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Air Emissions of Ammonia and Methane from Livestock Operations

Valuation and Policy Options

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RESOURCES FOR THE FUTURE

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Abstract

The animal husbandry industry is a major emitter of methane, which is an important greenhouse gas. The industry is also a major emitter of ammonia, which is a precursor of fine particulate matter—arguably, the number-one environment-related public health threat facing the nation. We present an integrated process model of the engineering economics of technologies to reduce methane and ammonia emissions at dairy operations in California. Three policy options are explored: greenhouse gas offset credits for methane control, particulate matter offset credits for ammonia control, and expanded net metering policies to provide revenue for the sale of electricity generated from captured methane gas. Individually, any of these policies appears to be sufficient to provide the economic incentive for farm operators to reduce emissions. We report on initial steps to fully develop the integrated process model that will provide guidance for policymakers.

Key Words: methane, ammonia, carbon dioxide, greenhouse gases, climate change, offset, particulate matter, net metering, environmental policy, CAFO, manure management, biodigester, electricity, global warming, cost-benefit, incentive approach

JEL Classification Numbers: Q2; Q4; Q53

Contents

1. Introduction **1**

2. Air Pollution Issues in Dairy Operations **4**

2.a. Methane 4

2.b. Ammonia 5

3. Process-Based Farm-Level Model of Animal Waste Management **6**

3.a. Model Structure 6

3.b. Baseline Emissions 7

3.c. Ammonia Control Options 8

3.d. Options for Methane Capture and Electricity Production 8

3.e. Health Effects of Air Emissions 9

4. Policy Simulations and Results **11**

4.a. GHG Policies 12

4.b. Policies Related to Ammonia and Fine Particulates 15

4.c. Important Uncertainties 16

5. Discussion **16**

References **18**

Figures **22**

Tables **24**

Air Emissions of Ammonia and Methane from Livestock Operations: Valuation and Policy Options

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1. Introduction

The animal husbandry industry is a major emitter of methane and ammonia in the United States. Methane, a greenhouse gas (GHG) 23 times as potent as carbon dioxide (CO_2), constitutes nearly one-tenth of all U.S. GHG emissions. Although methane has a shorter residence time than CO_2, methane's radically higher effect makes it an attractive target for policy measures, especially in the near term. Ammonia is a precursor of fine particulate matter ($PM_{2.5}$), arguably the number-one environment-related public health threat facing the nation.

The main method of controlling methane emissions in animal husbandry involves using methane digesters to generate and collect methane gas from manure. The captured biogas can then be burned and converted into heat or electricity. Electricity generation through methane digesters reduces farmers' need to purchase electricity and also can create surplus electricity that can be sold back onto the electricity grid. Control of methane is also a potential offset for CO_2 emissions, with a prospective value of tens of dollars per ton given forecasted CO_2 control costs in the U.S. regional programs under design (RGGI 2005).

The control of ammonia emissions has the potential to be tied to particulate control policies that offer offsets or emissions reduction credits. However, a large fraction of the benefits from the control of methane and ammonia in animal husbandry accrue outside of existing markets and cannot be appropriated by individual dairy operations that choose whether to invest in methane or ammonia control technology. For example, reductions in GHG emissions from livestock operations currently are not economically rewarded. As a consequence, dairy operations face only limited incentives for controlling methane emissions with digesters. This situation, in turn, can result in less-than-optimal adoption of technology for controlling emissions by the dairy industry overall.

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In this study, we examine the full potential for methane and ammonia control in animal husbandry. Our objectives are to identify (a) the potential of manure process control for reducing methane and ammonia emissions, (b) the cost thresholds that determine the sensible adoption of different technologies for controlling such emissions, (c) the benefits of controlling such emissions that accrue outside the dairy industry, and (d) the policies or institutions that are necessary to achieve these benefits. This information will be essential to future public policymaking that may give rise to new markets for emissions reductions or to direct financial and technical assistance for methane and ammonia control technologies in agriculture.

We select the California dairy industry for our application. California is a particularly well-suited study area because it is the number-one ranked dairy state in the United States and represents about one-fifth of all U.S. milk production and cows. The California dairy industry generates nearly $5.4 billion in cash receipts and almost a billion dollars in exports, which makes it one of the most economically important agricultural sectors in the state. California cows generate more than 70 billion tons of manure each year—more solid organic waste than the state's 35 million residents generate (U.S. EPA 2006).

Problems associated with dairy manure in California are heightened by the increasing average dairy size and the concentration of dairies in areas with rapidly growing population and a multitude of air quality problems existing. California had about 4,000 dairies in 1992, then the total number dropped to 2,100 by 2004. During the same time period, the total number of cows increased from roughly 1.2 million to 1.7 million, meaning that the average number of cows per dairy more than doubled from about 370 in 1992 to more than 800 in 2004.

California dairy farming is especially concentrated in the Central and San Joaquin Valley regions. These adjacent regions are home to, for example, the five U.S. counties with the highest number of cows per county (Tulare, Merced, Stanislaus, San Bernardino, and Kings Counties). Roughly 1.1 million cows, or about 12 percent of all U.S. cows, inhabit these counties. Tulare County alone has approximately 440,000 dairy cows (4.5 percent of all U.S. dairy cows), more than the total number of cows in any state outside California except for Wisconsin, New York, Pennsylvania, and Minnesota.

These dairy-intensive counties—as well as many other California counties with a significant dairy presence—are also nonattainment areas for particulate matter (PM) and ozone, which means that they do not meet the minimum federal air quality standards (U.S. EPA 2005a). Population growth in the top-five dairy counties in California was more than 20 percent between

1990 and 2000, well above the state average of 13.6 percent (U.S. Census Bureau 2006), which means that the human population exposure to pollution is increasing.

California has initiated several programs to encourage manure treatment with methane digesters, including the Dairy Power Production Program, the Self-Generation Incentive Program, and net metering assembly bills. The Dairy Power Production and Self-Generation Incentive Programs provide cost-share funding for capital investments toward the new installation of methane digesters.[1] Assembly Bills 2228 (signed into law in 2002) and 728 (signed into law in 2005) require the state's three largest investor-owned utilities (Pacific Gas & Electric [PG&E], Southern California Edison [SCE], and San Diego Gas & Electric [SDG&E]) to offer net metering to dairy farms that install methane digesters. These initiatives encourage the dairy industry to adopt methane digesters but do so without considering all the costs and benefits associated with reducing methane and ammonia emissions.

In this paper, we develop an integrated model to examine the control of methane and ammonia emissions in dairy farming. We pay special attention to the comprehensive accounting of private and social benefits and costs of controlling these emissions. The analysis focuses on the interaction of methane and ammonia with climate, energy, and public health polices, including the potential use of offsets for GHG or regional air pollution policies. The model is designed to provide policymakers a tool for understanding the technical and economic relationships in order to realize the benefits of managing air emissions and waste discharges from agriculture.

In the rest of this paper, we first explain the air pollution issues in dairy operations. We then describe the integrated process model of manure management that constitutes the core of our analysis. The model description includes a depiction of baseline emissions; control technologies for ammonia and methane; and the potential electricity generation, GHG reductions, and health benefits that could result from the adoption of control technologies. Then, we use the model to evaluate different policy options in California. A discussion of results and future plans close the paper.

[1] Some federal programs can also provide cost-share funding for methane digesters, including the Environmental Quality Incentives Program (EQIP), the Conservation Innovation Grants Program (CIG), and the Conservation Security Program (CSP) (NDESC 2005).

2. Air Pollution Issues in Dairy Operations

2.a. Methane

The decomposition of livestock manure, under anaerobic conditions, produces methane. According to the U.S. Environmental Protection Agency (EPA), in 2003, roughly 545 million CO_2 equivalent tons of methane were emitted from human-related activities in the United States (U.S. EPA 2005b). Approximately 28 percent of these emissions originated in the animal husbandry industry, including enteric fermentation and manure management.[2]

Enteric fermentation, which accounts for about three-quarters of methane emissions from animal husbandry, occurs when microbes in a ruminant animal's fore stomach convert feed into digestible products and create methane as an exhaled by-product. The rest of methane emissions from livestock operations come from manure management (U.S. EPA 2005b),[3] which accounts for roughly 7 percent of total anthropogenic methane emissions in the United States. Methane is produced during the anaerobic decomposition of organic material in manure. Methane production is particularly high when lagoons and holding tanks are used for liquid manure management. When dry manure is deposited on fields, methane emissions are much lower.

The main approach for controlling the methane emitted from manure is to capture the methane and then burn the biogas as a way to generate electricity—for on-farm use and potentially for sale in the electricity market. Methane combustion for electricity generation results in emissions of CO_2, another important GHG, but burning 1 ton of methane (equivalent to 23 tons of CO_2 if allowed to vent) yields only 2.75 tons of CO_2 and significantly lower GHG emissions from the farm. In addition, the electricity generated from this activity replaces other forms of electricity generation, including fossil fuels, and thereby potentially leads to a net reduction in GHGs.

Several methane digester systems are currently in use on dairy farms in California. More than 30 dairies have applied for the California Energy Commission's cost-share grants for the installation of methane digesters, and at least a dozen digesters are already operating (Sustainable Conservation 2005, 2006). As of February 2006, assessment data are available for four dairies

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[2] For more information, see U.S. EPA 2005b.

[3] Enteric fermentation and manure management contribute methane approximately equal to 115 and 39 teragrams of CO_2 ($TgCO_2$) equivalent emissions, respectively. All GHG emissions resulting from human activities total 6,072 $TgCO_2$ equivalents (U.S. EPA 2005a, 2005b).

that have installed methane digesters cofinanced by the California Energy Commission: Blakes Landing, Castelanelli Bros., Cottonwood, and Meadowbrook. Table 1, compiled from project evaluation reports (Western United Resource Development 2005a–d), summarizes information about these dairies and their methane digesters.

Generally, a dairy with a methane digester can generate more electricity than it can consume. Therefore, potential financial benefits to the dairy from a methane digester depend on the electricity output from the digester, on-farm electricity usage, and the retail and regeneration credit prices of electricity. The effective financial benefit to the dairy operation of generating a kilowatt of electricity with the methane digester varies between the net generation credit and the retail price of electricity (weighted by the relative volumes of on-farm electricity purchase offsets and net generation credits).

For example, the Castelanelli Bros. Dairy reports an average agricultural and residential energy usage of about 56,736 kilowatt-hours (kWh)/month, which would cost about $6,240 at a retail rate of $0.11/kWh. This amount is the potential monthly cost savings at the dairy from using the methane digester, given sufficient capacity to generate this much energy. In addition, any surplus energy output could generate revenue if it could be sold to the grid for a positive price. The amount of compensation for net generation is not yet well established. The two dairies for which regeneration credit pricing has been described (Castelanelli Bros. and Meadowbrook) suggest that a regeneration credit of roughly $0.06/kWh is realistic.

2.b. Ammonia

Animal husbandry operations produce approximately half of U.S. ammonia emissions (roughly 2.5 million tons/year),[4] and dairy farms are responsible for a little more than 20 percent of the emissions from animal husbandry (U.S. EPA 2004a). The amount of ammonia emissions from livestock farms depends on how animal waste is managed and varies substantially depending on ammonia concentration, temperature, pH, and how long the waste is stored before being applied to land as fertilizer. Ammonia concentrations and therefore emissions tend to be higher with higher temperatures and higher pH and lower when the waste is stored longer before land application.

[4] Total U.S. ammonia emissions are about 4.8 million tons/year (U.S. EPA 2005b).

For reducing ammonia emissions, numerous strategies have been discussed for different sources of emissions, including livestock housing facilities, manure storage facilities, and land application of manure.[5] One of the more effective approaches for housing facilities is the use of filters or biofilters to remove emissions from ventilation exhaust systems. Such systems, which remove approximately 74 percent of total emissions at a relatively low cost per animal, are the main focus of our analysis. The effectiveness of other approaches (such as dietary manipulation and the use of impermeable barriers to prevent air movement out of livestock housing facilities) is currently being studied. Other approaches that focus on manure storage are currently being tested, including urine–feces separation, acidification, and the application of additives to prevent ammonia production and volatilization.

Among these approaches, urine–feces separation appears to promise the largest reductions in ammonia emissions. As much as an estimated 35 percent of total ammonia emissions are emitted during or after the land application of manure. These emissions can be reduced if the manure is injected into the ground or if urease inhibitors are applied to the manure.

3. Process-Based Farm-Level Model of Animal Waste Management

3.a. Model Structure

In this paper, we develop an integrated model for methane and ammonia emissions from concentrated animal farm operations.[6] The integrated model framework includes a baseline with no emissions controls, and accounts for additional emissions from various emissions-management strategies for controlling ammonia and methane, including electricity generation and heat recovery as well as various ammonia emission control strategies. The model is intended to be transparent and useful for conducting a comparative analysis.

[5] The approaches to reducing ammonia emissions discussed in this paragraph are all described in greater detail in Iowa State University 2004.

[6] The National Research Council (NRC) has suggested that using a process-based model farm approach that incorporates “mass balance” constraints for some of the emitted substances of concern, in conjunction with estimated emissions factors for other substances, may be a useful alternative to the EPA model farm construct (NRC 2003). However, in this paper, we use an emissions factor approach to demonstrate our concept. After careful calibration, this simple conceptual model could be useful for policy analysis and for identifying data gaps and research needs. Outputs from more sophisticated process-based approaches could be incorporated or adopted in the integrated conceptual model.

The model also considers the costs associated with these strategies and their benefits, such as the value of electricity generation, GHG credit revenue and air quality (ozone and $PM_{2.5}$) impacts. Figure 1 lists the components of the conceptual model and identifies which are currently available.[7] The model is developed using Analytica software, which provides a graphical representation of relationships in the model (Figure 2) and easily incorporates quantitative measures of uncertainty. This latter capability is particularly important because of the considerable uncertainty and variability associated with emissions factor estimation, technology performance, and the costs of control technologies.

3.b. Baseline Emissions

The model includes estimates of baseline emissions of methane and ammonia in the absence of specific controls.[8] These estimates vary depending on the characteristics and location of the farming operation.

Methane emissions result from both enteric fermentation and the decomposition of animal waste under anaerobic conditions. Animal and feed characteristics have a significant impact on methane emissions. This paper focuses on methane emissions from dairy operations; however, the model accommodates enteric fermentation for six types of animals: nondairy cattle, dairy cattle, swine, sheep, goats, and horses. Methane emissions factors—which vary by region as a result of temperature and altitude differences—for enteric fermentation by region were obtained from *AP-42* (U.S. EPA 1995).

The amount of methane produced during waste decomposition is affected by the climate (temperature and rainfall) and the conditions (oxygen level, water content, pH, and nutrient availability) under which the manure is managed. Manure decomposes more rapidly when the climate encourages bacterial growth. For liquid manure systems, methane production increases with temperature. In our current model, methane emissions factors by climate region are obtained from *Revised 1996 IPCC Guidelines for National Greenhouse Gas Inventories* (IPCC 1996).

[7] At this moment, some components are created as placeholders. We plan to refine the model components and fill the data gaps as our research advances. One of the advantages of such an integrated model is that we are able to identify the information needs.

[8]Other types of livestock will be added.

The emissions factors for ammonia used in the model come from a U.S. EPA study (2004a) that developed ammonia emissions factors by animal type for 18 manure management trains. Zhang et al. (2005) are developing a process-based ammonia emissions model.

3.c. Ammonia Control Options

Ammonia emissions to the atmosphere are an environmental concern because they can contribute to odor, the eutrophication of surface water, and nitrate contamination of groundwater. Ammonia emissions also contribute to the formation of fine particulates, which have a negative impact on animal and human health. Strategies to reduce ammonia emissions include preventing the formation and volatilization of ammonia as well as its downwind transmission after volatilization.

Iowa State University (2004) provides information on the relative costs and effectiveness of nine ammonia-control practices (Figure 1). For example, the ammonia emissions can be reduced 40–50 percent by using biofiltration at the animal housing area. Also according to Iowa State, the estimated biofiltration costs for a 700-head farrow-to-wean swine facility are $0.25/piglet, amortized over a 3-year life of the biofilter. In the model, this cost ($0.25/animal) is assumed to apply to biofiltration applications at dairy operations as well.

3.d. Options for Methane Capture and Electricity Production

A biogas recovery system is one of three manure management techniques that can be used to capture methane. (The other two are gasification systems and composting.) Biogas recovery systems, sometimes known as anaerobic digesters, can provide renewable energy and alleviate some of the environmental problems associated with manure from large animal operations.

During anaerobic digestion, bacteria break down manure in an oxygen-free environment. One of the natural products of anaerobic digestion is biogas, which typically contains 60–70 percent methane, 30–40 percent CO_2, and trace amounts of other gases, with a combined heating value of 600 BTU per cubic foot (whereas that of natural gas is about 1,100 BTU per cubic foot). Biogas recovery systems offer several environmental benefits, including odor control, GHG reduction, ammonia emissions control, and water quality protection.

Three types of biogas recovery systems have been commercialized for managing manure. These systems range from the simple covered lagoon to the more complex plug-flow and complete-mix digesters. Which system is most appropriate depends on how the manure is collected and on the total solids content of the collected manure. For example, the appropriate total solids contents of these three systems are 0.5–3%, 3–10%, and 11–13%, respectively (U.S. EPA 2002). At this time, our model considers only the plug-flow digester biogas recovery system. Other recovery systems (covered-lagoon and complete-mix digesters) and other energy technology (gasification) will be added in the future.

The amount of electricity generated from the plug-flow digester for biogas recovery depends on daily manure production, the number of animals, the solids content of the manure, a fixed biogas production coefficient, the methane content of the biogas, and the efficiency of the electricity generator. We verified the model by comparing the electricity generated using our model with numbers reported in the literature. Our estimate—104 kilowatts (kW) for a farm with 1,000 cows—is in the range of reported values.

We developed a capital cost function using data collected from four dairy farms (Table 2). We first converted the cost to 2004 dollars. We estimated the cost function using the following functional form:

$$y = a x^b$$

Where the left hand side dependent variable, *y*, is the average cost per cow and the right hand side variable, *x*, is the number of cows; *a* and *b* are cost function parameters. Actually, *b* is the estimate of the scale elasticity. In our case, the coefficient estimate *b* equals –0.76, which means that for every 1 percent increase in farm size (in number of cows), the average capital cost decreases by 0.76%. We assume that *a* and *b* are normally distributed, using their estimates and standard errors. We amortized the capital cost by assuming a 7 percent compound interest rate and a 20-year lifetime. Annual operation and maintenance cost was assumed to be 20 percent of annual capital cost by default and can be changed easily in the model.

The GHG credit was calculated from the difference between baseline methane emissions (in CO_2 equivalents) and CO_2 emissions from biogas combustion (including both CO_2 in biogas and CO_2 emitted from biogas methane combustion). As noted earlier, we assumed that methane has a global warming potential 23 times that of CO_2. We also assume that combustion of 1 ton of methane yields 2.75 tons of CO_2. The GHG credit revenue is equal to the product of the number of credits and the credit price.

3.e. Health Effects of Air Emissions

The air quality impacts of farm operations considered in the model include reduced emissions associated with ammonia controls and increased emissions of NO_x from biogas combustion for electricity generation. Ammonia is a precursor of $PM_{2.5}$. Once emitted, depending on environmental conditions, ammonia can react with nitric acid to become ammonium nitrate, a secondary pollutant. NO_x is a precursor of both ozone and PM. To evaluate the health impact of particulates and ozone due to ammonia control and new NO_x emissions, we must analyze emissions transport and air chemistry as well as changes in exposures and impacts on human health.

The first task requires the development of a pollutant source–receptor relationship, which is how much secondary pollutant concentration will change at the receptor site as a result of a change in emissions of the primary pollutant at the source site. The second task requires the estimation of changes in exposure and related health impacts as a result of the change in exposure to the secondary pollutant.

For the first task, the current model requires source–receptor relationships for ozone with respect to NO_x emissions, $PM_{2.5}$ with respect to NO_x emissions, and $PM_{2.5}$ with respect to reductions in ammonia emissions. Palmer et al. (2005) and Shih et al. (2004) have quantified the source–receptor coefficients at the state level for the first two but could not find any farm-level empirical source–receptor coefficient. So, for ozone with respect to NO_x emissions, we average the 8-hour ozone source–receptor coefficients in the source–receptor coefficient matrix (for the entire study domain) as our default in the current model. We do the same thing for $PM_{2.5}$, using a 24-hour source–receptor coefficient matrix.

We were unable to locate any source–receptor coefficients for $PM_{2.5}$ with respect to ammonia control. The literature offers a range of perspectives on this issue: some papers argue that ammonia control has no effect on $PM_{2.5}$ concentration (LADCO 2002) for a specific region, whereas other research suggests that ammonia control has positive effects (Erisman and Schaap 2004). The differences in these findings depend on whether the region being studied is ammonia-limited. These differences in the literature suggest the existence of a huge uncertainty and variability in this coefficient among different regions and locations.

We use a simple box model to estimate the source–receptor coefficient for $PM_{2.5}$ with respect to ammonia control. We assume that emitted ammonia reacts with nitric acid completely to become ammonium nitrate and that this ammonium nitrate is uniformly mixed within the box (after considering deposition, because emissions from farm operations tend to be near the ground surface).[9] We then calculate the average change in the ammonium nitrate concentration within this box due to one unit of reduction in ammonia emissions. Given limited time and resources, we use the simple box model approach to produce the upper-bound estimate of the $PM_{2.5}$ with respect to ammonia source–receptor coefficient. We then use a uniform distribution between 0 and this upper bound to characterize this coefficient in our model.

To estimate the health benefits, we develop simple composite health benefit coefficients for ozone and $PM_{2.5}$ exposure using the Tracking and Analysis Framework (TAF; ORNL 1995). The health benefit coefficient is defined as the benefit (in dollars) per change in pollutant concentration per capita per year. The health effects considered include the number of days of acute morbidity effects of various types, the number of chronic disease cases, and the number of statistical lives lost. The pollutant concentration–response functions are published in the peer-reviewed literature, including epidemiological articles reviewed in EPA's Criteria Documents that, in turn, appear in key EPA cost–benefit analyses (Palmer et al. 2005). We first estimate change in pollutant concentration at a receptor by multiplying the emissions reduction from the source by the relevant source–receptor coefficient. We then multiply the change in concentration with the health benefit coefficient and exposure population to get the annual health benefit estimate.

4. Policy Simulations and Results

The integrated assessment model is used to study the atmospheric emissions from animal husbandry and their environmental consequences and to investigate potential policies to improve the environmental and economic performance of the industry. In the ongoing program of research, we investigate two types of policies: performance-based policies that would require specific technologies or management practices, and market-based policies that could provide economic incentives to reduce emissions. Some policies would involve the agricultural extension service in its traditional role of outreach, education, and technical assistance. Other policies could require mandated practices. However, all the policies that we describe involve creating

[9] In personal correspondence, Professor Ted Russell of the Georgia Institute of Technology in Atlanta indicated that this assumption is not strictly correct, because the reaction is an equilibrium and because the amount of nitric acid in the atmosphere is limited, and ammonia would not be able to convert to ammonium nitrate in a fully efficient manner (100%). The effect of this assumption is to overestimate the source–receptor coefficient that would serve as an upper bound for $PM_{2.5}$ reduction that would result from reducing ammonia emissions. We plan to refine this estimate with a more comprehensive three-dimensional air-quality simulation model in the future.

new markets that allow farm operators to internalize social benefits from more efficient management.

We illustrate the model by exploring three policies:

- the creation of GHG credits to account for the social benefit of reducing methane emissions,
- the creation of $PM_{2.5}$ offset credits to account for the social benefit of reducing ammonia emissions, and
- expanded net metering of electricity to provide financial payments to farm operators for providing electricity back to the electricity grid.

Underlying parameters in the model (e.g., population of farm operations, temperature, and background emissions inventories) exhibit large variability, and several parameters in our model are very uncertain or based on nonlinear processes. In the future, we plan to account for this variability and uncertainty by using simulation-based methods such as Monte Carlo analysis. To illustrate the model in this paper, we rely primarily on midpoint values for many parameters, often erring intentionally on the side of cautious choices that may underestimate the potential benefits of the policy options, partly to guard against bias due to omitted features of the problem at this juncture. We vary two fundamental parameters to give a flavor for the potential sensitivity of the results.

4.a. GHG Policies

Two pathways offer the potential to avoid GHG emissions: changing management practices (including dietary modification and methane capture), and using the methane by-product for electricity generation. Change in management practices could be mandated by fiat, but the regulatory burden of enforcement would be enormous and the economic impact on the farm sector severe. A market-based approach could lead to a more efficient technology choice at much less cost to government and with positive economic benefits for the industry.

We model a market-based policy that provides a payment for emissions offsets under GHG cap-and-trade programs. One such cap-and-trade program is in place in the European Union, another has been approved in seven states in the northeast United States, and others are under consideration in California and elsewhere as well as at the federal level.[10] In various ways, these programs are expected to allow for the use of offset credits awarded for emissions reduced beyond those from the sources that are directly regulated by the program. One tenet of this approach is that offsets qualify only for emissions reductions that would not have happened anyway (e.g., those that are additional to current laws, regulations, or practice). A key feature of offset programs is the documentation of baseline emissions and the certification of changes in practices that would lead to emissions reductions. To this end, the model calculates emissions under the baseline (in absence of a policy) as well as changes under various policies and management strategies.

In our central case, we model a specific management practice using a plug-flow digester for a 500-head farm operating in a warm climate such as California. We consider offset credits valued at $11/ton of CO_2 equivalents. This value is midpoint to values that might emerge given current policy.[11] Under the creation of an offset market for these emissions reductions, the economic value of avoiding additional reductions at facilities regulated under the emissions cap flows through to the farm operator. Electricity generation with the captured methane leads to residual CO_2 emissions, which are accounted for in the net emissions reductions.

The costs of the digester that we account for include those for installation and operation and for a generator that combusts methane to produce electricity, but they do not include opportunity costs such as the alternative use of land for the digester. The value of the electricity depends on its potential use on the farm or for resale onto the grid. Whether independent power producers can realize the value of the sale back onto the grid depends on whether the distribution companies will pay for the power. Net metering policies require payment to independent power producers at an avoided cost. We assume that net metering is not available to the farm operator

[10] See http://europa.eu.int/comm/environment/climat/emission.htm, http://www.rggi.org/, and http://www.climatechange.ca.gov/.

[11] Emissions allowances under the E.U. Emissions Trading Scheme are currently trading at about $30 per metric ton of CO_2. The Regional Greenhouse Gas Initiative Memorandum of Understanding for the northeast United States includes a trigger price of $10 per short ton to expand the offset market to include states outside the region.

in our central case and vary this feature in sensitivity analysis.[12] In the absence of a net metering policy, the farm operator can capture only the value of electricity at the farm—equivalent to displaced purchase from the grid— but extra electricity generation capability is unused. We assume a weighted value of $0.06/kWh for electricity generated.[13] In addition, we note that electricity generation results in an increase in emitted NO_x, which is a precursor of PM and ozone. The social cost of the NO_x increase is accounted for below.

Table 3 reports that methane capture for electricity generation at a 500-head farm in a warm climate imposes annualized costs of $31,350. The electricity savings on the farm operation total about $27,380, which is not sufficient to justify the investment. However, the additional revenue from GHG offset credits would yield $6,014, which is sufficient to tilt the balance to produce net economic benefits of $2,014/year.

One important aspect of the incentive structure of a GHG offset market that is made apparent in the integrated assessment model is the consequence of changing diet. We do not model offsets for diet management, even though such a credit could be attractive. However, we do note that changes in diet would affect ultimate methane production. If the farm operator receives payment for offsets from methane capture from manure, the operator would lack the incentive to change diet to reduce enteric methane because this change would also reduce the amount of methane available for capture from manure. Indeed, an unintended consequence of the GHG offset market associated with methane capture for electricity generation might be increases in enteric methane as well as methane in manure. Policy may need to link these management practices, perhaps making aspects of dietary management a prerequisite for GHG credits awarded for the capture of methane from manure.

Electricity generation creates another potential source of value external to the electricity market that is not included in this example. In the presence of a cap-and-trade program for CO_2,

[12] A California law passed in 2002 encourages net metering for farms that use digesters (Gaura 2004). PG&E has offered a limited net metering policy for biogas facilities called NEMBIO that became available in August 2003. Initially, this opportunity is available to farms that generate less than 1 MW and is limited to 5 MW from the first farms that apply (on a first come, first served basis). In 2005, Assembly Bill 729 extended these limits to authorize up to three digesters with up to 10 MW of capacity to be eligible for net metering, and the cap on total biogas digesters eligible for net metering was extended to 50 MW (DSIRE 2005).

[13] From representative statistics, we calculate that about 54 percent of the potentially generated electricity would be used on the farm, displacing retail electricity purchases that average $0.11/kWh for agricultural customers in California. The remaining generation potential would be unused. Hence, the weighted value of the electricity, in the absence of net metering, is $0.06/kWh.

electricity generation may qualify for additional offset credits associated with the avoided emissions from fossil-fired power plants. The avoided emissions are not equivalent to the average emissions of electricity on the grid. Instead, the proper measure is the change in generation at other facilities as a result of the methane-powered electricity. To identify this measure with confidence, one must solve an electricity market model, which is a component of our ongoing research project. For a proxy, it might be reasonable to assume that the displaced emissions come from a gas-fired facility because natural gas is typically the marginal generation technology, especially in California. A shortcut for regulators might be to associate the avoided emissions with the avoided generation source that determines the payment under a net metering program. In any event, this potentially substantial source of GHG credit revenue is not included in the results presented above.

4.b. Policies Related to Ammonia and Fine Particulates

The emission of ammonia, which is a precursor of $PM_{2.5}$, causes a second external effect. Management practices could reduce the ammonia emissions, but at a cost to the farm operator. One way to provide a positive incentive for improving management would be to account for the $PM_{2.5}$ reduction that is associated with reductions in ammonia emissions. NO_x and sulfur dioxide (SO_2) emissions, regulated directly through various programs, are important precursors of $PM_{2.5}$ but require ammonia for the conversion to $PM_{2.5}$. In areas that are not in attainment with the National Ambient Air Quality Standards, any new source must obtain offsets of emissions reductions at another source. Those offsets have potentially significant economic value, ranging from hundreds of dollars to tens of thousands of dollars per ton, depending on the air quality management district and varying by year due to changes in local economic conditions and other factors.

We consider the creation of offset credits for ammonia in the nonattainment districts in California. Using the model, we solve for the expected changes in health effects due to reductions in $PM_{2.5}$ and increases in ozone that probably would occur if ammonia reductions were to be achieved. Emission reductions would be achieved through the use of biofilters, which impose a cost of $120/year. Table 3 indicates the $PM_{2.5}$ benefits would be substantial ($14,712/year in our central case) and would dominate the change in ozone. The net benefit of this management strategy would be $14,592/year.

4.c. Important Uncertainties

Numerous uncertainties have been revealed already in our preliminary modeling. An important variable is the availability of net metering and the net generation credit price. In the main analysis, we assumed that net generation of electricity is not rewarded financially. If we assume instead that the farm operation can sell its surplus electricity back onto the electricity grid at $0.06 per kWh, then annual net benefits in our central case increase from $16,606 to $28,936.

The climate (temperature) in the location of the farm affects methane and ammonia emissions in the absence of control strategies. Table 3 indicates that differences between cold and warm climates cause the net benefits of the GHG offset management strategy (including electricity production) for a 500-head farm operation to vary from $11,040 to $16,606.

One of the most important policy considerations is the size of the farm. We characterize a range of sizes, from 400 to 1,000 head. This range provides opportunities for net benefits to vary by nearly an order of magnitude. For a 1,000-head farm operation in a warm climate, annual benefits can total $58,754.

From a scientific standpoint, one item with great uncertainty in this analysis is the characterization of the atmospheric dispersion of ammonia and its ultimate contribution to particulate formation. The relevant values vary significantly with geography and region of the country, with assumptions about background pollution and so on. Nonetheless, the proper accounting for ammonia reductions as offset credits for associated PM reductions could offer significant economic benefits to the farm operation and significant social benefits as well.

5. Discussion

The animal husbandry industry is a major emitter of methane (an important GHG) and ammonia (a precursor of $PM_{2.5}$, arguably the number-one environment-related public health threat facing the nation). Technologies are available to dramatically reduce these emissions, but their adoption by dairy operations has been limited.

In this paper, we explore market-based policies to provide farm operators with financial incentives to adopt technologies for the control of methane and ammonia emissions. We develop and demonstrate an integrated process model of dairy operations. Three policy options are explored: GHG offset credits for methane, PM offset credits for ammonia, and expanded net metering policies to provide revenue for the sale of methane-powered electricity generation. Taken individually, any of these policies appears sufficient to provide the economic incentive for farm operators to reduce emissions. The magnitude of the benefit depends of the scale of the system, farm location (i.e., specific climate region), and technology adopted as well as on important model assumptions regarding ammonia-to-PM source–receptor coefficients. We report on initial steps to fully develop the integrated process model to provide guidance for policymakers.

In future work, we plan to explore additional features of the policies discussed here. We plan to link the model with a dispatch model of the California electricity sector to estimate the CO_2 emissions displaced by expanded generation from methane digesters. We also plan to explore the effect of scaling up these operations and of using multiple-farm digesters and associated transportation costs. We also could develop an optimization model for siting such an energy facility, taking into account its environmental cost and benefit and integration with the existing power grid. Farm-level source–receptor coefficients for specific locations could affect our estimation results, and this issue deserves further investigation. Finally, we could extend the integrated model by considering a water quality impact component. This research is expected to provide additional insights about how to reduce the financial burden on the agriculture industry to improve productivity as well as environmental quality.

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Figures

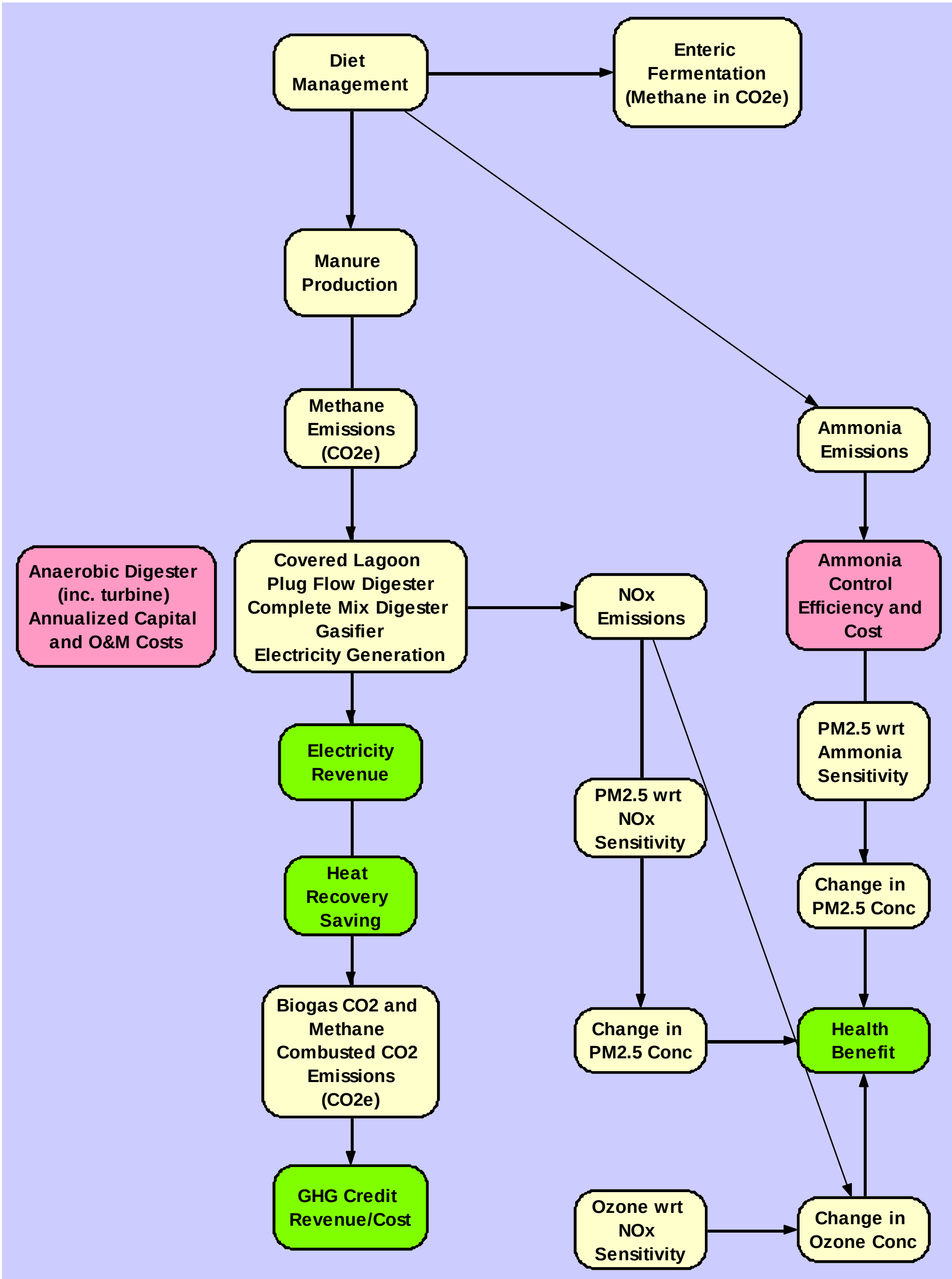
Figure 1. Integrated Model Components

- Baseline enteric methane fermentation*
- Baseline methane emissions*
- Baseline ammonia emissions*
- Ammonia emission control method*
    - Dietary manipulation
    - Filtration and biofiltration*
    - Impermeable covers
    - Permeable covers
    - Urine–feces separation
    - Acidification
    - Additives
    - Control land application
    - Manure amendments
- Methane production and energy recovery technology*
    - Covered lagoon
    - Plug-flow digester*
    - Complete-mix digester
    - Gasifier
    - Gas turbine electricity generation*
- Ammonia control cost*
- Methane-powered electricity production cost*
- Heat recovery cost savings
- GHG credit revenue*
- Air quality externality*
    - $PM_{2.5}$ wrt ammonia emission control*
    - $PM_{2.5}$ wrt NO_x emissions from energy recovery facility*
    - Ozone wrt NO_x emissions from energy recovery facility*

Note: * Component currently has data available in the model.

Figure 2. Model Relationships

Note: CO2e = CO_2 equivalents.



Tables

Table 1. Features of California Dairies with Methane Digester Systems

Feature	*Dairy*			
	Blakes Landing	*Castelanelli Bros.*	*Cottonwood*	*Meadowbrook*
No. of lactating cows	247	1,600	5,351	2,133
Gas production				
Total (cf/day)	20,000	70,751	241,990	67,912
Per cow (cf/day)	84	44	45	31.84
Electricity output				
Generator (kW)	75	160	300 (700 planned)	160
Total (kWh/year)	229,220	1,132,595 (~50 percent gas flared)	2,334,095 (~55 percent gas flared)	931,144
Per cow (kWh/ day)	2.54	1.94	1.14 (for 300kW)	1.20 (design 1.68)
Retail rate ($/kWh)	$0.10	$0.11 (regeneration credit $0.058)	$0.115	$0.069 regeneration credit (not final)
Capital costs	$336,362	~$800K (design $773K)	~$2.7M (design $1.29M)	~$800K (design $524K)
O&M, per month	~$100-800	~$600	~$5,000	~$560
Manure collection method	Covered lagoon	Covered lagoon	Covered lagoon	Plug flow digester
Agricultural and residential energy usage (kWh/month)	9,941	56,736 (summer 107,353)	N/A	42,778

Notes: O&M = operations and management, N/A = none.

Sources: Data were compiled from the California Energy Commission's 90-day evaluation reports (Western United Resource Development 2005a, 2005b, 2005c, 2005d).

Table 2. Capital Cost of Plug Flow Biogas Systems with Electricity Generation on Select Farms

Farm	*Installation Year*	*Animal Production*	*Installed Cost*	*Price/head (2004$)*
Haubenschild[a]	2002	1,000		$373
Craven[b]	1997	650	$253,000	$458
AA Dairy[b]	1998	550	$240,300	$506
Haubenschild[b]	1999	480	$295,800	$699

Sources: [a]Nelson and Lamb 2002, [b]Moser and Matocks n.d.

Table 3. Costs and Benefits to Farm Operator of Methane and Ammonia Capture under Market-Based Policy Scenario

Climate	*Warm*			*Cold*		
Farm size (head)	400	500	1,000	400	500	1,000
Baseline CH_4 (CO_2 equiv tons)	769	961	1,923	364	455	911
Digester cost	29,680	31,350	7,160	29,680	31,350	37,160
CO_2 in electricity generation (tons)	332	414	829	332	414	829
Ammonia control cost	120	150	300	120	150	300
Electricity revenue	21,910	27,380	4,770	21,910	27,380	54,770
GHG credit revenue	4,811	6,014	2,030	358	448	896
Health benefit: ozone	–263	–328	–656	–263	–328	–656
Health benefit: $PM_{2.5}$	12,030	15,040	30,070	12,030	15,040	30,070
Net benefits	8,689	16,606	58,754	4,236	11,040	47,620

Notes: Monetary estimates are dollars/year (2004$). Example excludes transportation costs, heat recovery value, and potential GHG credits from reduced generation of fossil fuel–fired facilities. Electricity revenue excludes the benefits of net metering.