flushed into vast open-air pits called “lagoons” which can extend to several acres in size. The bottoms of lagoons are lined with clay or plastic (Bonner et al., 2003), which can crack and leak, enabling slurry to seep into soil and groundwater (EPA, 1998). Older lagoons rely on the “self-sealing” properties of soil. In these situations, it is not a question of whether the lagoons leak, it is how much (Huffman and Westerman, 1995; Barrington and Broughton, 1988; DeTar, 1979). Flooding also poses a problem; while Clean Water Act regulations state that lagoons at the largest farms must be built to endure extensive storms, mass flooding can mean overflowing lagoons.

An oft-used method of disposing of manure in these holding pits is land application. Livestock workers periodically pump out a portion of the excrement in the lagoons and spray this manure onto cover crops such as bermudagrass (Mallin, 2000). The high nitrogen content of manure make it usable as fertilizer; however, crops can only absorb so many nutrients. Additionally, increased specialization of animal farming separates manure from farmland as livestock operations no longer incorporate field cropping (Letson and Gollehon, 1996). In the event where a farm has more usable manure than land (as is often the case with intensive animal operations), farm operators may over-apply waste to land (Hooda et.al., 2000; Hunt et al., 1995). This leaves excess amounts of nutrients on fields; rainfall can wash this excess into surface water and help transport it to groundwater.[2]

While the nitrogen in manure could be used as fertilizer, most crop farmers now use inorganic nitrogen fertilizers instead. The literature suggests several reasons for this preference. The first is spatial mismatch between where manure is produced and where it could be used. A second reason is that the nutrient content of slurry is not uniform, and thus the benefit of application to crops is not uniform. This could lead to over-application of the needed nutrient in some places resulting in crop destruction (Meyer and Schwankl, 2000). A third reason is that slurry contains large amounts of nitrogen and phosphorous in different amounts; meeting the nitrogen needs of a crop through the use of slurry can yield over-application of phosphorous (Lory, 1999).

More recent concern examines the possible air pollution associated with concentrated livestock farms. The concentration of animals in smaller locales may lead to higher concentrations of air pollutants. Pollutant levels below a certain threshold may not be harmful, while those above may be toxic. This belief is reflected in the EPA's national ambient air quality standards, which state that levels below a certain amount are permissible, while those above must be regulated.

Air pollutants arise from livestock farms via lagoons, spray application of manure, drying fecal matter in bars, and from the animals themselves. Bacteria act upon the manure in lagoons in the form of

[2] It should be noted that this is a simplification; the process through which nutrients move to groundwater is complex, depending on soil type, nutrient content of soil, slope of land, nearness to surface water, and depth of aquifer, amongst other things. Rainfall may also dilute the nutrient content of groundwater.

anaerobic digestion, during which process nitrogen-based gases are emitted. Agitation of liquid manure in lagoons, which occurs during pumping and transportation, also leads to the release of gases. Spraying liquid manure can lead to gases emitted into the air as well as the binding of particulates to air. The manure also breaks into gases once it has encountered the ground. The animals themselves and drying manure in barns can also lead to a host of air quality concerns in the forms of particulates, gases, vapors, and odoriferous compounds.

A number of geologic and weather variables may affect the concentrations of pollution from animal feedlots in groundwater and air. The nutrient content of soil can determine the absorption and retention of added nutrients. Additionally, soil texture can affect whether nutrients will flow throw it into groundwater; the more porous the soil, the more likely water will flow through it (Hooda et al., 2000; EPA, 1998). These features can also contribute to whether or not gases are emitted from manure; the more nutrients that are absorbed in soil, the less likely they are to contribute to air quality concerns.

Another factor affecting the amount of nitrogen that reaches groundwater as well as the level of air pollution is precipitation level. Precipitation and air pollution are intimately related in the form of acid rain; certain pollutants react with water in the atmosphere to form acidic compounds. Rainfall can affect how much nutrients are washed from land into soil, as well as the concentration of nutrients in the groundwater. Precipitation levels have been found to be positively correlated with how much nitrate leaches into soil, but negatively correlated with the concentration of nutrients in groundwater (Hooda et al., 2000).

Land use practices have also been found to affect both groundwater and air pollution. Types and density of plants can affect the level of different gases in the air. Crop practices can affect nitrogen leaching. Different types of plants use different amounts of nutrients, thus the type of crops of an area can affect the extent of nitrogen in soil and groundwater. Given this feature, the extent of integration of crop and livestock production can affect nitrogen leaching. Certain regions of the country more frequently balance manure production and nutrient application (Letson and Gellohon, 1996), thus human intervention can reduce groundwater pollution.

Literature on Public Health Effects of Livestock Farming

Only one study attempts to quantify the "reduced form" relationship between public health outcomes and livestock farming. Thu and coauthors (1997) perform a case-control study examining the physical and mental health of 18 residents living near a large-scale swine operation, and compare these to those of demographically comparable individuals not living near a swine farm. The researchers find that neighbors of swine farms are significantly more likely than controls to experience toxic or inflammatory effects on their upper respiratory tracts. However, due to the extremely small sample size, and what appears to be sample selection bias in the treatment group[3], these results are not conclusive.

This paper starts to fill this rather gaping hole in the literature. It provides national, longitudinal analysis and controls for a wide variety of observed and unobserved confounders. Further, the focus on reproductive and infant mortality may provide a better consideration of public health effects than adult outcomes. Adult outcomes may reflect exposure that has occurred at other points in life or at prior areas of residence. Examining infant health does not suffer from these same difficulties. Infants have not had an opportunity to be exposed to livestock in previous time periods, and low migration rates for pregnant women and infant suggest that exposure occurs in the same area as the witnessed outcome.

Given this lack of research, those attempting to demonstrate the possible negative public health consequences of livestock operations focus instead on links between livestock farms and pollution, and pollution and negative health outcomes. The next subsections provide overviews of this research.

Literature on Nitrate Contamination in Groundwater and Related Health Effects

While it is difficult to account for all possible contingencies connecting intensive animal production to groundwater, research has traced a path linking them. Research on the nutrient content of animal waste reveals high levels of nitrogen (Smith and Frost, 2000; Meyer and Schwankl, 2000).

[3] The authors state that the site was selected because "we knew certain neighbors had expressed environmental and health concerns" (p. 15).

Researchers have explored the placement of lagoons with respect to groundwater sources, and found that lagoons are frequently constructed over aquifiers supplying groundwater (Burkart and Simpkins, 1999). Research on nutrient transport through soil below lagoons has found differing degrees dependent on soil type and fullness of the lagoon (Ham, 1998). It is not surprising that researchers have found high nitrogen levels in surface and groundwater near animal feeding operations. The research that comes nearest to that undertaken in this paper is evaluation of groundwater in wells on or near animal production facilities. These are small, region-specific tests of groundwater in the vicinity of livestock farms. Furthermore, they are all observational studies, and many do not specifically look at livestock farming as a possible cause of nitrates in groundwater. The findings have been mixed. Becker, Peter and Masoner (2003) tested 79 high-nitrate wells at hog farms in Oklahoma to find the source of the contamination. They found definite animal waste sources in 10 out of 79 of the wells, and could not exclude animal waste as a source of nitrate in the other 69 wells. Mugel (2002) tested 47 Missouri wells twice in one year to discover whether the wells near poultry CAFOs had higher nitrate than control cases. The author concluded that poultry CAFOs do not affect groundwater quality. The Centers for Disease Control and Prevention (1998) looked at contamination of wells one year after massive flooding in nine Midwestern states. Using 5,500 samples, they found that wells where manure was applied within 100 feet were more likely to show contamination. Gould (1995) tested water from 172 wells on or near livestock farms in Georgia, and found that 30 violated the EPA's maximum contaminant level (MCL) for nitrate (as N). Of these 30 wells, 28 were on farms themselves. Hunt et al. (1995) examined a North Carolina watershed and found nitrogen in ground and surface waters was highest in areas closest to livestock operations.

Once in groundwater, numerous health problems in humans and animals can result from the ingestion of the nutrients in manure. The biggest worry is infant methemoglobinemia. Ingestion of nitrogen can lead to the oxygen-depleted state of cyanosis, particularly in infants. This yields a bluish tinge to the skin, resulting in the term “blue-baby syndrome”.[4] Left unchecked in extreme forms, methemoglobinemia can result in death (Winneberger, 1982), and can be sufficiently unrecognized to go untreated (Wolfe and Patz, 2002). Cures for the syndrome include methylene blue and treatment with oxygen (Winneberger, 1982).

A review by Fan and Steinberg (1996) outlines all cases of methemoglobinemia reported worldwide between 1941 and 1995; most of these cases resulted from the consumption of groundwater nitrates. Fan and Steinberg also summarize the five epidemiologic studies performed studying the link between infant health and nitrate in drinking water. These observational studies in different parts of the world show positive correlations between infant death and consumption of nitrates.

The one epidemiologic study on well-water nitrates and infant methemoglobinemia looks at 486 infants in Namibia and finds a positive correlation between high nitrate areas and methemoglobinemia (Super et al., 1981). These authors take blood samples from all of the newborns to test for methemoglobin levels, as well as water samples from all wells in the area to test for nitrates. They find that infants consuming high-nitrate water had markedly higher methemoglobin levels.

Aside from methemoglobinemia, other possible effects of nitrates have also been documented. A review by Wolfe and Patz (2002) found that long-term ingestion of nitrates was indicated in adult cases of bladder, stomach, ovarian, and liver cancers, as well as adult central nervous system tumors. The Centers for Disease Control (1996) suggested that nitrate-contaminated well-water was responsible for elevated rates of spontaneous abortion in humans.

The health effects of nitrate have also been documented in animals. Medical studies on rats have found that exposure of pregnant rats to nitrite leads to stunted growth of offspring and infant mortality (see Fan and Steinberg, 2002). Livestock are also affected by nitrates in fashions similar to those experienced by humans, a fact known amongst livestock veterinarians (Hovingh, 2004; Hutchinson, 2004; Hillman, 2002).

[4] The “blue baby syndrome” of methemoglobinemia occurs in infants some time after birth. Other conditions also result in infants with blue-tinged skin, most notably Rh sensitivity; this occurs when the mother’s blood is Rh-negative and that of the fetus is Rh-negative. Infants born under these circumstances may appear blue at birth.

Literature on Air Pollution from Livestock Operations and Related Health Effects

An extensive number of studies have examined the level and types of gases emitted by livestock facilities (see Hoff et. al., 2002 for a review). Particulate matter arises from fecal matter, feed dust, skin cells, and the decomposition of manure in storage. Myriad gases, vapors, and volatile organic compounds (VOCs) are associated with livestock farms; chief among them are hydrogen sulfide and ammonia. Additionally, livestock are a significant contributor of greenhouse gases such as methane and nitrogen dioxide. Through chemical processes, methane, VOCs, and nitrogen dioxide can create ozone.

Experiments with lab animals and studies on livestock have shown the effects of different gases emitted from livestock operations, particularly hydrogen sulfide and ammonia (see Carson, et al., 2002, and Holland, et. al., 2002, for reviews). Depending on level, frequency, and duration of exposure, these gases create different degrees of damage, particularly to the respiratory system. Prolonged exposure to ammonia can lead to lesions and inflammation in the upper respiratory tract.

Human health effects associated with hydrogen sulfide and ammonia have followed the symptomatology seen in laboratory animals and livestock (see Merchant et al., 2002, for a review). These studies are mostly on workers in different industries that are exposed to hydrogen sulfide and ammonia in the course of employment. Hydrogen sulfide exposure is associated with respiratory symptoms, headaches, and an elevated spontaneous abortion rate. The studies examining the effects of these gases of non-workers in the vicinities of the emissions found similar effects. Infants exposed to hydrogen sulfide had increased occurrence of respiratory infection.

Finally, studies examining health problems in and around livestock facilities without measuring air quality have found elevated occurrences of respiratory problems. A review piece by Donham (2002) covered the effects of indoor air pollution inside swine operations, finding that workers suffered from hydrogen sulfide poisoning and respiratory problems.

While the focus of gases from livestock operations is predominantly on hydrogen sulfide and ammonia, volatile organic compounds, a precursor to ozone, are also highly associated with livestock facilities. Ozone is also associated with irritation of the respiratory system (EPA, 1994). Additionally, ammonia converts to nitrogen dioxide (NO_2), and hydrogen sulfide converts to sulfur dioxide (SO_2); both NO_2 and SO_2 are also gases associated with respiratory problems. A number of studies have examined associations between these NO_2 and SO_2 and reproductive health. SO_2 has been associated with increased incidence of low birth weight and prematurity (Liu et al., 2003; Wang et al., 1997; Maisonet et al., 2001; Xu, Ding, and Wang, 1995). NO_2 has been associated with intrauterine growth retardation (Liu et al., 2003). Other studies have found no discernible relationship between NO_2 and "pre-birth" outcomes (Currie and Neidell, 2004; Ritz et al., 1999), but some evidence of a positive association between NO_2 and infant mortality (Currie and Neidell, 2004).

While certain symptoms are correlated with air pollution, there is still debate regarding the causal mechanism relating air pollution to infant and reproductive health. Gases are thought to damage tissues and constrict bronchial pathways, leading to reduced lung function. The tissue damage is also believed to make the exposed more susceptible to other infections.

These studies relating livestock farming to groundwater and air pollution, and these forms of pollution to negative health consequences, provide suggestive evidence as to possible public health outcomes associated with livestock farms. These studies generally find some linkage between animal production and pollution or pollution and health, but they all suffer from possible omissions of factors that could affect results, and thus are not generalizable to larger policy discussions. To begin, the studies are all region-specific; however, due to soil type, cropping practices, or a variety of other factors, what is true for one region may not be true for another. The studies for the most part are not longitudinal, and thus cannot account for possible changes over time. This paper attempts to correct many of these problems using a national, longitudinal dataset while controlling for unobserveable characteristics contaminating the relevant correlations.

IV. Data on Livestock Farming, Infant Mortality, and Groundwater and Air Quality

In order to evaluate the relationships between livestock farming, infant health, and pollution, I require data on animal numbers, natality, mortality, groundwater and air quality, and other factors that could mitigate any of these relationships. Compiling these needs creates a rich dataset with information from a variety of sources.

Information on livestock numbers and number of concentrated animal farms comes from a dataset created by Robert Kellogg at the National Resource Conservation Service (NRCS). Dr. Kellogg created this dataset using the 1982, 1987, 1992, and 1997 Censuses of Agriculture. Public-use data by county from the Census of Agriculture is censored when it is possible to discern specific farms within the county. As livestock operations have become increasingly concentrated, the observations by county have been increasingly censored.[5] Thus it is important to use data without this impediment.[6]

Restricted-use birth and death records from the National Center for Health Statistics (NCHS) provide the health and mortality data for 1980 to 1999. The NCHS's unrestricted public use natality and mortality files after 1988 are censored when the birth or death occurred in a county with less than 100,000 inhabitants. This amounts to a serious problem, as approximately a quarter of all births are censored in each year. Because I expect the largest effects from livestock farming will occur in rural and therefore less populated counties, censoring such counties would suggest a biased picture. Hence, the paper uses restricted-use data in which all counties are enumerated.

Because they arise from birth records, the natality data also include information on education of mother, age of mother, race, number of prenatal visits, birth history, as well as some information on the father. The paper uses U.S. Census and Bureau of Economic Activity data to control for socio-economic variables at the county level not available on the birth and death records, including per capita income and farm employment by county.

Water quality data come from the EPA's Storage and Retrieval (STORET) Legacy and regular

[5] In this situation, "censoring" means that the data is denoted as censored and "blacked out". The observation is not omitted from the sample.
[6] A full description of this appears in Kellogg, Lander, Moffitt, and Gollehon (2000). In order to provide more anonymity for individual farms, the data I have received has units of observation that sometimes contain more than one county.

datasets[7] and the United States Geological Survey's online National Water Inventory Survey (NWISWeb). These national datasets provide all observations on groundwater quality made in the contiguous United States between 1980 and 1999 (inclusive). Combining the data from both sources provides a dataset with over 460,000 individual water quality observations.[8] The analyses in this paper use data from two main water quality tests of groundwater nitrogen.[9] These two tests are unfiltered nitrate plus nitrite (mg/L as N) and filtered nitrate plus nitrite (mg/L as N).[10] Additionally, the EPA's maximum contaminant level (MCL) is set for unfiltered nitrate plus nitrite, making focus on this test relevant for policy.[11] In order to create a more representative sample for groundwater quality, I combine the data for unfiltered and filtered nitrate plus nitrite.[12]

Air quality observations come from the EPA's Air Quality System (AQS). These are annual summaries of different pollutants from fixed monitors. The observations include the state and county of the monitor, the number of observations, and the mean value. These monitors observe the ambient levels of specific "criteria" air pollutants, of which the EPA has defined only six. The ideal gases to study in terms of public health effects of air pollutants from livestock farms are hydrogen sulfide and ammonia. However, monitoring of these gases is not performed on a consistent, nationwide basis. Despite this, three of the criteria air pollutants are related in particular to livestock farms. These gases are nitrogen

[7] Legacy STORET was used for data from 1980-1998. The regular online STORET was used for data from 1999.

[8] In order to check for overlap between STORET and the NWISWeb, I attempted to match observations on the county, the latitude and longitude degree and minute, the date, the parameter, and the value of the observation. This resulted in 384 overlapping observations for unfiltered or filtered nitrate plus nitrite.

[9] Attempts to create a similar datasets for fecal coliform and total coliform bacteria yielded an extremely small, non-representative sample.

[10] Additionally, the two organizations employ different naming techniques. The EPA distinguishes much of its nutrient data between "total" versus "dissolved" measures. The USGS, on the other hand, uses "unfiltered" and "filtered". "Total" and "unfiltered" identify the same thing, as do "dissolved" and "filtered". This paper uses the terms "filtered" and "unfiltered".

[11] While other tests of groundwater nitrogen do exist, they are employed in a much smaller fraction of tests and do not yield a representative sample of U.S. counties

[12] To do this, I use the sample with observations for both unfiltered and filtered nitrate plus nitrite, and regress unfiltered nitrate plus nitrite on filtered nitrate plus nitrite and its square. The resulting equation is

$$\underset{}{\text{Unfiltered}_{it}} = \underset{(.321)}{.152} + \underset{(.048)}{1.151}(\text{Filtered}_{it}) - \underset{(.002)}{.004}(\text{Filtered}_{it})^2$$

dioxide (NO_2), ozone (O_3), and sulfur dioxide (SO_2).[13]

Certain variables arising from the Census of Housing may also be correlated with health and pollution. Densely populated places may have more available health care, but also more human waste per square mile of land, as well as more air pollution. Hence, a population density variable is included in the analysis. Additional housing variables include well water and septic tank usage as well as age of housing structure.

Hydro-geologic factors and land use practices may mitigate any correlations between livestock farming, health, and pollution. The National Resource Inventory (NRI), created by the National Resource Conservation Service (NRCS), provides a statistically representative sample of soils and groundcover in the U.S. The inventory is performed every five years, corresponding to the years of the Census of Agriculture.[14] Additionally, I use monthly precipitation data from the National Climactic Data Center, and create a percolation factor based on soil type and precipitation level.

The only federal regulation of livestock farms in effect between 1980 and 1999 was the Clean Water Act (CWA). The CWA requires facilities that confine livestock and are above a certain size to obtain National Pollution Discharge Elimination System permits. In order to obtain a permit, the facility must fulfill certain engineering requirements concerning the structure of the lagoon, and must observe certain limits on application of manure. I include a variable in the analysis for whether or not a county has permits in effect. This information was obtained via the EPA's online Envirofacts Data Warehouse.

A pivotal variable that may also affect the nitrogen content of groundwater is the amount of man-made nitrogen fertilizer applied to fields. If a livestock farm exists next to a crop farmer who applies copious nitrogen fertilizer to fields, one cannot tell with the water quality data used here whether groundwater nitrogen originated at the livestock or the crop farm. Unfortunately, no data exist on the

[13] While particulates are also related to livestock farming, the data on total suspended particulates (TSPs) is not consistent over the time period. Specifically, in the middle of the period the EPA deleted the national air quality standard for TSPs and instituted one for PM10 (particulate matter of up to 10 microns in diameter). The number of monitors recording data for TSPs dropped precipitously while those for PM10 grew. While PM10 are a subset of TSPs, combining the data requires knowledge of pollution conditions at each local area.
[14] A complete description of this dataset can be found in NRCS (2001).

application of commercial nitrogen fertilizer by county for the time period in question.[15] However, I should be able to control for this (at least in part) by including a variable for percentage of the county used for crop growth (from the NRI).[16]

The air pollutants studied arise mostly from combustion of fossil fuels, caused mostly by automobiles. Thus it is necessary to control for automobile emissions. No data of the scope needed for this study are available, but the fixed-effects model coupled with the population density variable should control for vehicle exhaust.[17]

In order to create similar units across the various datasets, all observations are put on a county basis. Hence, natality data reflects average birthweight by county, average age of mother by county, and so forth. In order to create consistent units of time across the datasets, I group the data into five-year time periods, each with a Census of Agriculture at its middle. Thus, I have four time periods: 1980 to 1984, 1985 to 1989, 1990 to 1994, and 1995 to 1999. The final units of observation are on the basis of the county-period.

Descriptive Means of Full Sample

Table 2 provides descriptive statistics by period for full sample.[18] The table shows that approximately 97.5 percent of all births occurring in the contiguous United States are covered by the

---

[15] The Census of Agriculture has a variable for amount of any commercial fertilizer used in a county. However, this is not recorded in all states, and is also censored in many situations. This results in a dataset in which 20 percent of observations have missing values.

[16] The fixed-effects model will control for the size of the county, and hence multiplying the percentage of the county used in crop growth by the size of the county will not elicit a better measure. Nitrogen fertilizer is also predominantly applied to three crops: corn, sorghum, and wheat. These crops are grown in certain areas of the country (Knox and Moody, 1991). Since geographic-specificity of cropping practices has not changed significantly between 1980 and 1999, the county fixed-effects model should also control for fertilizer application.

[17] The fixed-effects model by itself will non-parametrically control for vehicle emissions if the emissions do not change over the time period. This would occur if no new roads are built and a constant number of vehicles use the roads. Increases in the number of vehicles are proxied for by population density. Land-use variables (percentage of county in rural transportation land, percentage of county in urban and built-up land) will account for new roads. An additional validity check (later in the paper) will also test for the input of vehicle emissions.

[18] The total number of counties or combined counties for which I have livestock data in each period is 2,424. The reduction to around 2,300 county units is caused mostly by no births occurring in a county unit, or in a few situations a lack of data on covariates.

sample.[19] The number of births trends upwards in the first three periods, and then falls in the forth. The infant mortality rates decrease each period. The average number of animal units in a county remains fairly constant over the four periods, reflecting Figure 2. Farm employment remains at a constant level. The percentage of houses with well water or septic tanks or that were built before 1950 all decline each period.

The next set of rows in Table 2 provides means of a selected set of demographic variables. These suggest that between 1980 and 1999, mothers were more likely to be older, non-white, and single. Average number of prenatal care visits also rose, which may simply be a reflection of the increased likelihood of mothers being older, non-white, and single.

Infant health outcomes also are suggestive as to why the number of prenatal care visits is increasing. The percentages of low-birthweight and premature babies increased between 1980 and 1999. This may be reflective of more new technologies enabling particularly "at risk" (low birthweight and/or premature) infants to remain alive. It also suggests a possible source of selection bias in my sample. Specifically, my infant mortality statistics are based on the population of live births, and do not include the results of changes in fetal death. If presence of livestock causes damage to a fetus before birth, then this may increase the likelihood of miscarriage or stillbirth. If these fetal deaths, if surviving to birth, would have been more likely to die, then excluding them from the sample means that estimates of infant mortality associated with livestock are understated. This question will be addressed later in the paper.

Sub-Sample Descriptions

While the air and water quality data provide a great deal of information on many areas of the country, I do not have complete coverage of the entire U.S. for any measure. Neither STORET nor the NWISWeb claims to contain a statistically random sample of groundwater in the United States. These datasets house all observations on groundwater nutrients between 1980 and 1999 that the EPA and the

[19] Those that are not occur almost entirely in the "consolidated cities" of Virginia, for which I do not have livestock data.

USGS have digitized, culled from a variety of studies conducted for different reasons in different locations. A single source of groundwater is rarely observed more than once. The air quality observations also do not provide randomized samples of locations across the United States. This grouping of water and air data by county and time period creates more representative samples.

Because the pollution samples do not cover the entire United States while the livestock farming variables do, this requires the use of more restricted samples for analysis. It is important to note these differing samples and to pay attention to the effects of using them. Table 3 provides a summary of the samples used. Sample 1 contains the most comprehensive data for the United States. Sample 2 is focused around groundwater observations, while Samples 3 through 5 focus on nitrogen dioxide, ozone, and sulfur dioxide, respectively. Table 3 compares selected means across the samples. T-tests for whether these means of Samples 2 through 5 are significantly different from those of Sample 1 reveal that in most cases they are. Finally, Table 4 provides means by period of the water and air quality data and shows the concentration limits for these pollutants.

V. Correlations between Livestock and Infant Health

The first question that this study asks is whether there are measurable negative public health effects associated with large-scale livestock farming. Thus I first examine the "reduced form" relationship between livestock and infant health. The ideal research design is a controlled experiment in which livestock farming operations are randomly assigned to counties. In this case, exposure to any negative health effects associated with livestock is independent of other covariates that could be affecting health. However, doing this is implausible, and random exposure of infants to ill health-inducing factors in unethical.

The next best research design would be a "natural experiment" in which we have some exogenously-induced variation in livestock farming. However, no events have occurred in the time of this study that would induce such a variation. The Clean Water Act is the only federal law prompting changes in livestock farming, and this occurred in 1972 (with subsequent amendments in 1977), thus its effects cannot be captured in this study. Additionally, this study only covers four time periods, which does not allow for much consideration of pre- and post-event trends.

Without an exogenous assignment of livestock to counties, we must use the gradual differences across counties to estimate the effects of changes in livestock. This observational design is not ideal, but provides the only comprehensive study of the subject to date. Additionally, examining the correlation between livestock farming and infant health does not suffer from the same endogeneity problem as many observational studies. In these cases it is difficult to determine the direction of causality between the independent variable of interest and the dependent variable. The reason that livestock operations are locating in specific areas is not because of poor health in that area; rather, the literature suggests that livestock farming is moving due to lower labor costs and state legislation. While lower labor costs may be correlated with decreased infant health, I will be controlling for per capita income in subsequent analyses. It is unlikely that livestock farming legislation is systematically correlated with infant health; thus livestock farms are not induced by poor health. Instead, community members may witness poor health outcomes when a new livestock facility moves into the area. They pressure the legislature or the farm to move out of the area, hence we might see a correlation between lower infant health and reduced numbers of livestock. Thus any resulting correlations between reduced infant health and more livestock may actually be understated.

This study makes use of a fixed effects model to control for unobservable or not measurable characteristics of individual counties and different periods. This type of model allows me to non-parametrically control for the effects of each county that do not change over the four time periods observed, as well as events that occur in a certain time period in every county. Additionally, state-period effects control for state-wide events that occur in a particular period, such as a state-level policy. In the models that include these controls the source of variation on which I identify effects is between-county variation within a state.

I start with the cross-sectional results of regressing the infant mortality rate on the number of animal units (in 100,000) for each of the four periods. These yield the simplest correlations between livestock farms and infant health. The regression model takes the form

(1) $$H_{ik} = \delta L_{ik} + \mathbf{X_{ik}'\beta} + \nu_k + \varepsilon_i$$

H_{ik} refers to the health outcome variable in county i in state k, L_{ik} refers to number of animal units (in 100,000s) for county i in state k, $\mathbf{X_{ik}}$ is a vector of observable regressors that include demographic variables and housing indicators, and ν_k represents a dummy variable for state k. Table 5 shows the results of these regressions for each period; a 100,000 animal unit increase in a county corresponds to a higher level of infant mortality in each of the four time periods, ranging from .088 to .197. The other covariates respond in the expected ways; increased percentages of white mothers and married mothers are negatively correlated with infant mortality. The percentage of births that occur in a hospital is negatively correlated with infant mortality, and farm employment is positively correlated with infant death. Beyond these, the covariates vary in significance, size, and direction between the time periods.

The cross-sectional results do not control for possible unobserved qualities of individual counties that may be biasing results. In order to correct this problem I pool the data and employ a fixed-effects model. This uses a least-squares regression model of the form

(2) $$H_{ikt} = \delta L_{ikt} + \mathbf{X_{ikt}'\beta} + \alpha_{ik} + \gamma_t + \nu_{kt} + \varepsilon_{ikt}$$

H_{ikt} refers to the health outcome variable in county i and state k in period t, L_{ikt} refers to number of animal units for county i in state k in period t, and $\mathbf{X_{ikt}}$ is a vector of observable regressors that vary by county and period and include demographic variables, housing indicators, land-use variables, and precipitation values. α_i is a constant term for county i in state k; this term absorbs any unobserved characteristics of county i in state k that do not vary over the time periods. γ_t is a constant term for period t which captures unobserved events that effect all counties in period t. ν_{kt} is a dummy variable for state k in time period t that absorbs effects occurring to all counties in state k in time period t.

Equation 2 provides an estimate of how much the number of livestock in a county correlates with health; the addition of the demographic and socio-economic variables in X_{ikt} these characteristics that could be also be correlated with livestock farming. Suppose, for example, that when a livestock farm moves into an area, those that can afford to do so will move out, leaving a certain type of people who still must live in the vicinity. Any health change we witness might then be due to the changing composition of people in the area, instead of anything relating to the feedlot. Controlling for socioeconomic factors provides for this possibility.

Table 5 shows the results of estimating equation 2 with different covariates, where H_{ikt} is the infant mortality rate (IMR) or the neonatal infant mortality rate.[20] Columns I and V show results controlling for just period and county fixed effects. Columns II and VI include demographic covariates from the natality files, housing, and other socio-economic characteristics (as well as the period and county fixed effects). Columns III and VII include land-use, precipitation, and regulation variables. Finally, columns IV and VIII include the state-time controls. Without controlling for demographic covariates, an increase in 100,000 animal units in a county corresponds to an increase in the IMR of 1.64 and an increase in the neonatal IMR of 1.24.[21] With the addition of covariates to control for demographic and housing characteristics, these correlations drop to .78 and .62 (respectively). This suggests that demographic and socio-economic characteristics account for approximately half of the observed relationship between livestock and infant mortality. Finally, the addition of the state-time controls increases the size of the effect, to .60 and .54. However, we are still left with a sizable and statistically significant correlation between livestock and infant death. About 90 percent of the deaths associated with livestock farming occur within the first 28 days of life.

To estimate the adjusted elasticity between infant mortality and number of livestock, I perform a regression of the log of the infant mortality rate on the log of the number of animal units in a county. Table 5 shows the results of these regressions.[22] Without accounting for demographic covariates, a one percent increase in the number of animal units in a county corresponds to .21 percent increase in the

[20] The IMR is defined as the number of deaths under one year of age per 1,000 births. The neonatal mortality rate is the number of deaths under 28 days per 1,000 births. These are both period (rather than cohort) measures.

[21] This corresponds to 164 additional deaths under one year of age per 100,000 births, and 124 additional deaths under 28 days per 100,000 births.

[22] In order to perform these regressions, I must take the logs of the IMR in each county. However, some counties have an IMR of zero, in which case taking the log is not possible. Hence these observations are not used in the log-log analysis. The zero observations account for about three percent of all observations.

infant mortality rate or a .23 increase in the neonatal infant mortality rate. After controlling for the demographic, socio-economic, housing, and state-period covariates, these percentages drop by over one-half, giving us the adjusted elasticities between animal units and the infant mortality rates; a one hundred percent increase in the number of animal units corresponds to an 6.3 percent increase in the infant mortality rate and a 7.0 percent increase in the neonatal infant mortality rate.

To check the sensitivity of these results to the sample, I change the period of observation. In the above analysis, I used the infant mortality rates calculated over five-year periods corresponding to the Census of Agriculture. To evaluate whether the above correlations are specific to this unit of analysis, I change the time period of the health data, using two different specifications. These are 1) the four individual years associated with a Census of Agriculture (1982, 1987, 1992, and 1997), and 2) the three years after each Census of Agriculture (1982-1984, 1987-1999, 1992-1995, and 1997-1999). Tables 8 and 9 show the outcomes of these analyses. The results of using just the single years associated with the Censuses of Agriculture (Sensitivity Analysis 1) show larger correlations between infant mortality and livestock than those in the original analysis. The results of using the three years after each Census of Agriculture (Sensitivity Analysis 2) show slightly smaller coefficients than those in the original analysis. Hence the correlations between infant mortality and livestock using the five-year intervals are generally not a result of choosing that interval for analysis.

Infant Deaths from Increased Livestock Numbers or versus Changing Livestock Distribution

There are two ways to estimate the total number of deaths associated with increases in animal farming. The first looks at averages across counties in terms of changes in animal untis and numbers of births. This provides a measure of how many infant deaths are associated with a change in total animal units. To calculate this, I multiply the average county-level increase in animal units (AU) between Period 1 and Period 4 with the average county-level number of births born in all periods. This product is then multiplied by the estimated increase in IMR associated with increased animal units (scaled appropriately), then multiplied by the number of counties (N). Hence,

(3) $$\text{Deaths} = N(\Delta\text{IMR}/1000)[(1/N)\sum_{i=1}^{N}\Delta\text{AU}_i\,][(1/N)\sum_{i=1}^{N}\text{Births}_i\,]$$

where denotes the county. Between 1980 and 1999 there were 32,167 births on average in a county, and an average increase by county of 203 animal units; hence the coefficients estimated above correspond to 88 additional deaths under one year of age. Because the average number of livestock per county has not changed a great deal, the accompanying increase in infant mortality due to increases in livestock is very small.

Although the number of animal units in inventory has not changed much between Period 1 and Period 4, the geographic distribution has, and livestock operations have been moving to more populated places. In order to calculate the number of deaths associated with the changing distribution of livestock, I evaluate how the number of births changed assuming that the infant mortality rate at each level of the distribution of animal units stays the same. I first estimate the regression-adjusted infant mortality rate in Period 1 at each of 15 different levels (L = 1 to 15) of animal units. Multiplying these IMR's by the percent of counties in Period 1 at each level provides the regression-adjusted overall IMR in Period 1 (the infant mortality rate in Period 1 given the Period 1 distribution: $\text{IMR}_{\text{P1}}^{\text{P1}}$). Hence,

(4) $$\text{IMR}_{\text{P1}}^{\text{P1}} = \sum_{j=1}^{15}(\text{IMR}|\text{L} = \text{j})_{\text{P1}}\,\text{f}(\text{L} = \text{j})_{\text{P1}}$$

Multiplying $\text{IMR}_{\text{P1}}^{\text{P1}}$ by the number of births at each level provides the total number of deaths in Period 1 ($\text{Deaths}_{\text{P1}}^{\text{P1}}$).

(5) $$\text{Deaths}_{\text{P1}}^{\text{P1}} = (1/1000)\sum_{j=1}^{15}(\text{IMR}|\text{L} = \text{j})_{\text{P1}}\,\text{f}(\text{L} = \text{j})_{\text{P1}}\,(\text{Births}|\text{L} = \text{j})_{\text{P1}}$$

I next ascertain the number of deaths due to changes in the distribution of livestock. I calculate the number of deaths that occurred in Period 4 if the infant mortality rates associated with each level remained at Period 1 levels. I scale the number of births in Period 4 to equal the number of births in Period 1. This provides the deaths that occurred in Period 4 if we hold the IMR's constant at Period 1 levels (Deaths_{P4}^{P1}). Hence,

$$\text{(6)} \qquad \text{Deaths}_{P4}^{P1} = (1/1000) \sum_{j=1}^{15} (\text{IMR} | L = j)_{P1} f(L = j)_{P4} (\text{Births} | L = j)_{P4}^{P1}$$

The regression-adjusted number of deaths in 1982 (Deaths_{82}^{82}) is 47,738 deaths, while the number of deaths in Period 4 given Period 1 levels (Deaths_{P4}^{P1}) is 55,023. Hence the changing distribution of livestock results in 6,748 additional deaths over the 20-year interval between Period 1 and Period 4.[23] Thus it appears that the not very many deaths are associated with an increased number of livestock; instead, they are associated with a changing distribution of livestock.

What are the Causes of these Deaths?

Table 10 provides a summary of results of regressing the infant mortality rate from selected causes of death[24] on the number of animal units. These regressions include all possible covariates, fixed effects, and state-period controls, and take the form of equation (1) above. The first two rows of this table provide the results for two causes of death that we would not expect to be correlated with livestock farming. These include congenital syphilis and accidents and homicides.[25] From these results we see that livestock are not significantly correlated to either of these. The second two rows examine possible causes of death associated with bacterial infections arising from fecal coliform, given that numerous outbreaks of gastroenteritis have been associated with livestock farms (see, for example, Health Canada, 2000). However, I find no significant relationship between livestock farms and these causes of death. The next row shows the relationship between diseases of the blood and blood forming organs and livestock, which is the cause of death associated with methemeglobinemia, which may arise from nitrate-contaminated

---

[23] This estimation allows for non-linearity of the predicted IMR by level of animal unit, whereas the simple linear regressions described above do not. Thus the cross sectional results are not directly comparable to the predicted IMR's here. Performing this exercise to calculate the difference between Deaths_{P4}^{P4} and Deaths_{P1}^{P4} results in approximately the same number of excess deaths as the difference between Deaths_{P1}^{P1} and Deaths_{P4}^{P1}.

[24] The IMR from a specific cause of death is defined as the number of deaths attributed to the cause per 1,000 births.

[25] While children who live on farms are also twice as likely as their urban counterparts to die from accidents (Webster and Mariger, 1999), this is referring to children above the age of one.

water. While positive, the relationship is not significant. The next three rows show causes of death that we might believe are associated with air pollution arising from livestock farming. Livestock farming is strongly and positively correlated with respiratory distress syndrome and acute upper respiratory infections, but negatively correlated with bronchitis. This negative correlation with bronchitis may actually be due to the fact that children die from upper respiratory infections before they can die of bronchitis. The final four rows of the table show causes of death that could be related to air or groundwater pollution, or some other element for which I have not accounted. These rows show that livestock are positively and significantly correlated with infections and conditions arising in the perinatal period, [26] but unrelated to the cause of death including Sudden Infant Death Syndrome (SIDS) and congenital anomalies. This table suggests that causes of death associated with livestock farming are predominantly respiratory-related or arising in the perinatal period.

Is Livestock Negatively Correlated with Other Public Health Outcomes?

To further examine the link between livestock farming and public health, I investigate other measures of reproductive health. This also helps to elucidate whether negative effects of feedlots are occurring before or after birth. Thus I examine the correlations between livestock farming and birthweight, incidence of prematurity, and five-minute Apgar score.[27]

These health variables are all garnered from individual natality records, and thus I have information on the person level as well as the county level (via the means). In order to make use of all information, I estimate regressions that control for the person-level covariates before estimating the correlation of county-level covariates and the dependent health variables. Using the person-level

[26] The "perinatal period" is the period shortly before and shortly after birth.
[27] The 5-minute Apgar score is a composite of five tests given to an infant five minutes after its birth. The five tests are each scored on a scale of 0 to 2, with 2 being the best outcome. The five tests measure heart rate, breathing, activity and muscle tone, "grimace response", and appearance in terms of skin coloration. "Low birthweight" is defined as 2,499 grams or under. "Very low birthweight" is defined as 1,499 grams or under. "Premature" refers to a birth that occurred after less than 37 weeks of gestation.

observations for natality, I estimate the following equation:[28]

(7) $$H_{pikt} = \mathbf{X}_{\mathbf{pikt}}'\boldsymbol{\beta} + \delta_{ikt} + \varepsilon_{pikt}$$

H_{pikt} refers to the health variable for person p in county i, state k, and period t. $\mathbf{X}_{\mathbf{pikt}}$ represents a vector of regressors that vary over time and include the person-level demographic features that may affect health, as well as a full set of interaction variables among these covariates. δ_{ikt} is a dummy variable for county i, state k, in period t. Using the $\hat{\beta}$'s from (2), I next calculate:

(8) $$\hat{\delta}_{ikt} = \overline{H_{pikt}} - \overline{\mathbf{X}_{\mathbf{pikt}}}'\hat{\boldsymbol{\beta}} \text{ .}$$

$\hat{\delta}_{ikt}$ represents that amount of the health variable not accounted for by person-level characteristics. I then regress over the observations on county-period:

(9) $$\hat{\delta}_{ikt} = \lambda f(L_{ikt}) + \overline{\mathbf{X}_{\mathbf{pikt}}}'\boldsymbol{\omega} + \mathbf{Q}_{\mathbf{ikt}}'\boldsymbol{\theta} + \alpha_i + \gamma_t + \nu_{kt} + \varepsilon_{it}$$

where $f(L_{ikt})$ represents a function of the livestock farming variable of county i, state k, in period t, the $\mathbf{Q}_{\mathbf{ikt}}$ are the county-level regressors not available on the person level (i.e., per capita income, number employed in farm labor), α_i is the fixed-effect of county i, γ_t is the period fixed-effect for time t, and ν_{kt} is the state-period control for state k in time t. If the coefficients on the means by county over the individuals ($\boldsymbol{\omega}$ on the $\overline{\mathbf{X}_{\mathbf{pikt}}}'$) are zero, this means that the health variable is accounted for entirely by person-level effects.

Table 11 shows the results of the equation (4) regressions, with all possible covariates, fixed effects, and state-period dummies. In the linear model shown in Panel 1, the number of animal units is negatively correlated with incidence of low birthweight and prematurity, but positively correlated with Apgar score and birthweight[29]. None of these relationships are significant at the 95% level. The Panel 2 of Table 11 shows a different specification of the model, revealing a strong negative correlation between Apgar score and livestock when the square of livestock is included. From this regression we can estimate

[28] Between 1980 and 1999, there are over 76 million births; for efficiency, I use a random five-percent sample of the entire universe to estimate these equations. Thus my sample size is 3,798,966.
[29] "Low birthweight" is defined as 2,499 grams or under. "Very low birthweight" is defined as 1,499 grams or under. "Premature" refers to a birth that occurred after less than 37 weeks of gestation.

that at the median, a 100,000 animal unit increase corresponds to a decrease in the Apgar score of .44. This result is, however, specific to functional form. Regressions with fewer covariates yield approximately the same results.

In summary, livestock farming is strongly correlated with infant mortality. This finding is robust with respect to inclusion of covariates and specification changes. Most of this effect occurs within the first 28 days of life, with causes of death relating to respiratory conditions and perinatal conditions. Further, livestock farming is weakly correlated with a decreased Apgar score. These findings show that there are measurable negative public health effects associated with livestock farming.

Alternative Explanations

The correlation between livestock farming and infant mortality suggests some other inquiries into the matter in order to disregard them as reasons for this correlation. Suppose that a certain group of people with high levels of infant mortality is employed in livestock farming. Additionally, suppose that the reason for this high mortality rate is some characteristic for which I do not have data, either because such data is unavailable (such as genetics), or because the characteristic is not quantifiable (such as knowledge or maternal behavior). The correlations between infant mortality and livestock might then be due to this unobserved characteristic, rather than anything related to livestock farming. I endeavor to minimize this possibility by including a wide array of demographic and economic variables in my regressions; however, some may have been omitted.

The most obvious of possible omitted variables is Hispanic origin. Hispanic origin is not recorded on natality records in all states between 1980 and 1994, hence I can not use it as a covariate on analyses using the full sample. Suppose Hispanics are more likely to live in the counties with higher rates of livestock farming, and that Hispanics have infant health outcomes different from the general population. Thus any association between infant health and livestock may be due to the higher percentage of Hispanic-origin people in the county, not anything to do with livestock farming. However, Hispanic-origin people, in what is known as the "Hispanic paradox" have been found to be associated with *lower* rates of infant mortality and *higher* birthweights than non-Hispanics of comparable socio-economic status (see Palloni and Morenoff, 2001, for a summary). If the results of the above analyses showed that livestock farming was coupled with less infant mortality, then we might argue that we are capturing an effect of a higher percentage of Hispanic people in the areas around livestock farms. However, we see the opposite of this effect. Hence, if there were more people of Hispanic origin living near feedlots, this might actually have the benefit of reducing the infant mortality rate that we witness; controlling for Hispanic origin might therefore provide even higher estimates of the association between infant morality and livestock farming.

Another possibly omitted variable is access to abortion. Suppose that people in areas with more livestock have less access to abortion services. Suppose further that the fetuses that are aborted would be more likely to die once born. Therefore, women in high-livestock areas would be more likely to carry high-risk fetuses to full gestation. Hence the relationship between livestock farming and infant mortality may be due to higher-risk babies not being aborted. If this is the case, then the livestock farming variable will be capturing the effect of lack of abortion services. In a county fixed effects model, this would require that abortion services systematically change with the presence of livestock. It seems plausible that livestock farming may decrease and abortion services increase in an area seeing increased urbanization. However, the population density variable should capture the effect of urbanization. Further, exclusion of the most densely populated counties from the analysis does not change the results. Finally, the supposition that aborted fetuses would be more likely to die if born may not be tenable.

A final possibility is that areas with more livestock are less likely to have less access to medical services for newborns and infants. For example, neonatal intensive care units (NICUs) may be more prevalent in areas with lower numbers of livestock. In the county fixed effects model, this would require that these technologies change systematically with changes in livestock farming. Again, this may be due to effects of urbanization, but again, the population density variable should capture this effect.

VIII. Correlations between Livestock and Pollution, and Pollution and Infant Health

I now turn to the second question of the paper: Are the negative public health impacts associated with livestock farming due to pollution? As described above, I have constructed a panel data set with observations of individual counties over four time periods. The structure of data helps in more accurately exploring relationships between livestock production, groundwater and air quality, and infant health. Most studies examining these topics use only cross-sectional data. Doing so may give us an indicator of how these livestock and pollution are related at one point in time (in the best case scenario), but will not give us any indication if this is just something specific to the time period or if it is more permanent. For example, if data were collected following a flood, then any resulting correlations between livestock and water quality may only occur after floods and may not be representative of times with normal weather. The longitudinal data employed in this study provides the opportunity to study effects over time.

Another problem with just examining cross-sectional data is possible omitted variable bias. This occurs when the researcher does not control for something that may affect the variable of interest (in this case, groundwater and air quality). Without this variable, a correlation between livestock and pollution may be due not to these two factors varying together, but to the omitted variable. In deciding where to locate, livestock farm operators consider environmental factors such as slope, wind patterns, and permeability of soil. To allow for more drainage into surrounding soils, animal operations may locate at the top of inclines. Facilities raising animals outdoors desire locations with protection from winter winds. A significant source of water is necessary for livestock production, hence areas without abundant water are not good places to locate. Farming agencies advise livestock operations to avoid steep topography, porous geology, sink holes, and flood plains in order to limit environmental damage. Further, they are advised to locate where soil is permeable enough to allow some absorption of slurry nutrients, but not so permeable as to allow soil directly into groundwater, or so impermeable as to force total run-off (Olson, 1974; Fulhage, McNabb, and Rea, 1999).

The county and period fixed-effects model described above controls for unobservable or not measurable characteristics. I now regress pollution on livestock to see how much pollution correlates with increased animal farming, using a least-squares regression model of the form

$$(10) \qquad P_{ikt} = \delta f(L_{ikt}) + \mathbf{X_{ikt}}'\boldsymbol{\beta} + \alpha_{ik} + \gamma_t + \nu_{kt} + \varepsilon_{ikt.}$$

In this model, P_{ikt} refers to the water or air quality variable in county i and state k in period t, $f(L_{ikt})$ refers to a function of the number of livestock for county i in state k in period t, $\mathbf{X_{ikt}}$ is a vector of observable regressors that vary from period to period and include crop practices, precipitation levels, and population indicators. α_{ik} represents a dummy variable for county i in state k, γ_t is a dummy variable for period t, and ν_{kt} represents a dummy variable for state k in time t.

Table 12 shows the adjusted and unadjusted correlation between numbers of animal units by county and different measures of air and water quality. In this specification, nitrogen dioxide and ozone are the only pollutants that are correlated with livestock farming. A 100,000 animal unit increase corresponds to a .0018ppm increase in NO_2 and a .0016ppm increase in ozone. Table 13 provides a different specification of the model using a third-order polynomial for NO_2, ozone, and nitrate, and a fourth-degree polynomial for SO_2. At the median number of animal units, a 100,000 increase in the number of animal units corresponds to a 4.57mg/L increase in nitrate plus nitrite and a 0.000424ppm increase in sulfur dioxide. However, these correlations are fairly weak and specific to functional form. The number of animal units appears more strongly correlated with ozone and nitrogen dioxide than it does with groundwater nitrogen or sulfur dioxide. This may be arising from lack of accurate data, particularly for the water quality variable.

Validity check: Groundwater Lead, Air-based Lead, and Carbon Monoxide

If we believe that livestock farming is the mechanism leading to higher groundwater nitrates and certain forms of air pollution, then it should be the case that we should not see a significant correlation between livestock farming variables and water and air quality measures not associated with manure. Two such measures are the amount of lead in groundwater, and the amount of lead in the air. Elevated lead levels in drinking water are related to leaching from lead pipes. The use of lead pipes was discontinued in the early 1900's; however, lead pipes still exist in older homes and water distribution systems (Embrey, 2004). Lead in the air mostly arises from leaded gasoline, the manufacture of lead batteries, and lead-based paints.

I create a dataset of groundwater lead levels using the method described above to create the dataset on groundwater nitrates. This results in a dataset of nearly 47,000 water quality samples of unfiltered lead in groundwater (μg/L). Results from regressions of the lead water quality observations on the number of animal units are shown in Panel 1 of Table 14. This shows the results of the regression for each of the samples.[30] These show that groundwater lead is never significantly correlated with livestock, in any of the samples. One would not expect lead to be correlated with livestock farming, and indeed it appears that it is not.

Data on air-based lead arises from the EPA's AQS dataset, put together in the same manner as the air quality observations for nitrogen dioxide, ozone, and sulfur dioxide. Panel 2 of Table 14 provides results of regressing number of animal units on lead in the air for each of the samples.[31] We would not expect lead in the air to be correlated with number of livestock, and again it is not.

NO_2 and ozone are frequently associated with vehicle exhaust. Suppose that accompanying an increase in livestock is an increase in vehicle traffic. This may be due to trucks making more frequent trips to livestock operations based on higher volume. While this side-effect of increased farming may create public health problems in itself, it is not the mechanism through which most believe CAFO-related pollution arises. In order to discern whether the increased NO_2 and ozone levels associated with elevated numbers of livestock are due to higher frequency of traffic, I examine the relationship between carbon monoxide (CO) and animal units. Between 1980 and 1999, 85 percent of CO emissions were from

[30] Sample 1 includes all observations of groundwater lead in the country, although observations for groundwater lead do not span the entire country. Sample 2 (that covering groundwater nitrates) also covers all observations of groundwater lead in the country, so results for Sample 2 are the same as those for Sample 1. Different specifications of this model were also attempted (using different polynomials); none yielded significant relationships between livestock and groundwater lead.

[31] Sample 1 includes all observations of air lead in the country, although observations for air lead do not span the entire country. Different specifications of this model were also attempted (using different polynomials); none yielded significant relationships between livestock and air-based lead.

vehicle exhaust (compared to 54 percent of NO_2 emissions).[32] Hence we might expect to see higher CO levels associated with higher traffic frequency. I construct a dataset for carbon monoxide in the same manner as those for the other air quality measures. The third panel of Table 14 shows the results of regressing carbon monoxide levels on number of animal units (in 100,000s) for each of the samples. While positive, these correlations are not significant. Hence it appears that the NO_2 and ozone related to livestock is not arising from vehicle exhaust.

Instrumental Variables Analysis: Livestock-Induced Pollution's Effect on Health

The different tests conducted above have shown that increased livestock farming correlates with decreased air quality, but is not strongly correlated with water quality. Now I evaluate whether the negative health effects associated with livestock farming are due to this air pollution. I instrument for pollution with livestock farming, and then regress health on the predicted pollution level.

Instrumental variable analysis requires that the number of animal units is correlated with pollution, and that the number of animal units is uncorrelated with the error term in the regression of the health outcome variable on pollution and exogenous variables. Given my previous results, only two of my pollution measures are strongly correlated with livestock: nitrogen dioxide and ozone. Thus I can only instrument for these two variables. I only have one instrument (number of animal units) and thus I can only instrument for a single variable. Since nitrogen dioxide is a precursor to ozone, these two measures are collinear, hence including them both as covariates in a single regression would also provide misleading results. I instrument for ozone with animal units; thus in my "first stage" I create the predicted ozone level using the regression shown in column 6 of Table 12.[33]

In the second stage of the analysis, I regress the relevant health variables on predicted ozone as well as the exogenous variables. Nitrate plus nitrite is only weakly correlated with livestock, thus I will

---

[32] Data from "1970-2001 Average annual emissions, all criteria" table from the U.S. EPA, http://www.epa.gov/ttn/chief/trends/index.html. Accessed October 25, 2004.

[33] Ozone was chosen over NO_2 because I will be including nitrate plus nitrite as a covariate in the second stage of this analysis. This requires a sample with data for both measures; the sample with observations for ozone and nitrate plus nitrite is twice the size as that with observations for both NO_2 and nitrate plus nitrite.

control for it in the second stage. While the resulting coefficient on predicted ozone may capture some of the effects of SO_2, the correlation between SO_2 and animal units is weak, making this less likely. The second stage equation takes the form:

$$H_{ikt} = \delta(\hat{Z}_{ikt}) + \lambda(\text{Nitrate}_{ikt}) + \mathbf{X_{ikt}'\beta} + \alpha_{ik} + \gamma_t + \nu_{kt} + \varepsilon_{ikt} \tag{11}$$

In this model $\hat{Z}_{ikt}$ refers to predicted ozone in county i in state k in period t, and $\mathbf{X_{ikt}}$ is a vector of observable regressors that vary from period to period and include demographic and housing characteristics. α_{ik} represents a dummy variable for county i in state k, γ_t is a dummy variable for period t, and ν_{kt} is a control for state k in time t. For this second stage analysis I require data on both ozone and nitrates, thus my sample size is diminished slightly.

Table 15 shows the results of performing the instrumental variable analyses.[34] Here we see that for this sample, a .001ppm increase in ozone induced by a change in animal units corresponds to a 1.488 increase in the IMR, a 1.230 increase in the neonatal IMR, and a .181 decrease in the Apgar score. The use of this restricted sample, however, provides different reduced form and first stage results than those described in the preceding analysis.

Table 16 provides a summary table comparing the results for the different samples. Panel 1 shows the results regarding the IMR; Column (1), rows (a) and (d) reflect reduced-form results from Table 6 using the most complete sample (Sample 1). Column (3), rows (b), (e), and (h) reflect first-stage results from Table12. Column (4), rows (c), (f), and (i) reflect instrumental variable results from Table 15. This table shows that for the different samples, the reduced form analysis yields different coefficients. In the most restricted sample (Sample 6, which contains information on both ozone and nitrate plus nitrite), a 100,000 animal unit increase corresponds to a .39 increase in the IMR, while in the sample with the most observations (Sample 1), it only corresponds to a .60 increase.

[34] Because the first stage is weighted differently from the second stage, this system of equations could not be estimated simultaneously. However, using a predicted variable in the second stage of the analysis will provide incorrect standard errors. Thus the standard errors in the second stage are corrected following Murphy and Topel (1985).

IX. Discussion of results and policy implications

The first half of the paper demonstrated a strong positive relationship between livestock farming and infant mortality. A 100,000 animal unit increase corresponds to between 57 and 80 more deaths per 100,000 births. Livestock farming is indicated in pre-birth damage to the fetus through a reduced Apgar score and causes of death related to problems in the perinatal period. The changing distribution of livestock is associated with an additional 6,748 deaths between 1980 and 1999, or about 337 per year. If a statistical life is valued at $1.6 million, this loss of life amounts to about $540 million per year.

The results of the second half of the paper imply that many of the negative health effects associated with livestock are due to air pollution. These changes in air pollution from livestock farming are correlated with increases in the infant mortality rate, revealing that much of the negative health impacts of livestock farming are due to air pollution.

A health risk generation model is useful when considering the marginal benefits and costs of optimal regulation to protect humans against the pollution emitted from livestock farms. This type of model, used in public health and applied to environmental health risks by Zivin and Zilberman (2002), defines health risk as a multiplicative model of three components. These are contamination, exposure, and the dose-response function; the product of these is the population health risk of a toxin. In livestock farming, contamination arises from two sources: air and groundwater. Exposure occurs via inhalation and ingestion. The dose-response function is the human body's reaction to smaller or larger doses of a toxin.

Consideration of the contamination and exposure allows us to consider optimal policies for public health. The results of this paper provide evidence that contamination from livestock farms arises more from air pollution than from water pollution. Exposure to groundwater pollution arises from ingestion of drinking water, and exposure to air pollution occurs via inhalation. If livestock farms contaminate drinking water, then a possible policy response could be providing everyone in the nearby watershed with bottled water. Alternatively, protecting human health against air pollution from livestock farms would entail more costly engineering features, such as capping lagoons and installing air filtration systems.

Figure 4 provides a schematic showing marginal benefits and costs of limiting exposure to toxins from livestock farms. Benefits and costs pertain solely to human life years lost, and exclude for the moment costs relating to environmental damage and benefits involving lower meat prices. The marginal cost curve for limiting exposure to groundwater pollution (MC_{Water}) is constant and relatively low; this reflects a policy response of giving people bottled water. The marginal cost curve for limiting exposure to air pollution (MC_{Air}) is much higher and asymptotically trends toward infinity when it reaches 100 percent, reflecting more expensive engineering procedures. The marginal benefit curve is downward sloping because it reflects person-years lost. Since infants are the most susceptible to toxins, their deaths yield the largest loss of life in terms of years of life lost. Infants would also benefit most from small limitations on exposure. Further to the right along the marginal benefit curve reflects the person-years saved of less-susceptible individuals.

This figure shows that optimal limitation to drinking water contaminants is nearly 100 percent, while optimal limitation to air-borne contaminants is much lower and more expensive. The results of this paper suggest, however, that avoidance of negative health effects arising from livestock farms requires more expensive air pollution regulations. Attempts like those currently in debate to regulate large livestock farms under the Clean Air Act are well-founded if negative public health consequences are to be avoided, but will most likely be more expensive than regulation of water pollution.

Works Cited

Barrington, S.F. and Broughton, R.S. 1988. "Designing earthen storage facilities for manure," *Canadian Agricultural Engineering* 30, 289-292.

Becker, M.F., Peter, K.D., and Masoner, J. 2003. *Possible sources of nitrate in ground water at swine licensed-managed feeding operations in Oklahoma, 2001*. Oklahoma City: United States GPO.

Bonner, J., Moore, R., Thomas, J., Crenshaw, M., McKinley, B., and Burcham, T. 2003. "Managing animal waste nutrients." Publication 1937 of the Mississippi State University Extension Service. Accessed online.

Burkart, M.R. and Simpkins, W.W. 1998. "Hydrogeologic settings of earthen waste storage structures associated with confined animal feeding operations in Iowa." Paper presented at Technical Meeting on Effects of Animal Feeding Operations on Water Resources and the Environment, Fort Collin, CO.

Carson, T.L., Osweiler, G.D., and Thorne, P.S. 2002. "Adverse health effects: Toxicology," in *Iowa Concentrated Animal Feeding Operations Air Quality Study*. Iowa State University and The University of Iowa Study Group. Online publication. http://www.public-health.uiowa.edu/ehsrc/CAFOstudy.htm. Accessed Sept. 27, 2004.

Centers for Disease Control and Prevention. 1996. "Spontaneous abortions possibly related to ingestion of nitrate-contaminated well water – Lagrange County, Indiana, 1991-1994," *Morbidity and Mortality Weekly Report* 45(26), 569-572.

Centers for Disease Control and Prevention. 1998. *A survey of the quality of water drawn from domestic wells in nine Midwest states. Sept. 1998*. Online publication. http://www.cdc.gov/nceh/programs/emergenc/WellWater/MidwestWell.htm.

Currie, J. and Neidell, M. 2004. "Air pollution and infant health: What can we learn from California' recent experience?" National Bureau of Economic Research Working Paper 10251.

DeTar, W.R. 1979. "Infiltration of liquid dairy manure into soil," *Transactions of the American Society of Agricultural Engineers* 79, 520-531.

Donham, Kelley J. 2000. "The concentration of swine production: Effects on swine health, productivity, human health, and the environment," *Toxicology* 16(3), 559-597.

Dorsch, M.M, Scragg, R.K.R., McMichael, A.J., Baghurst, P.A., and Dyer, K.F. 1984. "Congenital malformations and maternal drinking water supply in rural South Australia: A case-control study," *American Journal of Epidemiology* 119(4), 473-486.

Environmental Protection Agency. 1994. "Ozone and your health." EPA publication

Environmental Protection Agency. 1998. "Environmental impacts of animal feeding operations." Online publication.

Environmental Protection Agency. 2004. *AirData* data system. Accessed at URL http://www.epa.gov/air/data/info.html.

Fan, Anna M. and Steinberg, Valerie. 1996. "Health implications of nitrate and nitrite in drinking water: An update on methemoglobinemia occurrence and reproductive and developmental toxicity," *Regulatory Toxicology and Pharmacology* 23, 35-43.

Fleming, Ron and Ford, Marcy. 2001. "Humans versus animals – comparison of waste properties." Accessed Jan. 6, 2004.

Fulhage, C.D., McNabb, C., Rea, J. 1999. "Confined feeding facilities – Site selection and management," Agricultural publication G1155, University Extension, University of Missouri-Columbia. http://muextension.missouri.edu/explore/agguides/agengin/g01155.htm. Accessed July 23, 2004.

Gould, M. Charles. 1995. "Nitrate-nitrogen levels in well water in the Little River/Rooty Creek agricultural non-point source hydrological unit area," in *Animal Waste and the Land-Water Interface*. K. Steele (ed.). Boca Raton: Lewis Publishers.

Greene, W.H. 2003. *Econometric Analysis. 5th Edition*. Upper Saddle River, N.J.: Prentice Hall.

Ham, J. 1998. "Field evaluation of animal-waste lagoons: Seepage rates and subsurface nitrogen transport." Paper presented at Technical Meeting on Effects of Animal Feeding Operations on Water Resources and the Environment, Fort Collin, CO.

Health Canada. 2000. "Waterborne outbreak of gastroenteritis associated with a contaminated municipal water supply, Walkerton, Ontario, May-June 2000," *Canada Communicable Disease Report* 26(20).

Hoff, S.J., Hornbuckle, K.C., Thorne, P.S., Bundy, D.S., O'Shaughnessy, P.T. 2002. "Emissions and community exposures from CAFOs" in *Iowa Concentrated Animal Feeding Operations Air Quality Study*. Iowa State University and The University of Iowa Study Group. Online publication. http://www.public-health.uiowa.edu/ehsrc/CAFOstudy.htm. Accessed Sept. 27, 2004.

Holland, R.E., Carson, T.L., and Donham, K.L. 2002. "Animal health effects," in *Iowa Concentrated Animal Feeding Operations Air Quality Study*. Iowa State University and The University of Iowa Study Group. Online publication. http://www.public-health.uiowa.edu/ehsrc/CAFOstudy.htm. Accessed Sept. 27, 2004.

Hooda, P.S., Edwards, A.C., Anderson, H.A., and Miller, A. 2000. "A review of water quality concerns in livestock farming areas," *The Science of the Total Environment* 250, 143-167.

Huffman, R.L. and Westerman, P.W. 1995. "Estimated seepage losses from established swine waste lagoons in the lower coastal plain of North Carolina," *American Society of Agricultural Engineers* 38(2), pp. 449-453.

Hunt, P.G., Stone, K.C., Humenik, F.J., and Rice, J.M. 1995. "Impact of animal waste on water quality in an eastern coastal plain watershed," in *Animal Waste and the Land-Water Interface*. K. Steele (ed.). Boca Raton: Lewis Publishers.

Kellogg, R.L., Lander, C.H., Moffitt, D.C., and Gollehon, N. 2000. *Manure nutrients relative to the capacity of cropland and pastureland to assimilate nutrients: Spatial and temporal trends for the United States*. Online publication of the USDA National Resources Conservation Service. http://www.nhq.nrcs.usda.gov/land/index/publication.html.

Kellogg, Robert. 2000. "Potential priority watersheds for protection of water quality from contamination by manure nutrients." Paper presented at the Animal Residuals Management Conference 2000, Kansas City, MO.

Knox, E. and Moody, D.W. 1991. "Influence hydrology, soil properties, and agricultural land use on nitrogen in groundwater," in *Managing Nitrogen for Groundwater Quality and Farm Profitability*, Follett, R.F., Keeney, D.R., and Cruse, R.M. (eds.). Madison, Wisconsin: Soil Science of America, Inc.

Lawrence, R.S. and Wallinga, D. 2004. "Moratorium on new Confined Animal Feeding Operations." http://www.apha.org/private/2003_Proposed_Policies/09_Moratorium_Confined_Animal.pdf. Accessed July 6, 2004.

Letson, D. and Gollehon, N. 1996. "Confined animal production and the manure problem," *Choices* Third Quarter, 18-24.

Liu, S., Krewski, D., Shi, Y., Chen, Y. and Burnett, R.T. 2003. "Association between gaseous ambient air pollutants and adverse pregnancy in Vancouver, Canada," *Environmental Health Perspectives 111*(14), pp. 1773-1779.

Lory, J.A. 1999. "Managing manure phosphorus to protect water quality." Agricultural publication G9182 of the University Extension, University of Missouri-Columbia. http://muextension.missouri.edu/explore/agguides/soils/g09182.htm. Accessed July 6, 2004.

Maisonet, M. Bush, T.J., Correa, A. and Jaakkola, J.K. 2001. "Relation between ambient air pollution and low birth weight in the Northeaster United States," *Environmental Health Perspectives* 109(Supplement 3), pp. 351-356.

Mallin, Michael. 2000. "Impacts of industrial animal production on rivers and estuaries," *American Scientist* 88, 26-34.

Merchant, J.A., Kline, J., Donham, K.J., Bundy, D.S., and Hodne, C.J. 2002. "Human health effects," in *Iowa Concentrated Animal Feeding Operations Air Quality Study*. Iowa State University and The University of Iowa Study Group. Online publication. http://www.public-health.uiowa.edu/ehsrc/CAFOstudy.htm. Accessed Sept. 27, 2004.

Meyer, D. and Schwankl, L. 2000. "Liquid dairy manure utilization in a cropping system: A case study," in *Land Application of Agricultural, Industrial, and Municipal By-Products*, Bartels and Dick (eds.) Madison, WI: Soil Science Society of America, Inc.

Mugel, D.N. 2002. Ground-*water quality and effects of poultry confined animal feeding operations on shallow ground water, Upper Shoal Creek Basin, Southwest Missouri, 2000*, Rolla, Mo.: U.S. Dept. of the Interior, U.S. Geological Survey.

Murphy, K. M. and Topel, R.H. 1985. "Estimation and inference in two-step econometric models," *Journal of Business and Economic Statistics* 3(4), pp. 370-379.

National Resources Conservation Service. 2001. *1997 National Resources Inventory: A guide for users of 1997 NRI data files.* Online publication.

Olson, E.A. 1974. "Locating a new feedlot" University of Nebraska Cooperative Extension publication G73-65-A. http://ianrpubs.unl.edu/beef/g65.htm. Accessed July 23, 2004.

Ritz, B., Yu, F., Chapa, G., and Fruin, S. 2000. "Effect of air pollution on preterm birth among children born in Southern California between 1989 and 1993," *Epidemiology* 11(5), pp. 502-511.

Schiffman, S.S., Sattely Miller, E.A., Suggs, M.S., and Graham, B.G. 1995. "The effect of environmental odors emanating from commercial swine operations on the mood of nearby residents," *Brain Research Bulletin* 37(4), 369-375.

Scragg, R.K.R, Dorsch, M.M., McMichael, A.J., and Baghurst, P.A. 1982. "Birth defects and household water supply: Epidemiological studies in the Mount Gambier region of South Australia," *Medical Journal of Australia* 11(25), 577-579.

Smith, K.A. and Frost, J.P. 2000. "Nitrogen excretion by farm livestock with respect to land spreading requirements and controlling nitrogen losses to ground and surface waters. Part 1: cattle and sheep," *Bioresource Technology* 71, 173-181.

Super, M., Heese, D.V. MacKenzie, D., Dempster, W.S., DuPlessis, J., and Ferreira, J.J. 1981. "An epidemiological study of well-water nitrates in a group of South West African/Namibian infants." *Water Research* 15, 1265-1270.

Thu, K., Donham, K., Ziegenhorn, R., Reynolds, S., Thorne, P.S., Subramanian, P., Whitten, P., and Stookesberry, J. 1997. "A case control study of the physical and mental health of residents living near a large-scale swine operation." *Journal of Agricultural Safety and Health* 3(1), 13-26.

United States Department of Agriculture. 1996. "Environmental practices/management by U.S. pork producers" Pamphlet of the USDA's Animal and Plant Health Inspection Service.

United States Geological Survey, 2001, *National Water Information System (NWISWeb)* data available on the World Wide Web, at URL http://waterdata.usgs.gov/nwis/.

Wang, X., Ding, H., Ryan, L., and Xu, X. 1997. "Association between air pollution and low birth weight: A community-based study," *Environmental Health Perspectives* 105(5), pp. 514-520.

Webster, J. and Mariger, S.C. 1999. *Risks for children in agriculture*. Pamphlet published by the Utah State University Extension Service. Fact sheet AHS-07. http://extension.usu.edu/files/agpubs/ahs07.pdf. Accessed June 20, 2004.

Williams, J.R. and Kissell, D.E. 1991. "Water percolation – An indicator of N leaching potential" in *Managing Nitrogen for Groundwater Quality and Farm Profitability*, Follett, R.F., Keeney, D.R., and Cruse, R.M. (eds.). Madison, Wisconsin: Soil Science of America, Inc.

Winneberger, J. H. T. 1982. *Nitrogen, public health, and the environment: Some tools for critical thought.* Ann Arbor, MI: Ann Arbor Science Publishers.

Wolfe, A. M. and Patz, J. A. 2002. "Reactive nitrogen and human health: Acute and long-term implications," *Ambio* 31(2), pp. 120-125.

Xu, X., Ding, H., and Wang, X. 1995. "Acute effects of total suspended particulates and sulfur dioxide on preterm delivery: A community-based cohort study," *Archives of Environmental Health* 50(6), pp. 407-415.

Figure 1:
Number of Livestock Farms, by Animal Type, 1930-1997

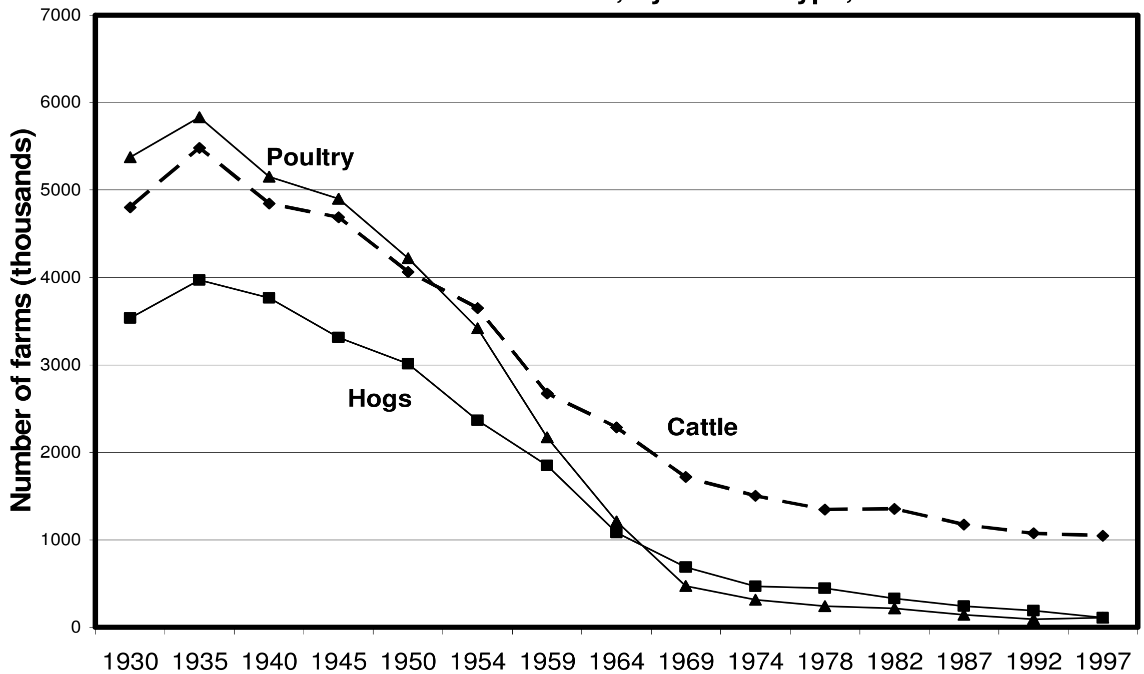
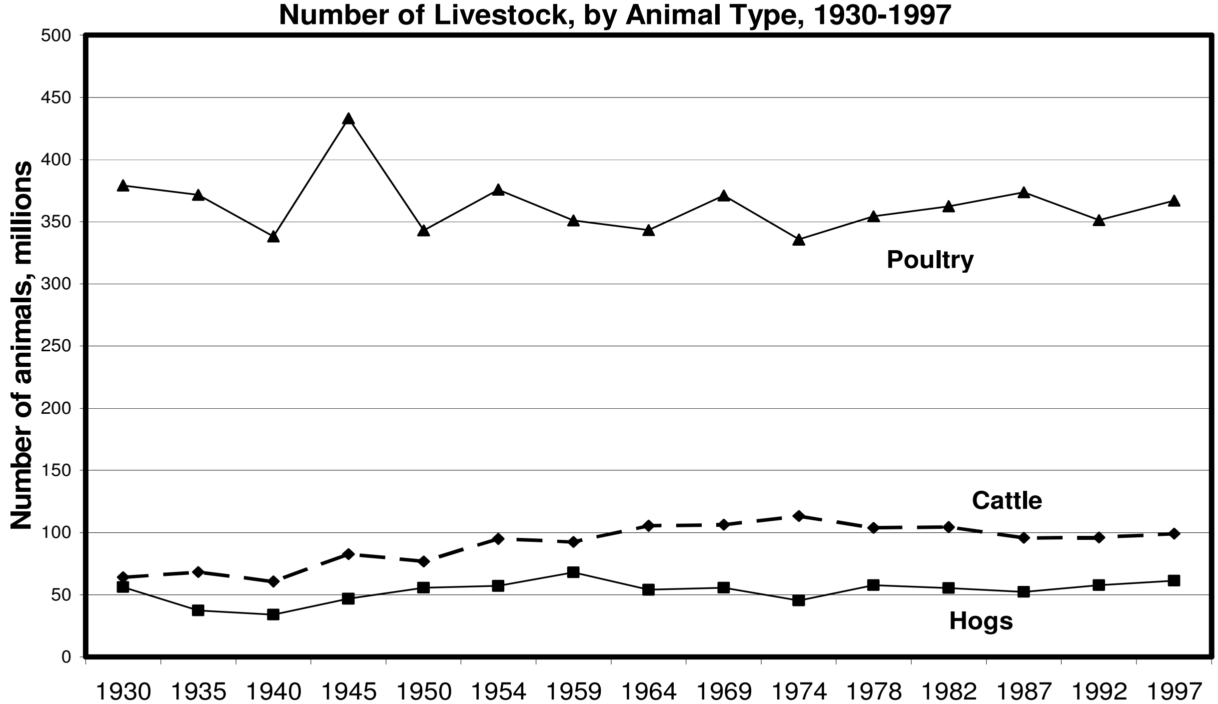
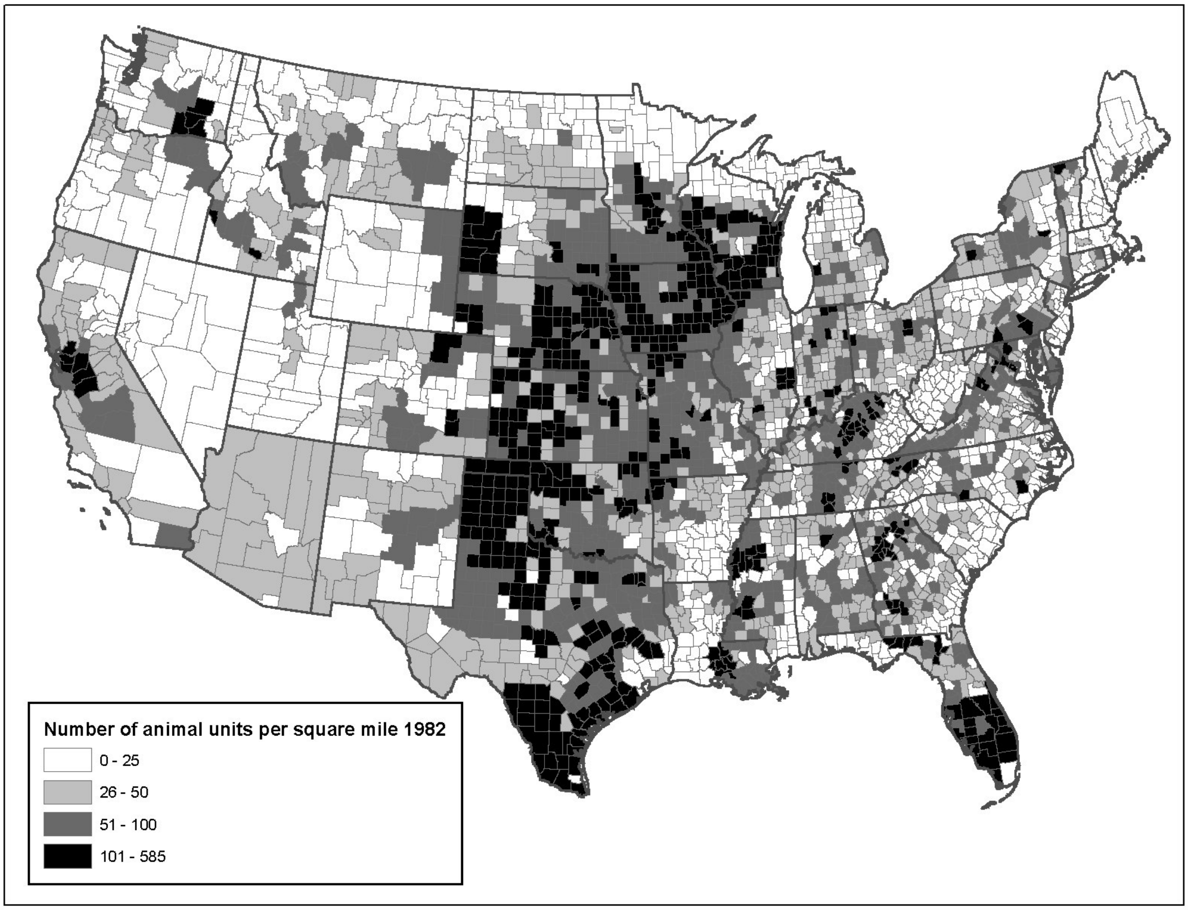


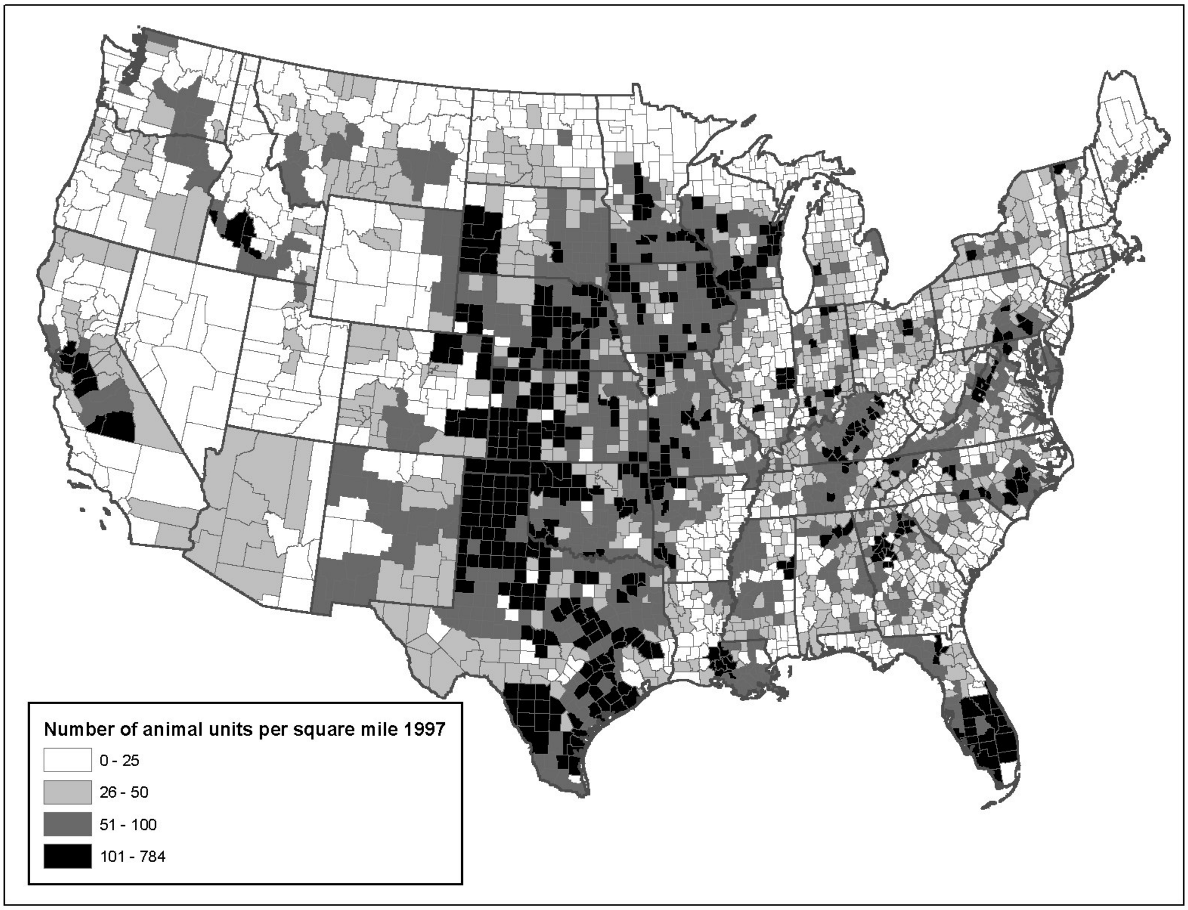
Figure 2:
Number of Livestock, by Animal Type, 1930-1997



Map 1: Number of Animal Units per Square Mile by County, 1982



Map 2: Number of Animal Units per Square Mile by County, 1997



Map 3: Percent Change in Number of Animal Units by County, 1982-1997

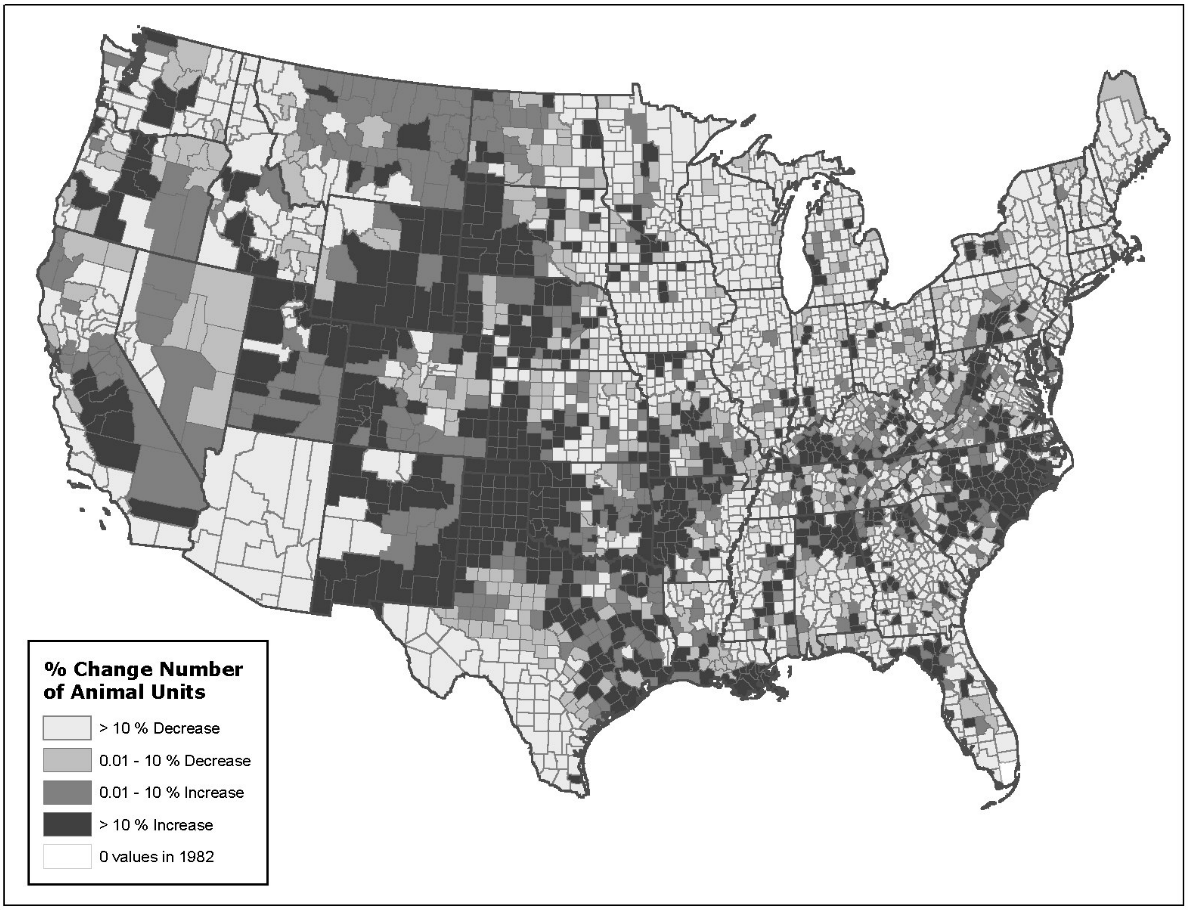


Table 1: Number of farms and animals, U.S., 1997

Panel 1

Type of animal	**Number of farms**	**Number of animals (inventory)**	**Number of animals/ Number of farms**
Cows	1,046,863	98,989,244	95
Hogs	109,754	61,206,236	558
Any poultry, layers 20 weeks old and older	69,761	313,851,480	4,499

Panel 2

Type of animal	**Size of large farm**	**Number of large farms**	**Number of animals (inventory)**	**Number of animals/ Number of large farms**	**% of all farms that are large farms**	**% of animals that are on large farms**
Cows	500 or more	25,510	37,827,098	1483	2.4%	38.2%
Hogs	1,000 or more	12,740	46,089,486	3618	11.6%	75.3%

Source: Author's calculations from United States Census of Agriculture, 1997. http://www.nass.usda.gov/census/ Website accessed January 5, 2004.

Table 2: Sample Statistics, by Period				
	Period 1	**Period 2**	**Period 3**	**Period 4**
	1980-1984	**1985-1989**	**1990-1994**	**1995-1999**
Number of counties or combined counties	2,300	2,303	2,303	2,317
Total births in sample	17,480,722	18,545,151	19,525,687	18,870,950
Total births in U.S.	17,930,501	19,071,312	20,075,545	19,393,294
Fatalities per 1,000 live births				
At 1 month	7.6	6.4	5.4	4.8
At 1 year	11.5	10.0	8.5	7.2
Mean county-level variables				
Number of animal units	40,522	38,690	39,046	40,432
Farm employment	1,325	1,175	1,097	1,089
% houses with well-water	31.9%	31.1%	30.4%	29.7%
% houses with septic tank	16.8%	4.0%	2.5%	1.8%
% houses built before 1950	40.4%	34.4%	30.0%	27.9%
Mean demograhic and socio-economic characteristics				
% of mothers without high school degree	17.0%	16.6%	23.3%	22.1%
% single mothers	19.5%	24.2%	29.9%	32.2%
% non-white	18.7%	19.6%	20.4%	20.0%
Age of mother	25.3	26.1	26.6	27.0
Average number of prenatal visits	9.4	9.8	11.2	11.6
Mean infant health variables				
Birthweight	3345.9	3348.4	3337.6	3322.9
% low birthweight (<2500 grams)	6.7%	6.8%	7.1%	7.4%
% very low birthweight (<1500 grams)	1.2%	1.2%	1.3%	1.4%
% premature	8.6%	9.7%	10.7%	11.2%

Notes: "Total births in U.S." excludes births in Hawaii, Alaska, and Washington, D.C. The births not covered by the sample occur mainly in the "consolidated cities" of Virginia. The Census of Agriculture data does not provide information on these units of analysis, hence they are excluded from the sample. Demographic means are weighted by number of births in a county.

Table 3: Sample description and means by sample

	SAMPLE				
	1 (Full sample)	**2 (Groundwater)**	**3 (NO_2)**	**4 (Ozone)**	**5 (SO_2)**
N	9,223	4,419	1,039	1,955	1,693
% of counties covered	95-96%	41-49%	8-16%	18-23%	15-22%
% of births covered	97%	65-68%	52-61%	65-73%	60-66%
Observations for unfiltered nitrate plus nitrite?	Partial	Y	Partial	Partial	Partial
Observations for NO_2?	Partial	Partial	Y	Partial	Partial
Observations for ozone?	Partial	Partial	Partial	Y	Partial
Observations for SO_2?	Partial	Partial	Partial	Partial	Y
Number of animal units	39,674	43,109	45,472	39,339	37,070
	(48,835)	(55,104)	(74,376)	(64,097)	(57,209)
Neonatal IMR	6.0	6.0	6.5	6.3	6.5
	(3.3)	(3.0)	(2.8)	(3.0)	(3.0)
IMR	9.3	9.3	9.9	9.5	9.8
	(4.4)	(4.1)	(3.8)	(4.1)	(4.1)
Farm employment	2,315.3	2,790.1	3,067.4	2,749.5	2,772.5
	(3,327)	(3,837)	(4,136)	(3,769)	(3,841)
% of mothers without high school degree	19.8%	19.3%	19.6%	19.2%	19.6%
	(0.104)	(0.101)	(0.107)	(0.104)	(0.104)
% non-white	19.7%	20.2%	22.3%	21.2%	21.8%
	(0.149)	(0.139)	(0.12)	(0.13)	(0.126)
Average age of mother	26.3	26.5	26.5	26.6	26.5
	(1.3)	(1.3)	(1.2)	(1.2)	(1.2)

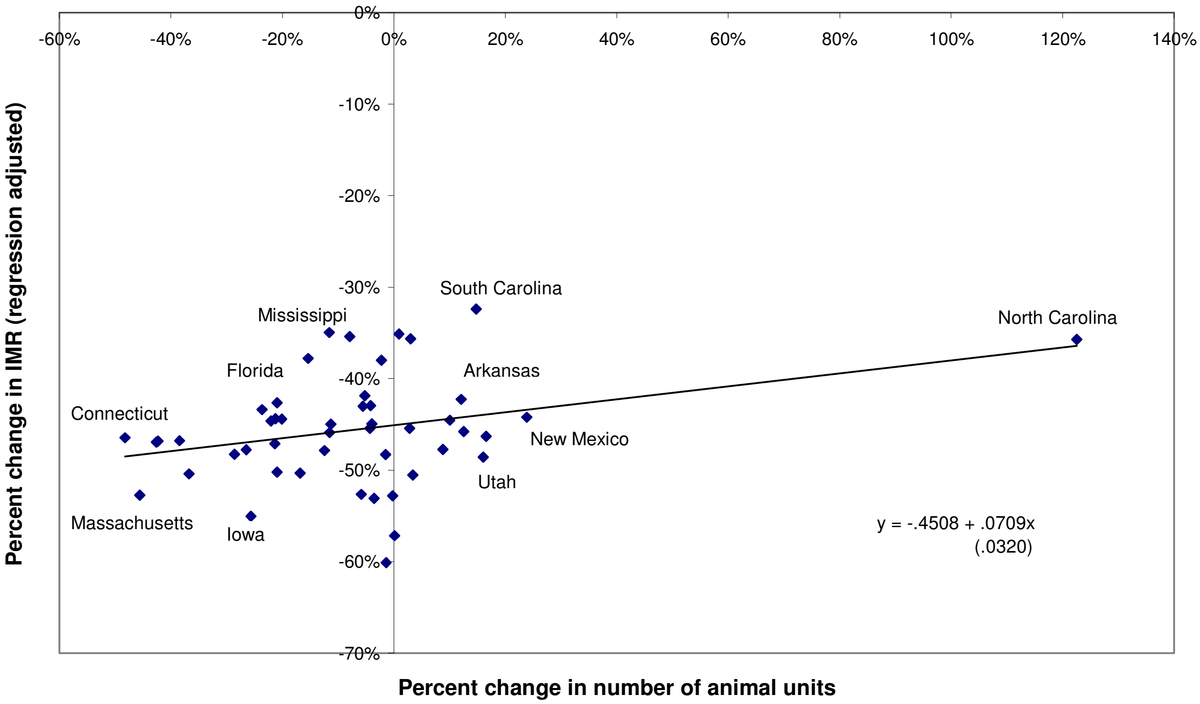
Notes: The unit of observation in these samples (N) is the county-period. "% of counties covered" refers to the contiguous counties, county-equivalents, or combined counties of the United States, excluding Hawaii, Alaska, and the District of Columbia. Excluded are the "consolidated cities" of Virginia. The total number of county or county equivalents in each period is 2,424. The range in this category is due to differing percentages being covered in different time periods.

Table 4: Water and Air Quality Means

	Sample #	Overall mean (1980-1999)	Period 1 (1980-1984)	Period 2 (1985-1989)	Period 3 (1990-1994)	Period 4 (1995-1999)
Unfiltered nitrate plus nitrite (as N) (mg/L)	2	5.7	8.3	5.7	4.4	4.7
Nitrogen dioxide (ppm)	3	0.0185	0.0215	0.0202	0.0176	0.0160
Ozone (ppm)	4	0.0495	0.0497	0.0507	0.0479	0.0497
Sulfur dioxide (ppm)	5	0.0074	0.0089	0.0081	0.0068	0.0051

	EPA maximum contaminant level or national ambient air quality standard
Unfiltered nitrate plus nitrite (as N) (mg/L)	10 mg/L
Nitrogen dioxide (ppm)	.053ppm (annual mean)
Ozone (ppm)	.12ppm (1-hour) or .08ppm (8-hour)
Sulfur dioxide (ppm)	.03ppm (annual mean) or.14ppm (24-hour)

Figure 3: Percent Change in IMR by Percent Change in Number of Animal Units, Period 1 to Period 4, by State



Note: Percent changes by state are averaged over counties. "Regression adjusting" refers to controlling for county and period fixed-effects.

Table 5: Cross Sectional Results: Regressions of Infant Mortality on Number of Animal Units, by Period

Observations weighted by number of births in the county

	Dependent Variable: IMR			
	Period 1	**Period 2**	**Period 3**	**Period 4**
Number of animal units (100,000)	0.197	0.135	0.186**	0.088**
	(0.162)	(0.187)	(0.052)	(0.044)
% male	-19.054	-9.037	4.356	-8.818**
	(12.85)	(15.8)	(4.962)	(4.473)
Average # prenatal visits	0.476**	0.567**	-0.044	-0.022
	(0.113)	(0.151)	(0.046)	(0.042)
% to white mother	-3.867**	-5.74**	-5.482**	-5.322**
	(1.79)	(1.877)	(0.545)	(0.489)
% mothers who were married	-23.215**	-23.332**	-6.01**	-5.018**
	(3.493)	(3.462)	(0.998)	(0.932)
Average mother's age	18.814**	33.746**	-0.945	-0.628
	(4.028)	(3.777)	(0.888)	(0.667)
Average mother's age squared	-0.39**	-0.665**	0.004	-0.003
	(0.079)	(0.072)	(0.017)	(0.013)
% births in hospital	-17.356**	-17.598**	-4.324*	-8.18**
	(7.523)	(8.942)	(2.407)	(2.265)
Log of per capita income	1.065	1.433	0.003	0.027
	(0.895)	(1.052)	(0.322)	(0.268)
Farm employment (/1000)	0.054	0.083*	0.027*	0.028**
	(0.042)	(0.05)	(0.016)	(0.014)
Population density (/1000)	-0.014	0.142**	-0.021*	-0.053**
	(0.037)	(0.044)	(0.012)	(0.011)
Controls for mother's education?	Y	Y	Y	Y
Controls for month of birth?	Y	Y	Y	Y
Housing covariates?	Y	Y	Y	Y
Land use covariates?	Y	Y	Y	Y
Precipitation covariates?	Y	Y	Y	Y
State controls?	Y	Y	Y	Y
R2	0.5	0.488	0.694	0.676
N	2,283	2,285	2,289	2,299

Table 6: Correlation between Number of Animal Units and Infant Mortality

Observations weighted by number of births in the county

	Dependent Variable							
	I	II	III	IV	V	VI	VII	VIII
	IMR	IMR	IMR	IMR	Neonatal IMR	Neonatal IMR	Neonatal IMR	Neonatal IMR
Number of animal units (100,000)	1.64**	0.777**	0.694**	0.601**	1.242**	0.616**	0.566**	0.542**
	(0.251)	(0.255)	(0.255)	(0.284)	(0.192)	(0.195)	(0.195)	(0.217)
% male		-11.777**	-10.564*	-9.403		-8.187*	-7.246	-6.88
		(5.893)	(5.856)	(5.82)		(4.521)	(4.486)	(4.448)
Average # prenatal visits		0.025	0.019	0.258**		0.032	0.029	0.169**
		(0.028)	(0.029)	(0.073)		(0.021)	(0.022)	(0.056)
% to white mother		21.387**	19.692**	27.435**		17.124**	15.734**	21.749**
		(2.069)	(2.116)	(2.486)		(1.587)	(1.621)	(1.9)
% mothers who were married		-9.946**	-7.589**	-16.027**		-6.112**	-4.5**	-11.727**
		(1.693)	(1.792)	(2.614)		(1.299)	(1.372)	(1.998)
Average mother's age		-18.437**	-15.56**	-18.653**		-13.845**	-11.564**	-13.591**
		(1.491)	(1.527)	(1.753)		(1.144)	(1.169)	(1.34)
Average mother's age squared		0.343**	0.294**	0.356**		0.256**	0.218**	0.26**
		(0.027)	(0.027)	(0.033)		(0.021)	(0.021)	(0.025)
Percent of births in hospital		-11.994**	-10.928**	-7.824		-11.242**	-10.399**	-7.722*
		(4.998)	(4.98)	(5.248)		(3.834)	(3.815)	(4.011)
Log of per capita income		-13.432**	-12.618**	-13.018**		-9.653**	-8.905**	-9.289**
		(0.867)	(0.885)	(1.151)		(0.665)	(0.678)	(0.88)
Farm employment (/1000)		0.31**	0.294**	0.386**		0.232**	0.22**	0.28**
		(0.103)	(0.104)	(0.109)		(0.079)	(0.08)	(0.083)
Population density (/1000)		-0.652**	-0.812**	-0.545*		-0.374**	-0.491**	-0.194
		(0.222)	(0.229)	(0.309)		(0.17)	(0.175)	(0.236)
Controls for mother's education?	N	Y	Y	Y	N	Y	Y	Y
Controls for month of birth?	N	Y	Y	Y	N	Y	Y	Y
Housing covariates?	N	Y	Y	Y	N	Y	Y	Y
Land use covariates?	N	N	Y	Y	N	N	Y	Y
Precipitation covariates?	N	N	Y	Y	N	N	Y	Y
Period fixed effects?	Y	Y	Y	Y	Y	Y	Y	Y
County fixed effects?	Y	Y	Y	Y	Y	Y	Y	Y
State*time controls?	N	N	N	Y	N	N	N	Y
R2	0.675	0.711	0.711	0.725	0.659	0.696	0.696	0.713
N	9,222	9,164	9,159	9,159	9,222	9,164	9,159	9,159

Table 7: Fixed Effects Regression of Log of IMR on Log of Animal Units

Observations weighted by number of births in the county

	Dependent Variable							
	Log of IMR	Log of IMR	Log of IMR	Log of IMR	Log of Neonatal IMR	Log of Neonatal IMR	Log of Neonatal IMR	Log of Neonatal IMR
Log of animal units	0.207**	0.089**	0.081**	0.063**	0.233**	0.102**	0.089**	0.07**
	(0.013)	(0.016)	(0.016)	(0.018)	(0.017)	(0.021)	(0.021)	(0.023)
% male		-0.994*	-0.771	-0.749		-1.313*	-1.032	-1.076
		(0.575)	(0.572)	(0.558)		(0.77)	(0.765)	(0.751)
Average number of prenatal visits		-0.001	-0.001	0.019**		0.002	0.002	0.017*
		(0.003)	(0.003)	(0.007)		(0.003)	(0.004)	(0.009)
% to white mother		1.341**	1.236**	1.986**		1.725**	1.623**	2.629**
		(0.199)	(0.204)	(0.236)		(0.26)	(0.266)	(0.31)
% of mothers who were married		-1.004**	-0.81**	-1.747**		-0.976**	-0.819**	-2.07**
		(0.163)	(0.172)	(0.248)		(0.214)	(0.224)	(0.327)
Average mother's age		-1.219**	-0.953**	-1.182**		-1.511**	-1.143**	-1.397**
		(0.145)	(0.149)	(0.169)		(0.19)	(0.194)	(0.222)
Average mother's age squared		0.023**	0.019**	0.024**		0.028**	0.022**	0.029**
		(0.003)	(0.003)	(0.003)		(0.003)	(0.003)	(0.004)
% of births in hospital		-1.599**	-1.487**	-1.243**		-2.456**	-2.275**	-1.871**
		(0.48)	(0.479)	(0.495)		(0.629)	(0.626)	(0.651)
Log of per capita income		-1.014**	-0.978**	-0.886**		-1.114**	-1.045**	-1.027**
		(0.085)	(0.087)	(0.112)		(0.111)	(0.113)	(0.147)
Farm employment (1000)		0.029**	0.031**	0.049**		0.039**	0.041**	0.062**
		(0.01)	(0.01)	(0.01)		(0.013)	(0.013)	(0.013)
Population density (1000)		-0.197**	-0.165**	-0.155**		-0.204**	-0.154**	-0.119**
		(0.037)	(0.037)	(0.045)		(0.048)	(0.048)	(0.059)
Controls for mother's education?	N	Y	Y	Y	N	Y	Y	Y
Controls for month of birth?	N	Y	Y	Y	N	Y	Y	Y
Housing covariates?	N	Y	Y	Y	N	Y	Y	Y
Land use covariates?	N	N	Y	Y	N	N	Y	Y
Precipitation variables?	N	N	Y	Y	N	N	Y	Y
County fixed effects?	Y	Y	Y	Y	Y	Y	Y	Y
Period fixed effects?	Y	Y	Y	Y	Y	Y	Y	Y
State*time controls?	N	N	N	Y	N	N	N	Y
R2	0.684	0.718	0.723	0.748	0.647	0.679	0.685	0.711
N	8,896	8,845	8,844	8,844	8,513	8,465	8,464	8,464

Table 8: Sensitivity Analyses: Fixed Effect Regressions of Infant Mortality on Number of Animal Units

Observations weighted by number of births in the county

	Dependent variable							
	IMR	**IMR**	**IMR**	**IMR**	**Neonatal IMR**	**Neonatal IMR**	**Neonatal IMR**	**Neonatal IMR**
Panel I: Sensitivity analysis 1 (One-year intervals)								
Number of animal units (100,000)	2.305**	1.209**	0.959**	0.943**	1.789**	1.027**	0.888**	0.889**
	(0.38)	(0.388)	(0.387)	(0.433)	(0.292)	(0.298)	(0.297)	(0.332)
Control for mother's education?	**N**	**Y**	**Y**	**Y**	**N**	**Y**	**Y**	**Y**
Controls for month of birth?	**N**	**Y**	**Y**	**Y**	**N**	**Y**	**Y**	**Y**
Controls for other demographic characteristics?	**N**	**Y**	**Y**	**Y**	**N**	**Y**	**Y**	**Y**
Housing covariates?	**N**	**Y**	**Y**	**Y**	**N**	**Y**	**Y**	**Y**
Land use covariates?	**N**	**N**	**Y**	**Y**	**N**	**N**	**Y**	**Y**
Precipitation covariates?	**N**	**N**	**Y**	**Y**	**N**	**N**	**Y**	**Y**
Period fixed effects?	**Y**	**Y**	**Y**	**Y**	**Y**	**Y**	**Y**	**Y**
County fixed effects?	**Y**	**Y**	**Y**	**Y**	**Y**	**Y**	**Y**	**Y**
State*period controls?	**N**	**N**	**N**	**N**	**N**	**N**	**N**	**N**
R2	0.581	0.621	0.624	0.643	0.57	0.611	0.614	0.634
N	9,222	9,156	9,151	9,151	9,222	9,156	9,151	9,151
Panel II: Sensitivity analysis 2 (Three-year intervals)								
Number of animal units (100,000)	1.923**	0.748**	0.576*	0.468	1.458**	0.58**	0.462**	0.433*
	(0.304)	(0.305)	(0.306)	(0.34)	(0.233)	(0.235)	(0.235)	(0.261)
Control for mother's education?	**N**	**Y**	**Y**	**Y**	**N**	**Y**	**Y**	**Y**
Controls for month of birth?	**N**	**Y**	**Y**	**Y**	**N**	**Y**	**Y**	**Y**
Controls for other demographic characteristics?	**N**	**Y**	**Y**	**Y**	**N**	**Y**	**Y**	**Y**
Housing covariates?	**N**	**Y**	**Y**	**Y**	**N**	**Y**	**Y**	**Y**
Land use covariates?	**N**	**N**	**Y**	**Y**	**N**	**N**	**Y**	**Y**
Precipitation covariates?	**N**	**N**	**Y**	**Y**	**N**	**N**	**Y**	**Y**
Period fixed effects?	**Y**	**Y**	**Y**	**Y**	**Y**	**Y**	**Y**	**Y**
County fixed effects?	**Y**	**Y**	**Y**	**Y**	**Y**	**Y**	**Y**	**Y**
State*period controls?	**N**	**N**	**N**	**N**	**N**	**N**	**N**	**N**
R2	0.619	0.666	0.667	0.687	0.602	0.65	0.651	0.674
N	9,222	9,157	9,152	9,152	9,222	9,157	9,152	9,152

Table 9: Sensitivity Analyses: Fixed Effect Regressions of Log of Infant Mortality on Log of Animal Units

Observations weighted by number of births in the county

	Dependent variable							
	Log of IMR	Log of IMR	Log of IMR	Log of IMR	Log of Neonatal IMR	Log of Neonatal IMR	Log of Neonatal IMR	Log of Neonatal IMR
Panel I: Sensitivity analysis 1 (One-year intervals)								
Log of animal units	0.261**	0.12**	0.11**	0.107**	0.237**	0.13**	0.118**	0.096**
	(0.023)	(0.028)	(0.028)	(0.032)	(0.03)	(0.037)	(0.037)	(0.042)
Control for mother's education?	N	Y	Y	Y	N	Y	Y	Y
Controls for month of birth?	N	Y	Y	Y	N	Y	Y	Y
Controls for other demographic characteristics?	N	Y	Y	Y	N	Y	Y	Y
Housing covariates?	N	Y	Y	Y	N	Y	Y	Y
Land use covariates?	N	N	Y	Y	N	N	Y	Y
Precipitation covariates?	N	N	Y	Y	N	N	Y	Y
Period fixed effects?	Y	Y	Y	Y	Y	Y	Y	Y
County fixed effects?	Y	Y	Y	Y	Y	Y	Y	Y
State*period controls?	N	N	N	N	N	N	N	N
R2	0.592	0.628	0.636	0.666	0.58	0.613	0.621	0.656
N	6,943	6,900	6,899	6,899	5,659	5,627	5,626	5,626
Panel II: Sensitivity analysis 2 (Three-year intervals)								
Log of animal units	0.27**	0.114**	0.111**	0.092**	0.3**	0.139**	0.135**	0.109**
	(0.017)	(0.02)	(0.02)	(0.022)	(0.022)	(0.026)	(0.026)	(0.03)
Control for mother's education?	N	Y	Y	Y	N	Y	Y	Y
Controls for month of birth?	N	Y	Y	Y	N	Y	Y	Y
Controls for other demographic characteristics?	N	Y	Y	Y	N	Y	Y	Y
Housing covariates?	N	Y	Y	Y	N	Y	Y	Y
Land use covariates?	N	N	Y	Y	N	N	Y	Y
Precipitation covariates?	N	N	Y	Y	N	N	Y	Y
Period fixed effects?	Y	Y	Y	Y	Y	Y	Y	Y
County fixed effects?	Y	Y	Y	Y	Y	Y	Y	Y
State*period controls?	N	N	N	N	N	N	N	N
R2	0.629	0.68	0.687	0.713	0.595	0.642	0.651	0.679
N	8,498	8,446	8,445	8,445	7,686	7,641	7,640	7,640

Table 10: Causes of infant death associated with livestock

IMR from cause of death (Dependent variable)	Coefficient on animal units (100,000)	Number of deaths per year
Congenital syphilis	-0.001	-4
	(0.001)	
Accidents and homicides	0.03	114
	(0.023)	
Gastritis, duodenitis, and noninfective enteritis and colitis	0.005	19
	(0.006)	
Certain intestinal infections	0.001	4
	(0.006)	
Diseases of blood and blood-forming organs	0.006	23
	(0.005)	
Acute upper respiratory infections	**0.016****	**61**
	(0.006)	
Bronchitis and bronchiolitis	**-0.016****	**-61**
	(0.006)	
Respiratory distress syndrome	**0.16****	**608**
	(0.051)	
Infections specific to the perinatal period	**0.05****	**190**
	(0.019)	
Certain conditions originating in the perinatal period*	**0.256****	**973**
	(0.118)	
Symptoms, signs, and ill-defined conditions	0.06	228
	(0.052)	
Congenital anomalies	0.108	410
	(0.094)	

*See text for listing of these conditions.

Notes: Total number of births in the period: 75,979,320.

Table 11: Fixed Effect Regressions of Other Health Outcomes on Number of Animal Units

Observations weighted by number of births in the county

	Dependent Variable				
	Birthweight	**% low birthweight (*100)**	**% very low birthweight (*100)**	**Five-minute Apgar score**	**% premature (*100)**
Panel 1: Linear					
Number of animal units (100,000)	5.895*	-0.101	-0.024	0.009	-0.1
	(3.319)	(0.135)	(0.064)	(0.025)	(0.165)
Demographic controls?	Y	Y	Y	Y	Y
Housing covariates?	Y	Y	Y	Y	Y
Land use and precipitation covariates?	Y	Y	Y	Y	Y
Precipitation variables?	Y	Y	Y	Y	Y
County fixed effects?	Y	Y	Y	Y	Y
Period fixed effects?	Y	Y	Y	Y	Y
State*time controls?	Y	Y	Y	Y	Y
R2	0.806	0.658	0.662	0.657	0.759
N	9,155	9,155	9,155	8,707	9,155
Panel 2: Nonlinear					
Number of animal units (100,000)	-0.388	0.113	0.104	-0.547**	0.424
	(7.413)	(0.301)	(0.143)	(0.052)	(0.368)
Number of animal units squared (100,000)	1.14E-5	-4.0E-7	-2.0E-7	1.1E-6**	-9.0E-7
	(1.2E-5)	(5.0E-7)	(2.0E-7)	(0.1E-6)	(6.0E-7)
Demographic controls?	Y	Y	Y	Y	Y
Housing covariates?	Y	Y	Y	Y	Y
Land use and precipitation covariates?	Y	Y	Y	Y	Y
Precipitation variables?	Y	Y	Y	Y	Y
County fixed effects?	Y	Y	Y	Y	Y
Period fixed effects?	Y	Y	Y	Y	Y
State*time controls?	Y	Y	Y	Y	Y
R2	0.806	0.658	0.662	0.665	0.759
N	9,155	9,155	9,155	8,707	9,155

Table 12: Regressions of Groundwater and Air Quality on Number of Animal Units

Regressions weighted by number of air quality observations.

	Dependent Variable							
	Nitrate plus nitrite	**Nitrate plus nitrite**	**NO2 (*1,000)**	**NO2 (*1,000)**	**Ozone (*1,000)**	**Ozone (*1,000)**	**SO2 (*1,000)**	**SO2 (*1,000)**
Number of animal units (100,000)	-1.707	-0.243	2.913**	1.772**	0.306	1.573**	0.091	0.391
	(1.09)	(1.227)	(0.734)	(0.668)	(0.591)	(0.547)	(0.696)	(0.712)
Percolation factor		-0.152		-0.202*		-0.341**		-0.062
		(0.201)		(0.116)		(0.096)		(0.102)
Total annual precipitation		0.151		0.093		0.33**		0.051
		(0.14)		(0.08)		(0.066)		(0.058)
% cultivated cropland		-2.135		31.111**		32.43**		2.354
		(12.766)		(13.145)		(10.317)		(7.254)
% noncultivated cropland		6.896		39.512**		44.448**		4.441
		(17.566)		(15.903)		(12.193)		(8.329)
% pastureland		25.111		28.544**		35.809**		4.063
		(18.294)		(14.402)		(11.116)		(7.892)
% rangeland		-39.662**		58.882**		77.08**		10.226
		(15.761)		(11.654)		(9.373)		(7.774)
% forest		-6.572		30.472**		40.432**		2.188
		(17.372)		(14.053)		(10.793)		(7.67)
% other rural land		-104.513**		-31.882		10.331		-1.841
		(36.738)		(22.766)		(15.715)		(10.541)
%urban land		25.597		-2.147		18.014*		-7.909
		(17.692)		(14.413)		(10.751)		(7.503)
% rural transportation land		-213.75		62.386		-74.594		78.432
		(219.828)		(146.222)		(92.258)		(54.821)
% small water areas		-415.148*		273.175*		260.605**		85.071
		(250.254)		(158.943)		(104.543)		(69.566)
Population density		-17.323**		-2.548*		-0.113		1.668**
		(5.26)		(1.469)		(1.171)		(0.656)
Controls for well, age of home, septic tank?	**N**	**Y**	**N**	**N**	**N**	**N**	**N**	**N**
County & period fixed effects?	**Y**	**Y**	**Y**	**Y**	**Y**	**Y**	**Y**	**Y**
State*period controls?	**N**	**Y**	**N**	**Y**	**N**	**Y**	**N**	**Y**
R2	0.741	0.863	0.943	0.973	0.877	0.931	0.887	0.932
N	4,418	4417	1,038	1,038	1,954	1,954	1,695	1,695

Table 13: Fixed Effects Nonlinear Regressions of Pollution on Animal Units

Regressions weighted by number of air quality observations.

	Dependent Variable							
	Nitrate plus nitrite	**Nitrate plus nitrite**	**NO2 (*1,000)**	**NO2 (*1,000)**	**Ozone (*1,000)**	**Ozone (*1,000)**	**SO2 (*1,000)**	**SO2 (*1,000)**
Animal units (100,000)	5.881	8.165*	24.418**	15.989**	22.507**	15.395**	9.383**	5.242*
	(5.218)	(4.731)	(2.065)	(2.429)	(1.825)	(1.998)	(3.048)	(3.112)
Animal units squared (100,000)	-3.5E-5*	-4.1E-5**	-8.0E-5**	-5.0E-5**	-8.0E-5**	-5.0E-5**	-1.3E-4**	-5.7E-5
	(2.-E-5)	(1.9E-5)	(9.1E-6)	(1.0E-5)	(7.1E-6)	(7.6E-6)	(0.3E-4)	(3.5E-5)
Animal units cubed (100,000)	4.0E-11*	5.0E-11**	7.7E-11**	4.7E-11**	7.3E-11**	4.4E-11**	4.8E-10**	2.1E-10*
	(2.0E-11)	(2.0E-11)	(1.1E-11)	(1.1E-11)	(0.8E-11)	(0.8E-11)	(1.2E-10)	(1.3E-10)
Animal units ^4 (100,000)							-5.4E-16**	-2.6E-16*
							(1.4E-16)	(1.4E-16)
Controls for well, age of home, septic tank?	**N**	**Y**	**N**	**N**	**N**	**N**	**N**	**N**
Precipitation controls?	**N**	**Y**	**N**	**Y**	**N**	**Y**	**N**	**Y**
Land use covariates?	**N**	**Y**	**N**	**Y**	**N**	**Y**	**N**	**Y**
County & period fixed effects?	**Y**	**Y**	**Y**	**Y**	**Y**	**Y**	**Y**	**Y**
State*period controls?	**N**	**Y**	**N**	**Y**	**N**	**Y**	**N**	**Y**
R2	0.741	0.862	0.954	0.975	0.892	0.934	0.889	0.932
N	4,418	4417	1,038	1,038	1,954	1,954	1,695	1,695

Table 14: Validity Checks: Regressions of Groundwater and Air-based Lead and Carbon Monoxide on Animal Units

	Dependent variable				
	Sample 1	Sample 2	Sample 3	Sample 4	Sample 5
Panel 1: Groundwater lead					
	Groundwater lead	Groundwater lead	Groundwater lead	Groundwater lead	Groundwater lead
Number of animal units (100,000)	-1123.926	-1123.926	12.592	-2189.57	-2535.231
	(900.294)	(900.294)	(56.979)	(2335.425)	(3108.033)
Land use, precipitation covariates?	Y	Y	Y	Y	Y
Housing controls?	Y	Y	Y	Y	Y
County fixed effects?	Y	Y	Y	Y	Y
Period fixed effects?	Y	Y	Y	Y	Y
State*period controls?	Y	Y	Y	Y	Y
R2	0.575	0.575	0.969	0.626	0.53
N	1,338	1,338	266	468	446
Panel 2: Air-based lead					
	Air-based lead (ppm)	Air-based lead (ppm)	Air-based lead (ppm)	Air-based lead (ppm)	Air-based lead (ppm)
Number of animal units (100,000)	0.1	0.119	0.047	0.034	0.057
	(0.134)	(0.091)	(0.127)	(0.133)	(0.17)
Land use, precipitation covariates?	Y	Y	Y	Y	Y
Housing controls?	Y	Y	Y	Y	Y
County fixed effects?	Y	Y	Y	Y	Y
Period fixed effects?	Y	Y	Y	Y	Y
State*period controls?	Y	Y	Y	Y	Y
R2	0.868	0.959	0.927	0.851	0.899
N	1,175	740	579	800	773
Panel 3: Carbon monoxide					
	Carbon Monoxide (ppm) (*1000)	Carbon Monoxide (ppm) (*1000)	Carbon Monoxide (ppm) (*1000)	Carbon Monoxide (ppm) (*1000)	Carbon Monoxide (ppm) (*1000)
Number of animal units (100,000)	89.993	105.873	70.692	78.622	115.896
	(64.61)	(72.393)	(69.769)	(66.015)	(76.569)
Land use, precipitation covariates?	Y	Y	Y	Y	Y
Housing controls?	Y	Y	Y	Y	Y
County fixed effects?	Y	Y	Y	Y	Y
Period fixed effects?	Y	Y	Y	Y	Y
State*period controls?	Y	Y	Y	Y	Y
R2	0.923	0.943	0.937	0.925	0.945
N	928	628	606	821	723

Table 15: Instrumental variable results: Ozone and infant health

	Dependent variable		
	IMR	**Neonatal IMR**	**Five-minute Apgar score**
Predicted Ozone	1488.328**	1230.179**	-181.006**
	(510.602)	(422.034)	(62.09)
Nitrate plus Nitrite	-0.004	-0.002	-0.002
	(517.603)	(427.821)	(62.941)
Natality covariates?	Y	Y	Y
Economic covariates?	Y	Y	Y
Housing covariates?	Y	Y	Y
Land use covariates?	Y	Y	Y
Precipitation covariates?	Y	Y	Y
County & period fixed effects?	Y	Y	Y
State*period effects?	Y	Y	Y
R2	0.869	0.85	0.716
N	1,132	1,132	1,132

Table 16: Summary of results by sample

			Column (1)	Column (2)	Column (3)	Column (4)
Panel 1: IMR						
			Reduced form	**Reduced form**	**First stage**	**Instrumental Variables**
			Dep. Var.: IMR	Dep. Var.: IMR	Dep. Var.: Ozone	Dep. Var.: IMR
			(without Nitrate as covariate)	(with Nitrate as covariate)		(with Nitrate as a covariate)
Row	**Sample**	**N**	Coefficient on AU	Coefficient on AU	Coefficient on AU	Coefficient on predicted Ozone
(a)	1	9,159	0.601			
(b)	4	1,957	0.115		0.0016	
(c)	6	1,161	0.392	0.382	0.000257	1488.3
Panel 2: Neonatal IMR						
			Reduced form	**Reduced form**	**First stage**	**Instrumental Variables**
			Dep. Var.: Neonatal IMR	Dep. Var.: Neonatal IMR	Dep. Var.: Ozone	Dep. Var.: Neonatal IMR
			(without Nitrate as covariate)	(with Nitrate as covariate)		(with Nitrate as a covariate)
Row	**Sample**	**N**	Coefficient on AU	Coefficient on AU	Coefficient on AU	Coefficient on predicted Ozone
(d)	1	9,159	0.542			
(e)	4	1,957	0.173		0.0016	
(f)	6	1,161	0.322	0.316	0.000257	1230.2
Panel 3: 5-minute Apgar score						
			Reduced form	**Reduced form**	**First stage**	**Instrumental Variables**
			Dep. Var.: Apgar	Dep. Var.: Apgar	Dep. Var.: Ozone	Dep. Var.: Apgar
			(without Nitrate as covariate)	(with Nitrate as covariate)		(with Nitrate as a covariate)
Row	**Sample**	**N**	Coefficient on AU	Coefficient on AU	Coefficient on AU	Coefficient on predicted Ozone
(g)	1	9,159	0.01			
(h)	4	1,957	-0.018		0.0016	
(i)	6	1,132	-0.042	-0.046	0.000257	-181

Notes: Sample 6 refers to the sample with observations for both nitrate plus nitrite and ozone. "AU" refers to animal units in the 100,000's. See text for further explanation of table.

Figure 4: Marginal benefits versus marginal costs of protection against air versus water pollution from livestock farms