Multiple Environmental Externalities and Manure Management Policy

Nigel D. Key and Jonathan D. Kaplan

This paper considers the economic and environmental implications of regulating water and air nitrogen emissions under single and multi-environmental media policies in the U.S. hog industry. We examine tradeoffs from policies designed to correct an externality in one medium, when there are multiple environmental externalities. We separately and jointly analyze: (a) nitrogen land application restrictions consistent with recently adopted EPA requirements under the Clean Water Act, and (b) hypothetical air quality restrictions under the Clean Air Act, both with and without EQIP payments available to mitigate the costs of complying with nutrient application regulations.

Key words: ammonia emission, livestock waste, mathematical programming, multiple externalities, nutrient management

Introduction

One of the difficulties in addressing the environmental problems associated with livestock waste is that manure can pollute multiple media (air, water, and soil) along multiple dimensions. Air quality concerns related to manure include odorous gases (ammonia and hydrogen sulfide), particulate material (by-products of ammonia), and greenhouse gases (methane and nitrous oxide). Water pollutants from manure include nitrogen, phosphorus, antibiotics, and pathogens. The theory of the second best demonstrates that the correction of a single market distortion without simultaneously correcting other sources of market failure can lead to Pareto-inferior resource allocations (Lipsey and Lancaster, 1956). The theory implies that policies to address pollution in a single medium could worsen pollution in other media, resulting in lower societal welfare. This paper considers the economic and environmental implications of regulating both water and air nitrogen emissions under single-environmental medium and multi-environmental media policies in the U.S. hog industry. Particular attention is paid to tradeoffs which occur when policies are designed to correct an externality in one medium without considering externalities in other media.

The U.S. Environmental Protection Agency (USEPA) continues to revise regulations for concentrated animal feeding operations (CAFOs) under the Clean Water Act. These

---

1 Only certain chemical compounds of nitrogen are considered potential pollutants because they are nutrients for plants and microorganisms (e.g., ammonium and nitrate), or because they can be precursors for particulate matter (ammonia), or because they are considered “green house gas” (nitrous oxide).

2 CAFOs are defined in this study using the December 2004 EPA definition of a “large CAFO” as 2,500 head of swine weighing 55 pounds or more (Aillery et al., 2005).
regulations require, among other things, that CAFOs which land-apply manure meet nutrient application standards defined by a Comprehensive Nutrient Management Plan (USEPA, 2003). To help defray the costs of meeting the new regulations, producers can apply for financial assistance from the U.S. Department of Agriculture's (USDA's) Environmental Quality Incentives Program (EQIP). Producers can receive up to $450,000 per farm during 2002–2007 to help them develop and implement a nutrient management plan, and to transfer and apply manure to land in an approved manner (Ribaudo, Cattaneo, and Agapoff, 2004).

Although livestock are the largest source of ammonia emissions in the United States [National Research Council (NRC), 2003], neither state nor federal governments currently regulate nitrogen air emissions from animal feeding operations. However, ammonia nitrogen emissions could be regulated under the PM2.5 particulate standard of the Clean Air Act. According to the National Research Council, "Ammonia is regulated as a precursor for PM2.5, which is a criteria pollutant. Hence it may be considered a regulated air pollutant" (p. 42). The EPA is currently developing Federal PM2.5 rules for animal feeding operations (USEPA, 2004, 2006).

Some past research has considered the effect of livestock production across multiple environmental media. Innes (2000) develops a spatial model of regional livestock production and three associated externalities: spills from animal waste storage facilities, nutrient runoff from excess application of manure to croplands, and ambient pollution. He models the regulation of waste storage lagoon "quality," the number of animals in the production facility, or the distances between facilities. An important premise of Innes' analysis is that regulators are unable to monitor environmental outcomes, including manure application rates. In fact, recently implemented EPA CAFO regulations are predicated on verifiable nutrient application plans. Feinerman, Bosch, and Pease (2004) extend Innes' analysis by evaluating state regulatory standards for manure spreading in Maryland and Virginia. Their approach uses a derived manure demand function to simulate the effects of manure spreading regulations on welfare and excess nutrient loading in soil.

In this study, we empirically analyze the theory of the second best by extending the scope of these past analyses to consider current federal manure spreading regulations and potential federal air emission regulations. To our knowledge, this is the first analysis of potential air emission controls on livestock operations in conjunction with land application restrictions. The analysis also provides an empirical estimation of the potential rate and cost of policy-induced technology adoption. Specifically, this analysis assesses the environmental and economic implications of: (a) nitrogen land application restrictions consistent with recently adopted EPA requirements for CAFOs under the Clean Water Act, (b) hypothetical air quality (PM2.5) restrictions for CAFOs under the Clean Air Act, and (c) joint manure application and PM2.5 restrictions. The study

---

2 This study considers only a restriction on the land application of manure based on the nitrogen content of the manure, sometimes referred to as an N standard, rather than based on the phosphorus content (a P standard), or on a restriction based on both nitrogen and phosphorus content. With a P standard, some farms could face a binding soil nutrient constraint at lower levels of applied manure. That is, the P standard could become binding before the N standard, so that less manure could be land-applied per acre, and thus the magnitude of the changes in cropping and animal decisions would increase. There are several reasons why we consider only an N standard. First, adding a restriction on phosphorus into the model would complicate the analysis but would not alter the qualitative results. The main purpose of this analysis is to illustrate tradeoffs between air and water pollution in the regulation of air and soil nitrogen emissions. The use of the N standard is the most
focuses on the hog sector, and the three policy scenarios are analyzed with and without EQIP payments that are currently available to CAFOs to mitigate the costs of manure application regulations. We consider the effect of these policies on both water quality via excess soil nutrient applications and on air quality via ammonia emissions from manure storage facilities and land applications.

To assess the impact of these policy alternatives, we construct a positive mathematical programming (PMP) model where producers maximize returns above select variable costs, hereafter referred to simply as returns, subject to resource and regulatory constraints. This approach calibrates the model to base year data without having to add constraints that cannot be justified by economic theory (Howitt, 1995). PMP takes advantage of the fact that it is easier to collect information about output and input levels at the operation level than information about costs. The observed output and input levels result from a complicated decision process based in part on cost function that is known to the operator but difficult or impossible to observe directly. Some costs—perhaps associated with the environment, risk, or technology—may be hidden to the researcher even when a detailed survey instrument is available. PMP incorporates information about unobservable costs by using quadratic cost function that approximates the true underlying cost function.

In the model, nitrogen enters through the feed ration and is retained by the animals or excreted in manure. Nitrogen from manure may be released into the atmosphere through air emissions from barns, manure storage and handling facilities, or fields on which manure has been applied. Nitrogen enters cropland through commercial and manure fertilizer applications. Crops retain some nitrogen, some is bound in the soil substrate, and some is released through air emissions, leaching, and water runoff. Using relationships from the scientific literature, we estimate the level of nitrogen available for runoff into surface and groundwater based on the estimated quantity of nutrients applied to the land and the crop nutrient uptake. Air emissions are estimated based on total animal production, type of storage facility, and the manure application technology used by the animal feeding operation.

The model is calibrated with data compiled from the 1998 USDA Agricultural Resource Management Survey (ARMS) of hog operations. We model the decisions of eight representative CAFOs—corresponding to four major hog-producing regions (East Corn Belt, West Corn Belt, Mid-Atlantic, and the South and West) and two major manure storage technologies (lagoon and pit). The model considers two technological options currently available to hog operations that influence the level of ammonia released to the air: (a) the injection of manure into the soil and (b) covering lagoons.

Results demonstrate that policies designed to account for only one environmental externality may have unintended consequences in other environmental media. Specifically, imposing ammonia nitrogen standards on CAFOs in the absence of nutrient application standards would result in an increase in excess nitrogen applied to soil. However, imposing nutrient application standards consistent with 2003 EPA regulations...
results in negligible changes in air nitrogen emissions. Somewhat counterintuitively, the introduction of government payments to defray the cost of complying with application standards is found to lead to greater on-farm use of chemical fertilizer. EQIP payments lower manure transport costs and make it relatively cheaper for CAFOs to transport manure off-farm than to increase on-farm manure applications. The study also provides information about the rate and cost of ammonia abatement technology adoption and the levels of ammonia nitrogen reduction for operations complying with joint air and soil nitrogen standards.

**Multimedia Manure Management**

The model presented in the next section captures the essential tradeoffs between air and water emissions. How manure is stored and disposed of largely determines the relative degradation of air and water quality. The application of manure to fields when nutrients in the manure exceed what crops can absorb has been associated with increased algae production, reduced fish populations, and diminished recreational opportunities (USEPA, Office of Water, 1998). Because of the high cost of transporting manure relative to the value of the nutrients contained in the manure, CAFO operators have an incentive to over-apply manure to land located near their livestock facilities. A nutrient application standard can force operators to transport manure a significant distance from their hog facility. Operators constrained by an application standard can apply more manure per acre, and thereby reduce their manure transportation costs, by reducing manure’s nutrient content through storage in lagoons prior to application.

Ammonia emissions from manure storage facilities and from manure applied to fields may impair air quality downwind and contribute to acidification, fertilization, and eutrophication through atmospheric deposition (NRC, 2003). Lagoons reduce the manure nutrient content through nitrogen volatilization in the form of ammonia. Manure lagoons may be covered to reduce ammonia emissions, but this raises the manure nitrogen content and increases the land required for manure disposal under an application constraint. Ammonia nitrogen emissions from fields can be reduced through subsurface injection of the manure. Injecting manure into the soil increases the nitrogen available to the crops, but this reduces the quantity of manure that can be applied to a field under a nutrient application standard, increasing the land required for manure disposal and therefore raising manure transportation costs.

Figure 1 illustrates how single-medium policies can raise or lower social welfare in the context of multiple environmental externalities. The figure shows an isocost curve for a representative CAFO and four social indifference curves. The origin represents the state of no environmental regulations. Moving out along the x-axis implies less excess soil nitrogen and hence less surface water degradation. Moving out along the y-axis implies less ammonia nitrogen emissions. First, consider a single-medium soil nitrogen application standard that reduces excess soil nitrogen to \( S \) with no change in ammonia emissions. This policy raises welfare, illustrated by the movement from the indifference curve IO to IS. Now consider a single-medium ammonia nitrogen standard \( \hat{A} \) that costs producers the same as the application standard \( \hat{S} \). For the specific case illustrated, society is worse off with a single-medium ammonia standard than with no regulations at all because the ammonia standard results in an increase in excess soil nitrogen.
Figure 1. Isocost for representative CAFO and hypothetical social indifference curves

Figure 1 also illustrates how a coordinated multimedia regulatory regime could achieve a constrained optimum combination of emissions reductions. For the same cost as the single-medium policies (same isocost), social welfare is maximized at the soil and ammonia standards indicated by \((S^*, A^*)\). If both standards \(A\) and \(S\) are imposed, higher social welfare could be obtained, but at a higher cost (not illustrated in the figure).

**Empirical Model**

A PMP model to evaluate the economic consequences of soil and air nitrogen standards is developed in three stages. First, a constrained linear programming model is used to derive dual values associated with the calibration constraints defined below. Second, the dual values are used to parameterize a calibrated quadratic objective function. Finally, the calibrated model is used for economic analysis, by imposing environmental policy constraints.

**Linear Program to Calculate Dual Values**

The linear objective is to maximize total net revenues:

\[
\max_{X_{1,r}} \sum_r \sum_i X_{1,i,r}(P_{i,r} - C_{i,r}),
\]

where \(X_{1,i,r}\) is the level of each output \(i\) in region \(r\), and \(P_{i,r}\) is the price. The cost of producing each output is:
\[ C_{i,r} = \sum_j A_{i,j,r} W_{j,r}, \]

where \( A_{i,j,r} \) is the amount of input \( j \) required to produce a unit of output, and \( W_{j,r} \) is the input price. The optimization is subject to \( j \times r \) resource constraints:

\[ \sum_i A_{i,j,r} X_{1,i,r} \leq \sum_i A_{i,j,r} X_{0,i,r}, \quad \forall j, r, \]

where \( X_{0,i,r} \) is the initial observed activity level, so that

\[ \sum_i A_{i,j,r} X_{0,i,r} \]

is the initial level of input \( j \).

Inputs include land, capital, feeder pigs, feed corn, feed soy, and chemical fertilizer nitrogen. Outputs include hogs, corn, soybeans, and “other crops” (defined as the value of all other crops produced). All three crops can be produced under three fertilization regimes: (a) chemical fertilizer, (b) manure fertilizer surface applied, or (c) manure fertilizer injected into the soil. The calibration constraints for all 10 activities are:

\[ X_{1,i,r} \leq X_{0,i,r}(1 + \varepsilon_1), \quad \forall i, r \quad \text{dual: } \hat{\lambda}_{i,r}, \]

where \( \varepsilon_1 \) is a small perturbation (see Howitt, 1995). The shadow values associated with the calibration constraints (\( \hat{\lambda}_{i,r} \)) are used in the next subsection to estimate a cost function which characterizes the agent’s objective function.

When there is an exogenous policy change, a greater elasticity of substitution would be expected between a single crop’s three fertilization regimes than between different crops, because the variant activities are relatively similar (for further discussion, see Röhm and Dabbert, 2003). For example, if an exogenous policy change raises the cost of using manure, we would expect a relatively large shift in land from corn-manure (surface applied or injected) to corn-chemical fertilizer, and a relatively small shift in land between corn and “other crops.” However, the standard PMP model treats crops produced under different fertilization regimes as if they were different crops, resulting in “too little” substitution within a crop and “too much” substitution across crops. To allow for a greater policy response within crop “variant activities,” which here correspond to three fertilization regimes (chemical, surface-applied manure, and injected manure), we use the extension of PMP developed by Röhm and Dabbert (2003), which in this application requires three additional calibration constraints corresponding to each crop’s set of variant activities:

\[ \sum_{i \in \text{cov}} X_{1,i,r} \leq \sum_{i \in \text{cov}} X_{0,i,r}(1 + \varepsilon_2), \quad \forall r \quad \text{dual: } \hat{\lambda}_{\text{corn},r}, \]

\[ \sum_{i \in \text{soy}} X_{1,i,r} \leq \sum_{i \in \text{soy}} X_{0,i,r}(1 + \varepsilon_3), \quad \forall r \quad \text{dual: } \hat{\lambda}_{\text{soy},r}, \]

and

\[ \sum_{i \in \text{other}} X_{1,i,r} \leq \sum_{i \in \text{other}} X_{0,i,r}(1 + \varepsilon_4), \quad \forall r \quad \text{dual: } \hat{\lambda}_{\text{other},r}, \]
where \( cv \) is the set of corn variant activities: \( cv = \{ \text{corn chemical fertilizer, corn surface-applied manure, corn injected manure} \} \); \( sv \) is the set of soybean variant activities; \( ov \) is the set of “other crops” variant activities; and \( \varepsilon_5, \varepsilon_3, \) and \( \varepsilon_i \) are small perturbations.\(^4\)

From the 1998 ARMS and other sources, we observe prices \( P_{1,r} \) and \( W_{1,r} \), the output levels \( X0_{i,r} \), and most of the input-output coefficients \( A_{i,j,r} \) (for details, see Allerly et al., 2005, web Appendix A). It would be desirable to include manure nitrogen as an input. However, we do not observe manure application rates, only the amount of land on which manure is applied.

**Estimation of Calibrated Quadratic Cost Function**

Next, quadratic total variable costs are defined as \( \frac{1}{2} \dot{Q}_{i,r} X2_{i,r}^2 \), where

\[
\begin{align*}
\dot{Q}_{1,r} &= (\dot{\lambda}_{1,r} + C_{1,r}) / X0_{1,r} \quad \text{for } i = \text{hogs}, \\
\dot{Q}_{i,r} &= (\dot{\lambda}_{i,r} + \dot{\lambda}_{corn,r} + C_{i,r}) / X0_{i,r} \quad \text{for } i \in cv, \\
\dot{Q}_{i,r} &= (\dot{\lambda}_{i,r} + \dot{\lambda}_{soy,r} + C_{i,r}) / X0_{i,r} \quad \text{for } i \in sv, \\
\dot{Q}_{i,r} &= (\dot{\lambda}_{i,r} + \dot{\lambda}_{other,r} + C_{i,r}) / X0_{i,r} \quad \text{for } i \in ov,
\end{align*}
\]

and \( X2_{i,r} \) is output in this stage. The objective in this stage is to maximize total net revenues:

\[
\max_{X2_{i,r}} \sum_r \sum_i P_{i,r} X2_{i,r} - \frac{1}{2} \dot{Q}_{i,r} X2_{i,r}^2
\]

subject to the resource constraints:

\[
\sum_i A_{i,j,r} X2_{i,r} \leq \sum_i A_{i,j,r} X0_{i,r}, \quad \forall j, r.
\]

Solution of the nonlinear optimization problem defined by (6) and (7) results in the initial output levels \( X0_{i,r} \) (within a very small error).

**Estimation of Activity Levels for Policy Scenarios**

**Using Calibrated Cost Function**

Having characterized the operation's nonlinear optimization problem that results in the observed initial values, the final stage involves imposing policy constraints and comparing solutions to the initial values. The policies considered here are the CAFO nitrogen application constraint and a potential ammonia emission constraint. CAFOs can respond to policy constraints by adjusting input and output levels. Pit storage operations can

---

\(^4\) As noted by Howitt (1995), the positive yet small perturbation coefficients are chosen so the technology constraint is not dependent on the calibration constraint, the number of constraints is reduced so the problem is no longer degenerative, and the technology constraint remains unchanged. To ensure the constraints on the total crops are more limiting than the constraints on the variants, the perturbation coefficients for equations (4a), (4b), and (4c) are smaller than the perturbation coefficient for equation (5) (i.e., \( \varepsilon_2 = \varepsilon_3 = \varepsilon_i = 0.0001 \) and \( \varepsilon_1 = 0.00011 \)). Röhm and Dabbert (2003) provide further discussion on this latter condition.
vary the amount of land on which they inject versus surface-apply manure slurry in order to alter the ammonia emitted to the air and the nutrients available to plants. Lagoon operations can cover their lagoons to reduce air ammonia emissions.\textsuperscript{5} EQIP payments enter the operation's decision problem by reducing costs of abiding by the CAFO rules.\textsuperscript{6}

To evaluate alternative policies, we incorporate into the optimization manure transportation costs that depend on manure storage and application technologies. Prior to implementation of the CAFO manure application rules, CAFOs had little incentive to transport manure off-farm, and few did. According to the 1998 survey, fewer than 2\% of all animal feeding operations transported manure off-farm. The CAFO manure application rules require CAFOs to apply manure at a rate not exceeding the crop nutrient uptake. As discussed above, CAFOs who do not cultivate adequate cropland will respond to the application regulations by transporting some manure off-farm (Ribaudo et al., 2003).

For the policy analysis, the objective becomes:

\[
\max_{X3_{i,r}, COV_r, MAF_r} \sum_r \sum_i (1 + s_{crop}) P3_{i,r} X3_{i,r} - \frac{1}{2} Q_{i,r} X3_{i,r}^2 - (1 - s_{tran}) MTC_r - COV_r \cdot \kappa \cdot X3_{hogs,r},
\]

where \(X3_{i,r}\) is the optimal output level given the policy constraints. With nutrient application standards, costs now include off-farm manure transportation costs \(MTC_r\), which depends in part on the rate at which manure is applied on-farm \(MAF_r\). CAFOs eligible for EQIP payments receive subsidies equal to a share \(s_{tran}\) of their manure transportation costs. CAFOs also receive a per acre EQIP subsidy \(s_{crop}\) for applying manure at the agronomic rate. The decision to install a lagoon cover is reflected in the binary choice variable \(COV_r\) (1 if covered, 0 otherwise). Since lagoon size is proportional to hog output, the cost of a lagoon cover is assumed to be a fixed proportion \(\kappa\) of total hog output (for sources and values of the parameters used in the analysis, see Aillery et al., 2005, web Appendix A).

Manure transportation costs equal the quantity of hogs used to produce manure transported off-farm \((H_{.OFF,r})\) multiplied by manure transportation costs per hundredweight of hog:

\begin{align}
MTC_r &= H_{.OFF,r} \cdot COV_r \cdot t_c + \left(1 - COV_r\right) \cdot t_{tu}, \\
MTC_r &= H_{.OFF,r} \cdot INJ_r \cdot t_i + \left(1 - INJ_r\right) \cdot t_{ts}.
\end{align}

Manure transportation costs are distinguished for lagoon operations (9) which may or may not cover their lagoons, and for pit storage operations (10) which may inject (versus surface-apply) manure into some portion of the land on which manure is applied. Estimates for the transportation costs per hundredweight of hog \((t_c, t_{tu}, t_i, t_{ts})\) depend on the manure storage and handling technology: covered lagoon, uncovered lagoon, covered pit, and uncovered pit.

\textsuperscript{5} Because they represent large sunk costs, manure storage facilities (lagoon/pit) are considered exogenous in this analysis. In addition, the anaerobic process characteristic of lagoons generally limits lagoon use to warmer climates. Injection is not considered an option for lagoon operations because, following Fulitage, Pfost, and Schuster (2002), "lagoon effluent applied by irrigation is assumed to be incorporated as soon as it enters the soil."

\textsuperscript{6} For this analysis it is assumed all CAFOs are eligible for and receive EQIP payments. In fact, operators must apply for EQIP payments and be accepted into the program. In addition, EQIP may face financing constraints that would limit payment availability. This possibility is not considered in this analysis.
injected pit storage, and surface-applied pit storage, respectively, and are based on a transportation cost model proposed by Fleming, Babcock, and Wang (1998).\footnote{For a complete listing of the variables and data sources for the variables used in the programming model, see Aillery et al. (2005, web Appendix A).}

For lagoon operations, $COV$, is a binary choice variable. For pit storage operations, $INJ$, is the share of manure-applied cropland on which manure is injected:

\[
INJ_r = \frac{\sum_{i \in m} A_{i,\text{land},r} X_{i,r}}{\sum_{i \in m} A_{i,\text{land},r} X_{i,r}},
\]

where $m$ is the set of all manure-applied cropping activities (corn, soybeans, and other crops, either spread or injected) and $mi$ is the set of manure-injected cropping activities.

The quantity of hogs that produce manure applied off-farm equals the total hogs produced minus the number of hogs required to produce the nitrogen from manure applied on-farm:

\[
H_{\text{OFF},r} = X_3\text{hogs},r - \left(MAF_r \sum_{i \in m} X_{3_i},r A_{i,fertN},r \right) \left(\frac{COV_r}{nc} + \frac{1 - COV_r}{nu}\right),
\]

\[
H_{\text{OFF},r} = X_3\text{hogs},r - \left(MAF_r \sum_{i \in m} X_{3_i},r A_{i,fertN},r \right) \left(\frac{INJ_r}{ni} + \frac{1 - INJ_r}{ns}\right),
\]

for lagoon (12) and pit operations (13). The number of hogs required to produce the nitrogen from manure applied on-farm equals the manure nitrogen used on-farm divided by the manure nitrogen available to crops per hundredweight of hogs ($nc, nu, ni, and ns$ for covered and uncovered lagoons and injected or surface-applied manure, respectively). The manure nitrogen used on-farm equals the pounds of manure nitrogen applied on-farm if it was applied at an agronomic rate,

\[
\sum_{i \in m} X_{3_i},r A_{i,fertN},r
\]

(the rate at which nitrogen from chemical fertilizer fertN is applied) multiplied by a manure application factor, $MAF_r$. We assume CAFOs apply manure at the same factor $MAF$, above the agronomic rate for all crops.\footnote{We only observe the total amount of land on which manure is applied, not the amount applied to each crop. If crop-specific application rates were observed, it would be possible to solve a more detailed model wherein the manure application factor is chosen separately for each crop.} In the model, the variable $MAF_r$ is constrained to be less than or equal to 1 if the nutrient application standard is in force (see policy 1 below). If the nutrient application standard is not in force, the optimal manure application factor minimizes manure transportation costs—i.e., all manure is applied on-farm, so $H_{\text{OFF},r} = 0$.

The following three policies are considered:

- **Policy 1.** Nitrogen application standard. CAFO rules mandate a nutrient management plan that requires growers to apply manure nitrogen at or below the agronomic rate.\footnote{Agronomic rates used in the analysis are taken from Kellogg et al. (2000).} This policy is imposed by constraining the manure application factor $MAF_r$ to be less than or equal to 1.
POLICY 2. Ammonia nitrogen emission standard. Hypothetical ammonia emissions regulations are modeled by imposing a limit on the quantity of nitrogen from ammonia per unit of hog produced. The ammonia limit is defined as some factor ($\theta_L$, $\theta_P \geq 1$) above the minimum level obtainable using the least polluting technology:

\begin{align*}
\text{(14)} \quad COV_r * ac + (1 - COV_r) * au & \leq \theta_L ac, \\
\text{(15)} \quad INJ_r * ai + (1 - INJ_r) * as & \leq \theta_P ai,
\end{align*}

for lagoon operations (14) and pit storage operations (15). Ammonia nitrogen emissions per unit of hog produced ($ac$, $au$, $ai$, and $as$) depend on manure storage and handling technologies: covered lagoon, uncovered lagoon, injected pit manure, surface-applied pit manure. Note that the ammonia emission constraint does not depend on the quantity of manure transported off-farm. The application method (surface-apply/inject) is assumed to be the same on-farm and off-farm.

POLICY 3. Simultaneous enforcement of nitrogen application standard and ammonia nitrogen emission standard. Future policy decisions may focus on the design of regulations to reduce ammonia nitrogen emissions while maintaining CAFO nutrient application standards. This analysis can provide useful information about the rate and cost of ammonia abatement technology adoption and ammonia nitrogen reduction for this regulatory approach.

Policies 1, 2, and 3 above are considered with and without EQIP payments. EQIP payments are modeled by varying $s_{\text{mon}}$—the share of off-farm manure transportation costs borne by EQIP, and by varying $s_{\text{crop}}$—the per unit subsidies for crops produced in accordance with CAFO manure application guidelines. The per unit subsidies effectively raise the commodity price for crops fertilized by manure applied at the agronomic rate.

Results

This section discusses the model simulations of single medium and multimedia environmental policies. First, we analyze the recently adopted EPA requirements for CAFOs under the Clean Water Act and separately consider the effects of EQIP payments accompanying the CAFO regulations. This is followed by a discussion of a potential air quality (PM2.5) restriction for CAFOs under the Clean Air Act—assuming the nutrient application standards had not been implemented. The environmental tradeoffs associated with these single-medium policies are illustrated. Finally, we consider implementation of multimedia environmental policies.

Tables 1–3 present the levels of production, inputs, nitrogen to soil and air, and emission technologies for the three policy scenarios.\(^{10}\) Table 1 presents the results without EQIP payments, table 2 disaggregates the results according to manure storage technology (lagoons or pit), and table 3 reports the results with EQIP payments.

\(^{10}\) The results of the dual parameter estimates, the quadratic cost parameter estimates, the parameterization of the objective function, and constraints in the policy simulation programming models can be obtained from the authors upon request.
Table 1. Production, Select Input Use, Revenue and Input Costs, Emissions, and Technology Adoption for Hog Operations Under Nitrogen Application Standard (NAS) and Ammonia Nitrogen Standard (ANS): All CAFOs (no EQIP payments)

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Hogs (mil. cwt)</td>
<td>119.10</td>
<td>117.96</td>
<td>118.26</td>
<td>115.61</td>
</tr>
<tr>
<td>Corn—chemical fertilizer (mil. bu.)</td>
<td>106.14</td>
<td>108.11</td>
<td>106.82</td>
<td>108.27</td>
</tr>
<tr>
<td>Corn—manure surface (mil. bu.)</td>
<td>58.97</td>
<td>70.06</td>
<td>39.42</td>
<td>42.69</td>
</tr>
<tr>
<td>Corn—manure injection (mil. bu.)</td>
<td>32.26</td>
<td>32.16</td>
<td>38.31</td>
<td>43.16</td>
</tr>
<tr>
<td>Soybeans—chemical fertilizer (mil. bu.)</td>
<td>47.91</td>
<td>48.27</td>
<td>47.87</td>
<td>48.03</td>
</tr>
<tr>
<td>Soybeans—manure surface (mil. bu.)</td>
<td>5.19</td>
<td>6.36</td>
<td>2.69</td>
<td>3.07</td>
</tr>
<tr>
<td>Soybeans—manure injection (mil. bu.)</td>
<td>0.54</td>
<td>0.51</td>
<td>0.56</td>
<td>0.58</td>
</tr>
<tr>
<td>Other crops—chemical fertilizer ($ mil.)</td>
<td>98.02</td>
<td>80.31</td>
<td>96.42</td>
<td>89.05</td>
</tr>
<tr>
<td>Other crops—manure surface ($ mil.)</td>
<td>11.39</td>
<td>14.51</td>
<td>11.41</td>
<td>12.54</td>
</tr>
<tr>
<td>Other crops—manure injection ($ mil.)</td>
<td>7.25</td>
<td>4.95</td>
<td>11.68</td>
<td>13.32</td>
</tr>
<tr>
<td>Land (mil. acres)</td>
<td>3.58</td>
<td>3.58</td>
<td>3.46</td>
<td>3.52</td>
</tr>
<tr>
<td>Chemical nitrogen (1,000 tons)</td>
<td>113</td>
<td>112</td>
<td>113</td>
<td>113</td>
</tr>
<tr>
<td>Revenue ($ mil.)</td>
<td>6,643</td>
<td>6,620</td>
<td>6,552</td>
<td>6,454</td>
</tr>
<tr>
<td>Input costs ($ mil.)</td>
<td>2,943</td>
<td>2,928</td>
<td>2,887</td>
<td>2,801</td>
</tr>
<tr>
<td>Hog enterprise returns above select costs ($ mil.)</td>
<td>3,047</td>
<td>2,837</td>
<td>2,805</td>
<td>2,568</td>
</tr>
<tr>
<td>Ammonia N—storage (1,000 tons)</td>
<td>327.5</td>
<td>325.3</td>
<td>203.3</td>
<td>198.8</td>
</tr>
<tr>
<td>Ammonia N—field (1,000 tons)</td>
<td>33.8</td>
<td>34.9</td>
<td>53.1</td>
<td>52.1</td>
</tr>
<tr>
<td>Excess N—soil (1,000 tons)</td>
<td>137.7</td>
<td>0.0</td>
<td>246.4</td>
<td>0.0</td>
</tr>
<tr>
<td>Application rate (factor of agronomic rate)</td>
<td>7.3</td>
<td>1.0</td>
<td>17.6</td>
<td>1.0</td>
</tr>
<tr>
<td>Manure transportation costs ($ mil.)</td>
<td>0.0</td>
<td>205.6</td>
<td>0.0</td>
<td>231.9</td>
</tr>
<tr>
<td>Manure N on-farm (1,000 tons)</td>
<td>183.6</td>
<td>51.8</td>
<td>284.6</td>
<td>42.3</td>
</tr>
<tr>
<td>Manure N off-farm (1,000 tons)</td>
<td>0.0</td>
<td>127.7</td>
<td>0.0</td>
<td>235.7</td>
</tr>
<tr>
<td>Cover lagoon (% all CAFOs)</td>
<td>0.00</td>
<td>0.00</td>
<td>36.42</td>
<td>36.42</td>
</tr>
<tr>
<td>Inject manure (% land, all CAFOs)</td>
<td>25.56</td>
<td>22.55</td>
<td>37.66</td>
<td>37.46</td>
</tr>
</tbody>
</table>

* Base year = 1998.

The outcome of each policy is compared to the base year, 1998—the year of the survey used to calibrate the model. As seen from column 1 of table 1, in the base year before implementation of the CAFO rules, all hog manure is applied on-farm to corn, soybeans, and other crops at an average rate equivalent to 7.3 times the agronomic rate. This very high rate reflects the quantity of manure produced by CAFOs relative to the amount of land on which manure was spread in 1998. Initially, about two-thirds of the total manure nitrogen produced was volatilized as ammonia prior to or after spreading/injection, and there is almost three times as much nitrogen volatilized as ammonia as applied to the soil and not absorbed by crops. About 10 times as much ammonia nitrogen is released from manure storage facilities as compared to fields.

Column 1 of table 2 shows lagoon operations, located primarily in the Mid-Atlantic region, apply manure at 9.4 times the agronomic rate, compared to 5.5 times the agronomic rate for pit operations, located primarily in the Corn Belt region. Differences in application rates reflect the relative abundance of cropland on which to apply manure. For pit operations, the amount of excess nitrogen applied to land that is not absorbed
Table 2. Estimated Percentage Change by Storage Type in Production, Returns, Emissions, and Technology Adoption for Hog Operations Under Nitrogen Application Standard (NAS) and Ammonia Nitrogen Standard (ANS): Lagoon and Pit CAFOs (no EQIP payments)

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Lagoon Operations:</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Hogs (mil. cwt)</td>
<td>70.76</td>
<td>-0.34</td>
<td>-1.18</td>
<td>-3.20</td>
</tr>
<tr>
<td>Corn–manure surface (mil. bu.)</td>
<td>20.14</td>
<td>20.92</td>
<td>5.39</td>
<td>10.61</td>
</tr>
<tr>
<td>Soybeans–manure surface (mil. bu.)</td>
<td>1.68</td>
<td>27.78</td>
<td>5.17</td>
<td>12.52</td>
</tr>
<tr>
<td>Other crops–manure surface ($ mil.)</td>
<td>11.01</td>
<td>26.27</td>
<td>0.79</td>
<td>9.26</td>
</tr>
<tr>
<td>Total returns above select costs ($ mil.)</td>
<td>2,019</td>
<td>-4.47</td>
<td>-11.95</td>
<td>-16.50</td>
</tr>
<tr>
<td>Hog enterprise returns above select costs ($ mil.)</td>
<td>1,827</td>
<td>-4.88</td>
<td>-13.22</td>
<td>-18.26</td>
</tr>
<tr>
<td>Ammonia N–storage (1,000 tons)</td>
<td>255.0</td>
<td>-0.34</td>
<td>-48.69</td>
<td>-49.74</td>
</tr>
<tr>
<td>Ammonia N–field (1,000 tons)</td>
<td>14.8</td>
<td>-0.34</td>
<td>175.05</td>
<td>169.43</td>
</tr>
<tr>
<td>Ammonia N–total (1,000 tons)</td>
<td>269.8</td>
<td>-0.34</td>
<td>-36.43</td>
<td>-37.73</td>
</tr>
<tr>
<td>Excess N–soil (1,000 tons)</td>
<td>42.4</td>
<td>-100.00</td>
<td>221.64</td>
<td>-100.00</td>
</tr>
<tr>
<td>Application rate (factor of agronomic rate)</td>
<td>9.4</td>
<td>-89.31</td>
<td>171.11</td>
<td>-89.31</td>
</tr>
<tr>
<td>Cover lagoon (% lagoon CAFOs)</td>
<td>0.00</td>
<td>0.00</td>
<td>76.70</td>
<td>76.70</td>
</tr>
<tr>
<td><strong>Pit Operations:</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Hogs (mil. cwt)</td>
<td>48.34</td>
<td>-1.86</td>
<td>0.00</td>
<td>-2.54</td>
</tr>
<tr>
<td>Corn–manure surface (mil. bu.)</td>
<td>38.84</td>
<td>17.68</td>
<td>-53.15</td>
<td>-47.53</td>
</tr>
<tr>
<td>Corn–manure injection (mil. bu.)</td>
<td>32.26</td>
<td>-0.32</td>
<td>18.76</td>
<td>33.81</td>
</tr>
<tr>
<td>Soybeans–manure surface (mil. bu.)</td>
<td>3.51</td>
<td>20.11</td>
<td>-73.48</td>
<td>-66.36</td>
</tr>
<tr>
<td>Soybeans–manure injection (mil. bu.)</td>
<td>0.54</td>
<td>-5.38</td>
<td>3.68</td>
<td>8.65</td>
</tr>
<tr>
<td>Other crops–manure surface ($ mil.)</td>
<td>0.39</td>
<td>57.80</td>
<td>-17.32</td>
<td>33.11</td>
</tr>
<tr>
<td>Other crops–manure injection ($ mil.)</td>
<td>7.25</td>
<td>-31.81</td>
<td>61.02</td>
<td>83.57</td>
</tr>
<tr>
<td>Total returns above select costs ($ mil.)</td>
<td>1,681</td>
<td>-7.33</td>
<td>-1.94</td>
<td>-10.71</td>
</tr>
<tr>
<td>Hog enterprise returns above select costs ($ mil.)</td>
<td>1,220</td>
<td>-9.91</td>
<td>0.00</td>
<td>-11.91</td>
</tr>
<tr>
<td>Ammonia N–storage (1,000 tons)</td>
<td>72.5</td>
<td>-1.86</td>
<td>0.00</td>
<td>-2.54</td>
</tr>
<tr>
<td>Ammonia N–field (1,000 tons)</td>
<td>19.0</td>
<td>6.27</td>
<td>-34.54</td>
<td>-35.52</td>
</tr>
<tr>
<td>Ammonia N–total (1,000 tons)</td>
<td>91.5</td>
<td>-0.17</td>
<td>-7.17</td>
<td>-9.39</td>
</tr>
<tr>
<td>Excess N–soil (1,000 tons)</td>
<td>95.3</td>
<td>-100.00</td>
<td>15.53</td>
<td>-100.00</td>
</tr>
<tr>
<td>Application rate (factor of agronomic rate)</td>
<td>5.5</td>
<td>-81.88</td>
<td>93.27</td>
<td>-81.88</td>
</tr>
<tr>
<td>Inject manure (% land, pit storage CAFOs)</td>
<td>48.67</td>
<td>-11.79</td>
<td>-23.30</td>
<td>22.65</td>
</tr>
</tbody>
</table>

* Lagoon operations do not inject manure.

by crops is about the same as the amount of nitrogen released to the air as ammonia. Lagoon operations, in contrast, release far more nitrogen into the air, primarily from the lagoons.

**Single-Medium Nitrogen Application Standards**

The “NAS” column in tables 1 and 2 presents the effect of the 2003 CAFO nitrogen soil application standard without EQIP payments. The application standard requires CAFOs
Table 3. Estimated Percentage Change in Production, Select Input Use, Revenue and Input Costs, Emissions, and Technology Adoption for Hog Operations Under Nitrogen Application Standard (NAS) and Ammonia Nitrogen Standard (ANS): All CAFOs (with EQIP payments)

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Hogs (mil. cwt)</td>
<td>-0.49</td>
<td>-0.74</td>
<td>-1.46</td>
</tr>
<tr>
<td>Corn—chemical fertilizer (mil. bu.)</td>
<td>1.16</td>
<td>0.68</td>
<td>1.37</td>
</tr>
<tr>
<td>Corn—manure surface (mil. bu.)</td>
<td>11.02</td>
<td>-31.42</td>
<td>-28.64</td>
</tr>
<tr>
<td>Corn—manure injection (mil. bu.)</td>
<td>0.53</td>
<td>20.93</td>
<td>28.46</td>
</tr>
<tr>
<td>Soybeans—chemical fertilizer (mil. bu.)</td>
<td>0.72</td>
<td>-0.05</td>
<td>0.11</td>
</tr>
<tr>
<td>Soybeans—manure surface (mil. bu.)</td>
<td>13.43</td>
<td>-45.82</td>
<td>-42.21</td>
</tr>
<tr>
<td>Soybeans—manure injection (mil. bu.)</td>
<td>-2.13</td>
<td>4.85</td>
<td>7.39</td>
</tr>
<tr>
<td>Other crops—chemical fertilizer ($ mil.)</td>
<td>-12.99</td>
<td>-4.27</td>
<td>-8.08</td>
</tr>
<tr>
<td>Other crops—manure surface ($ mil.)</td>
<td>24.22</td>
<td>10.09</td>
<td>15.31</td>
</tr>
<tr>
<td>Other crops—manure injection ($ mil.)</td>
<td>-9.77</td>
<td>72.53</td>
<td>84.14</td>
</tr>
<tr>
<td>Land (mil. acres)</td>
<td>0.00</td>
<td>-3.02</td>
<td>-2.17</td>
</tr>
<tr>
<td>Chemical nitrogen (1,000 tons)</td>
<td>-0.79</td>
<td>-0.29</td>
<td>-0.42</td>
</tr>
<tr>
<td>Revenue ($ mil.)</td>
<td>0.08</td>
<td>-1.13</td>
<td>-1.53</td>
</tr>
<tr>
<td>Input costs ($ mil.)</td>
<td>-0.18</td>
<td>-1.75</td>
<td>-2.54</td>
</tr>
<tr>
<td>Hog enterprise returns above select costs ($ mil.)</td>
<td>-3.55</td>
<td>-7.94</td>
<td>-11.88</td>
</tr>
<tr>
<td>Ammonia N—storage (1,000 tons)</td>
<td>-0.37</td>
<td>-37.93</td>
<td>-38.41</td>
</tr>
<tr>
<td>Ammonia N—field (1,000 tons)</td>
<td>1.80</td>
<td>57.10</td>
<td>55.94</td>
</tr>
<tr>
<td>Excess N—soil (1,000 tons)</td>
<td>-100.00</td>
<td>78.07</td>
<td>-100.00</td>
</tr>
<tr>
<td>Application rate (factor of agronomic rate)</td>
<td>-86.38</td>
<td>119.69</td>
<td>-86.38</td>
</tr>
<tr>
<td>Manure transportation costs ($ mil.)</td>
<td>205.60*</td>
<td>0.00*</td>
<td>231.90*</td>
</tr>
<tr>
<td>Manure N on-farm (1,000 tons)</td>
<td>-72.95</td>
<td>54.97</td>
<td>-77.47</td>
</tr>
<tr>
<td>Manure N off-farm (1,000 tons)</td>
<td>127.70*</td>
<td>0.00*</td>
<td>235.70*</td>
</tr>
<tr>
<td>Cover lagoon (% all CAFOs)</td>
<td>0.00*</td>
<td>36.42*</td>
<td>36.42*</td>
</tr>
<tr>
<td>Inject manure (% land, all CAFOs)</td>
<td>-6.06</td>
<td>47.33</td>
<td>46.94</td>
</tr>
</tbody>
</table>

Note: Percentage change is relative to base case depicted in column 1 of table 1. * Indicates level (not percentage change) because base value equals zero.

to adhere to a nutrient management plan specifying that nutrients are applied to crops at an agronomic rate. To conform to nutrient management plans, CAFOs increase the share of their own land on which they apply manure, decrease the share of the land cultivated using chemical fertilizer, and increase exports of manure off-farm. Returns from the hog operation and total returns decline about 6.9% and 5.8%, respectively. Note that baseline returns amount to 55% of baseline revenue. Implementation of the nutrient application standard effectively eliminates excess nitrogen applied to the soil. The nutrient application standard induces a 3.4% increase in the quantity of ammonia nitrogen emitted from fields. As shown in the “NAS” column of table 2, this increase results because pit operations respond to the standard by switching from injection to surface manure application techniques to minimize their off-farm manure transportation costs. However, the net effect of the policy is a negligible decline in ammonia nitrogen emissions, which can be mainly attributed to the small decline in hog production.
The "NAS" column of table 3 reports the results of the policy scenario allowing for
EQIP payments.\footnote{In this study only existing EQIP payments corresponding to nutrient application standards are considered. We do not consider hypothetical EQIP payments for ammonia abatement practices.} EQIP is assumed to pay 50\% of the costs of transporting manure
off-farm, and offers payments to CAFOs for land cultivated according to a manure
management plan. Comparing the "NAS" columns of tables 1 and 3 reveals that CAFOs
respond to the EQIP payments by transporting more manure off-farm. The drop in
manure transport costs makes it relatively cheaper for the CAFOs to transport manure
off-farm compared to increasing on-farm manure applications at the expense of fertilizer
application. Consequently, the substitution away from chemically fertilized land toward
manure fertilized land on-farm actually declines when EQIP becomes available. EQIP
payments cause hog enterprise and total returns to decline from the base level by only
3.6\% and 2.6\%, respectively. This is about half the decline experienced without EQIP
payments, and implies that EQIP provided a $218 million benefit to CAFOs.

Single-Medium Ammonia Nitrogen Standards

The "ANS" columns in the tables present the effects of ammonia nitrogen limits. The
limits are based on the minimum level obtainable employing available ammonia-
reducing technologies (we consider lagoon covers and manure injection). For pit oper-
ations, ammonia nitrogen emissions are constrained to 10\% above the minimum obtain-
able if all manure is injected. For lagoon operations, ammonia emissions are constrained
to 20\% above what is obtainable if lagoons are covered. These limits were chosen so that
costs to producers are in the same range as the CAFO application standards, and pit
and lagoon operations experienced roughly the same regulatory costs under the multi-
media policy (column "NAS + ANS").

As shown in the "ANS" column of table 2, the ammonia nitrogen standard induces pit
operations to switch from surface application to injection of manure on some land, and
induces some lagoon operations to cover their lagoons. For pit operations, the standard
does not affect the returns to the hog enterprise, so there is no hog production response.
The standard causes a 38\% decline in ammonia emissions from the manure storage
facilities (the largest source of emissions) and a 57\% increase in emissions from the field,
for a net decline in air ammonia of 29\%. The increase in emissions from fields results
because more lagoons are covered, which raises the nutrient content of the manure
applied to fields, resulting in greater nitrogen volatilization. Of particular note, the
ammonia standard resulted in a 79\% increase in excess nitrogen applied to soil—
revealing an important tradeoff between water and air quality.

To further explore the tradeoffs between water and air emissions associated with the
ammonia standard, two simulations are performed. First we examine how the levels of
excess soil nitrogen and ammonia nitrogen vary for different nitrogen application
standards. Tightening the application standard from 50\% above minimum to full imple-
mentation results in a large decrease in excess nitrogen applied to the soil, but almost
no change in the quantity of ammonia nitrogen released to the air. Tightening the soil
nitrogen standard causes CAFOs with pit storage to shift from injection to surface-
application of manure on some land, which increases ammonia emissions from fields.
However, the policy causes a decline in total hog production, so the increase in ammonia
from fields is counterbalanced by a reduction in ammonia from the manure storage facilities. Since lagoons are not covered (without ammonia regulations), there is only a minimal change in ammonia emissions for lagoon operations.

The second simulation, shown in figure 2, examines how soil and air nitrogen levels respond to varying ammonia nitrogen standards. Moving along the x-axis toward the origin corresponds to a tightening of the ammonia standard to the minimum ammonia nitrogen emissions attainable under widely available technologies (lagoon covers and manure injection). Tightening the ammonia limit from 50% above the minimum to the minimum results in a sizeable decrease in ammonia emissions and a comparable increase in excess soil nitrogen. These large increases in excess soil nitrogen occur for two reasons. First, with a tighter ammonia standard, more operations cover their lagoons. Because more lagoons are covered, the nutrient content of the manure is higher, resulting in more nitrogen available for crops. Second, a tighter ammonia standard induces pit operations to expand their use of manure injection as opposed to manure spreading. This increase in manure injection also increases the nitrogen available to crops.

**Multimedia Environmental Policies**

Future policy decisions may focus on the design of regulations to reduce ammonia nitrogen emissions while maintaining CAFO nutrient application standards. This analysis can provide useful information for this regulatory approach. Figure 3 illustrates the rate of ammonia abatement technology adoption as a function of the ammonia nitrogen standard. As with figure 2, the minimum standard is defined as the minimum level of ammonia that would be emitted using the available technology (lagoon covers and manure injection). Lagoon operations begin to cover lagoons when the ammonia standard is above 90% of the minimum ammonia limit. Below this level, the rate of lagoon coverage increases proportionally with the ammonia limit. In contrast, about 47% of pit operations inject manure into the soil in the absence of any ammonia policy. Injection rates do not increase until the ammonia limit is about 30% above the minimum limit, after which the injection rate increases at an increasing rate. By definition, all lagoon CAFOs cover their lagoons, and all pit operations inject manure when the ammonia limit is at the minimum level.

Figure 4 illustrates the ammonia nitrogen reduction and the cost of this reduction at varying levels of the ammonia limit. Dividing the total cost of reducing ammonia by total quantity of ammonia reduction gives the average cost per pound for ammonia N abatement. We estimate that the minimum abatement cost is $1.22 per pound when the ammonia limit is set at 40% above the minimum. The cost of reducing ammonia nitrogen is below $1.50 per pound if the ammonia limit is set below 80% above the minimum. The cost of reducing ammonia emissions calculated directly from the data is $1.26, which suggests our estimates are not far from what would be expected. This cost provides a benchmark for comparing alternative ammonia emission abatement technologies.

Finally, consider the effects of a multimedia policy consisting of the 2003 CAFO manure application regime (table columns “NAS”) and the hypothetical ammonia nitrogen emission standard previously discussed (table columns “ANS”). Results of this analysis are presented in the right-most column of the tables. Relative to the single-medium soil application standards, the multimedia policy is quite costly—resulting in a decline in hog enterprise and total farm returns which is slightly more than the losses
Figure 2. Tradeoff between ammonia nitrogen emissions and excess soil nitrogen under varying ammonia nitrogen standards

Figure 3. Rate of technology adoption as a function of ammonia nitrogen standard
Figure 4. Ammonia nitrogen reduction and compliance cost as a function of ammonia nitrogen standard

from the individual single-medium policies combined. Hog enterprise and total returns decline by 15.7% and 13.9% relative to the base year without EQIP payments, and decline by 11.9% and 10.4%, respectively, with EQIP payments. The joint policy is more costly than the sum of the individual policies because the ammonia standard raises the cost of satisfying the nutrient application standard. Lagoon farmers respond to the ammonia standard by covering their lagoons, thereby raising the nitrogen content of their lagoon water. Under an application standard, this means less manure can be spread on-farm so more must be transported off-farm, which increases transportation costs. The same logic applies to pit farms because injecting manure makes more nitrogen available to plants.

Conclusions

The U.S. Environmental Protection Agency recently began enforcing regulations requiring certain CAFOs to develop and follow a nutrient management plan. These regulations are designed to reduce excess nitrogen applied to the soil, and are not aimed at controlling ammonia nitrogen emissions from manure storage facilities or fields. Ammonia nitrogen emissions can cause acid rain, odor nuisances, and can react with trace gases in the atmosphere to affect particulate matter and haze. Livestock is the nation's largest source of ammonia emissions, and these emissions could conceivably be regulated under the PM2.5 particulate standard of the Clean Air Act (NRC, 2003). This study has considered the economic and environmental implications of regulating both water and air nitrogen emissions under single-environmental medium and multi-environmental media policies.
Based on the model results, nutrient application standards lower hog CAFO returns by an average of 5.8%. However, assuming all CAFO operations apply for and receive EQIP payments, then these payments reduced CAFO losses to 2.6%. A hypothetical ammonia nitrogen standard that reduces ammonia emissions by 29% was estimated to reduce total returns by 7.4%. A multimedia policy incorporating both the soil application and air ammonia standards lowered returns by 13.9% without EQIP payments and by 10.4% with EQIP payments. An important caveat of the current analysis is that it did not consider the deposition of volatilized nitrogen, which would likely contribute to soil nitrogen loading and runoff both on- and off-farm. Accounting for the deposition of nitrogen would require detailed information about the location of ammonia emissions and the pathways for transmission, which is beyond the scope of this analysis.

Results also suggest the hypothetical ammonia restriction causes a disproportionate decline in profits for lagoon operations relative to pit operations (12% versus 1.9%), but also a disproportionate drop in emissions (36.4% drop for lagoon operations versus 7.2% for pit operations). Lagoon operations are located primarily in the Southern Seaboard region, while pit operations are concentrated in the Heartland (McBride and Key, 2003, p. 36). The geographic distribution of large lagoon and pit operations implies farms in the Southern Seaboard would face greater declines in profits but would be responsible for larger reductions in air pollution than farms in the Heartland. The analysis considered only large-scale operations (CAFOs)—future work could evaluate the distribution of economic and environmental costs and benefits of the regulatory regimes across a range of farm sizes (Key, 2004).

This study highlighted the environmental and economic tradeoffs that can occur with single-medium environmental policies. Enforcement of single-medium ammonia nitrogen standards results in higher levels of excess nitrogen in the soil—a result which is likely to diminish water quality through increased nitrogen runoff and leaching. The ammonia standard increases excess soil nitrogen for two reasons. First, the ammonia standard induces some operations to cover their lagoons, which raises the nutrient content of manure. When manure with higher nutrient content is applied to fields, more nitrogen is available for crops. Second, the ammonia standard induces some operations to inject rather than surface-apply some manure. This increase in manure injection also increases the nitrogen available to crops. Because of high manure transportation costs, CAFOs do not fully compensate for the additional nutrients available to crops from manure by increasing the amount of land on which they spread manure.

The study also found that imposing a single-medium nutrient application standard consistent with the 2003 EPA regulations has a negligible effect on ammonia nitrogen emissions. Lagoon operations, which are initially uncovered, cannot respond in a way that exacerbates air ammonia emissions. Pit operations do face an increased incentive to surface-apply rather than inject the manure, but the effect on air emissions is small.

There is significant scope for future work. First, while we were able in this study to estimate the costs of reducing excess soil nitrogen and ammonia nitrogen emissions, estimating an “optimal” policy would require additional information about the social benefits of water and air emissions abatement. Second, the analysis presented in this paper only represents the short-term adjustments for hog operations. In the future, a long-term analysis could consider the exit and entry decisions of hog operations and corresponding environmental consequences resulting from the imposition of water and air emission restrictions. Third, the model could be used to evaluate possible EQIP
payments to promote air emission abatement technologies and practices, lagoon covers, and manure injection. The model developed could also be used to estimate the type and level of payments required to induce operators to adopt these emission-mitigating technologies, and could estimate the economic costs of adoption. Fourth, the analysis could be expanded to other major manure nitrogen producers including dairy, livestock, and poultry operations to better understand the aggregate implications of these policies. Finally, an inquiry into the economic and environmental consequences of a phosphorus-based restriction on land-applied manure could provide further insight into the coordination of policies across media and pollutants.

[Received May 2005; final revision received November 2006.]

References


