POLICY ALTERNATIVES FOR CONTROLLING NITRATE POLLUTION FROM NEW MEXICO'S DAIRIES

By

Jingjing Wang, Assistant Professor
Janak Raj Joshi, Doctoral Candidate
Department of Economics
University of New Mexico

TECHNICAL COMPLETION REPORT NO. ###
Account Number ######

June 2015

New Mexico Water Resources Research Institute
In cooperation with
University of New Mexico

The research on which this report is based was financed in part by the U.S. Department of the Interior, Geological Survey, through the New Mexico Water Resources Research Institute.

DISCLAIMER

ACKNOWLEDGMENTS

Financial support of the study was provided by New Mexico Water Resources Research Institute and the Department of Economics at the University of New Mexico. The authors thank conference participants at the 59th Annual New Mexico Water Conference and the 2014 New Mexico Academy of Science Research Symposium. The authors are also grateful for helpful comments and suggestions from Dr. Robert Hagevoort of New Mexico State University.

ABSTRACT

Consolidation in livestock production generates higher farm incomes due to economies of scale. However, it also brings manure disposal problems. New Mexico ranks number one in the nation in dairy herd size. Dairy manure is a significant source of nitrates and improper management of manure from the state's large dairy farms can produce adverse environmental and health effects. In this study, we use a combination of life cycle assessment (LCA), cost-benefit analysis (CBA), and sensitivity analysis to investigate policies for controlling nitrogen pollution from large dairy farms in New Mexico. We first construct an integrated farm-level model that is suitable to investigate alternative policies for controlling nitrate pollution from a typical large dairy farm in New Mexico. Based on this typical dairy farm, we then conduct the LCA and CBA analyses of dairy manure management under three cases: direct land application of dairy manure (DLA), anaerobic digestion of dairy manure (AD), and anaerobic digestion of dairy manure coupled with microalgae cultivation (ADMC). Four environmental impacts of the alternative manure management cases are assessed in the LCA analysis and net benefits of each case are evaluated in the CBA analysis under a baseline scenario and different incentive-based policy scenarios. We also conduct sensitivity analysis of cropland availability, rangeland availability, and policy strength to check the robustness of our results. We find that, for a typical large dairy farm in New Mexico, the DLA case is the least sustainable with regard to any of the environmental impacts. AD is most profitable in the baseline, tax credit, and carbon credit scenarios while ADMC is most profitable in the presence of a market for nutrient credits. We also discuss the most effective approaches and policy tools for manure management on large dairy farms of New Mexico.

Keywords: Dairy, CAFOs, livestock manure, nitrates, algae, bioenergy

TABLE OF CONTENTS

List of Tables

List of Figures

LIST OF TABLES

LIST OF FIGURES

1 BACKGROUND

1.1 Dairy Industry of New Mexico

Higher farm incomes due to economies of scale have sustained the worldwide trend toward larger and more concentrated animal feeding operations in the past four decades. In the United States, the national average stocking density (average number of milk cows per operation) for dairy operations increased from 57 to 159 heads per operation from 1992 to 2012 (NASS, 1994, 2013). Figure 1 ranks the top twelve dairy states based on the total number of milk cows, using data from the 2012 Census of Agriculture. The rank is almost the same when the states are ranked based on the average of total number of milk cows over the past two decades. The only difference is that Idaho's fast growing dairy industry brought Idaho from the 6th largest dairy state on average to the 4th in 2012.

[Figure 1 here]

To examine the trends in the U.S. dairy sector, figures 2 and 3 show the total number and average stocking density of milk cows in the top twelve dairy states from 1997 to 2012. Although the total number of milk cows are relatively constant for these states after 2007, the average stocking density has been continuously rising, especially in California, Idaho, New Mexico, and Texas. The situation is particularly noticeable in New Mexico. The average size of a dairy herd in the state increased from 300 to 1200 heads from 1997 to 2007, growing four times in ten years and ranked number one in the nation. Interestingly, this number dropped significantly in 2012.

[Figure 2 here]

[Figure 3 here]

In this study, we focus on an important category of animal feeding operations – concentrated animal feeding operations (CAFOs). CAFOs are the largest of the animal operations and the one that poses the greatest risk to environmental quality and public health. By definition, a large CAFO is a facility with 1,000 or more animal units, which is the equivalent of 1,000 beef cattle, or 700 dairy cattle, or 2,500 hogs, or 10,000 sheep, or 55,000 turkeys, or 100,000 broilers or laying hens (EPA, 2003).[1] There is little information available on dairy operations with 700 or more milk cows, but the Census of Agriculture provides statistics for dairy farms with 500 or more milk cows. We thus use this category of dairy farms (with 500 or more milk cows) as a proxy for large dairy CAFOs (with 700 or more milk cows) and hereafter define it as "large dairy farms." Figure 4 again shows the average stocking density of milk cows in the top twelve states from 1997 to 2012, but this time only large dairy farms are included. Compared to the other states, New Mexico has ranked top in the average stocking density of large dairy farms since 2002 and the state's average stocking density was up to 3000 milk cows per farm in 2012. A further examination of the 2012 Census of Agriculture data indicates that the declining average stocking density of all dairy farms in New Mexico was due to a sharp increase of small farms with only 1-9 milk cows. Most of these emerging small dairy farms are probably hobby farms that have recently become popular in New Mexico.

[Figure 4 here]

Another characteristic of the dairy sector in New Mexico is that most cows are concentrated in a small agricultural area. In 2012, five counties in southern and eastern New Mexico − Chaves, Curry, Roosevelt, Dona Ana and Lea − accommodate 90% of all the 318,878 milk cows in the

---

[1] For the dairy sector, a facility confining 700 or more mature dairy cattle is a Large CAFO, a facility confining 200 to 699 mature dairy cattle is a Medium CAFO and a facility confining less than 200 mature dairy cattle is a Small CAFO (EPA, 2003, Table 4.1).

state, as shown in figures 5 and 6 (USDA, 2012). The dairy sector has been an economic development driver in Southern New Mexico and has a significant economic impact on the region and the state. Cabrera et al. (2008) use an input-output model to estimate the economic impact of milk production in the state. Their results show that the New Mexico dairy industry accounted for 13.1% of the total agricultural outputs and 20.5% of the agricultural jobs, making it the top agricultural industry in the state. The increasing trends in sector consolidation and milk productivity indicate that the dairy industry will continue to play an important role in the economic development of New Mexico.

[Figure 5 here]

[Figure 6 here]

1.2 Risk of Nutrients Emissions from Large Dairy Farms

The large dairy farms in New Mexico lead to challenges in proper manure management. Livestock manure is a good source of nutrients and applying it to cropland has been a traditional way of manure management. When properly managed, livestock manure makes an excellent fertilizer promoting crop growth and improving soil quality. Consolidation in livestock production generates higher farm incomes, but it also brings manure disposal problems, especially when consolidation combined with limited acreages for field crops leads to less land suitable for manure spreading. Relative to manure of other livestock species, dairy (and swine) manure is costly to move relative to its nutrient value due to high liquid contents. Therefore, the common practice of dairy operators continues to be (over-) application of dairy manure on land adjacent to the facility.

Excess nutrients transported off farms through volatilization, run-off or leaching can produce adverse environmental and health effects. For surface water, either nitrogen or phosphorus can lead to algal blooms in receiving aquatic ecosystems and a variety of problems including clogged pipelines, fish kills, and reduced recreational opportunities (EPA, 2000). An example is the toxic algae bloom occurred in Lake Erie in early August 2014 that provoked a tap water ban in Toledo, Ohio where nearly half a million people were told not to use water for drinking, cooking, or bathing for two days.[2] Although this algae bloom is in part due to climate change, agricultural nutrients runoff from the watershed plays an important role of feeding the algae bloom. For groundwater, nitrate-nitrogen is a potential threat to public health. Excessive concentration of nitrates in drinking water can lead to blue-baby syndrome in infants and stomach cancer in adults (Addiscott, 1996; Powlson et al., 2008).

According to the New Mexico Environment Department (NMED) in 2009, two-thirds of the state's dairies were contaminating groundwater with excess nitrogen from lagoon leaking or over-applying manure to crop fields. Groundwater nitrate pollution from large dairy farms in New Mexico was featured on the National Public Radio in 2009.[3] Approximately 90% of the total population in New Mexico depends on groundwater as drinking water and about 10% of the population depends on private wells for drinking water without any treatment (NMED, 1998). Given New Mexico's leading trend in dairy consolidation and severe scarcity of water resources, proper management of dairy manure is one of the greatest challenges to the state and its dairy industry. In this study, we investigate alternative approaches and policy tools to control nitrate emissions from the large dairy farms in New Mexico.

---

[2] Jane J. Lee, National Geographic, August 06, 2014. *Driven by Climate Change, Algae Blooms Behind Ohio Water Scare Are New Normal.* URL: http://news.nationalgeographic.com/news/2014/08/140804-harmful-algal-bloom-lake-erie-climate-change-science/.

[3] John Burnett, December 09, 2009. *New Mexico Dairy Pollution Sparks 'Manure War.'* URL: http://www.npr.org/templates/story/story.php?storyId=121173780.

1.3 Bioenergy Production from Dairy Manure

Fossil fuels such as coal, oil and natural gas are dominant over other energy sources in the world energy market due to several advantages, including low price, high efficiency, and attributes of mobility and storability (EIA, 2013; Ellabban et al., 2014). However, the consumption of fossil fuels is regarded as the major source of greenhouse gas emissions and thus, affects the environment at the local and global level The other problems of the fossil fuels are exhaustibility and foreign dependency (Goldemberg, 2006; Shafiee and Topal, 2009). In order to mitigate the negative externalities associated with fossil fuel consumption and maintain the sustainability of energy sources, renewable energy has attracted the attention of industries and policy-makers. The major regulatory policy in the promotion of green energy in the state of New Mexico is the renewable portfolio standard (RPS) according to which the investor-owned utilities should supply renewable power by no less than 20% of the total power sales by 2020. Several credits and subsidies such as green energy production tax credits and net metering have been adopted by the state to enhance renewable energy sector. These policies can potentially encourage bioenergy production from large dairy farms by protecting bioelectricity markets. The additional benefits to large dairy farms from the adoption of alternative manure management systems are discussed below.

1.3.1 *Anaerobic Digestion of Dairy Manure*

Manure-to-bioenergy treatments can provide livestock operators with renewable energy products that can meet heating and power needs or serve as transportation fuels (Cantrell et al., 2008). Compared to biological production of methanol and hydrogen, anaerobic digestion of livestock manure is an established method of generating methane-rich biogas. For dairy operations, potential benefits of anaerobic digestion of dairy manure include generation of renewable bioenergy (e.g., biogas and electricity), reduction in odor and greenhouse gases (GHGs) emissions, by-product sales (e.g., solid manure can be sold off farm), and potential pathogen reduction in manure (Beddoes et al., 2007; Demirer and Chen, 2005). Cantrell et al. (2008) compare alternative technologies of converting livestock manure to bioenergy with reference to bioenergy generation, added economic benefits to the farmers, and eutrophication control. They evaluate the environmental and economic benefits of biochemical (anaerobic digestion) and thermochemical (pyrolysis, gasification, and direct liquefaction) conversion technologies and conclude that integration of these technologies into livestock operations is efficient in producing bioenergy from manure and a sustainable way of reducing manure related emissions. Thus, while generating additional income to dairy farms through the conversion of dairy manure into the valuable products like biogas and digested co-products, this method also reduces the environmental costs of the dairy operators.

Currently, the anaerobic digestion system of waste management has received worldwide popularity (An, 2002; Rajendran et al., 2012), particularly in developing countries due to cheap labor costs and shortage of traditional fossil fuels. However, it has not gained popularity among the U.S. dairy farmers, mainly due to high capital costs and low energy efficiency. For instance, there is only one anaerobic digester under construction in New Mexico despite being one of the leading states in dairy (US EPA, 2015). Beddoes et al. (2007) conduct a cost-benefit analysis of anaerobic digestion of livestock manure in the U.S. They find that the capital cost of digester installation, machinery maintenance, operational costs, and costs of power plant installation for electricity generation are the major obstacles for the commercialization of anaerobic digestion systems of dairy manure management. The underlying reason is the low energy price available to the agricultural sector through various subsidies. The price (or cost) of energy generated through anaerobic digestion is much higher than the subsidized market price. Despite various economic hurdles, the number of operational anaerobic digesters are increasing in the United States. For instance, the number of operational digesters in the U.S. are more than 247 in 2014 which were 171 in 2011 (Klavon, 2011; US EPA, 2015). Among the 247 operational digester of 2014, 202 are operated by the dairy manure. Thus, given the varied economic and environmental benefits, the promising prospects of increasing anaerobic digestion of dairy manure management have been observed over time.

1.3.2 *Co-digestion of Dairy Manure with Microalgae*

One of the co-digestible materials with dairy manure is microalgae biomass. Microalgae is a type of unicellular photosynthetic microorganism that grows in aquatic environments. Through the photosynthetic process, microalgae converts sunlight, carbon dioxide (CO_2), nutrients and water into algal biomass. The photosynthetic conversion efficiency of microalgae is very high compared to other photosynthetic species, and its biomass volume can double within a few hours (Brennan and Owende, 2010). Microalgae is emerging as a promising renewable energy resource because it can survive in low quality water (e.g., industrial, municipal and agricultural waste water, saline water, and sea water) and grow rapidly. As nutrients are major inputs for microalgae growth, integrating dairy manure management with microalgae cultivation to produce bioenergy can be an advantageous approach of dairy manure management from both environmental and economic perspectives.

Microalgae can be cultivated on non-arable or marginal-quality lands using low quality water as long as the water is treated to prevent other microorganisms from contaminating the microalgae strain. Nutrients can be supplied from livestock or municipal waste so that production costs can be reduced. The CO_2 gas is a major input that can be obtained from anaerobic digestion systems or combustion of fossil fuels at power plants. Microalgae usually becomes ready for harvesting within few months depending on the microalgae species. It is harvested by removing water content from the biomass (also called dewatering). Common methods of harvesting include flocculation, micro-screening and centrifugation.

There are two types of established systems that can be used to cultivate microalgae: open ponds (or raceway ponds) and photobioreactors. Open ponds are designed in raceway styles with a shallow water depth so that algae, water, CO_2 and nutrients can be easily circulated with paddlewheel. These ponds are also designed in such a way that microalgae uptakes sunlight at optimal levels. The advantage of the open pond system is low production costs. The weaknesses of the system include risk of contamination by other species thereby slowing the biomass growth and the requirement of maintaining optimum temperatures (Hannon et al., 2010). A photobioreactor is another artificial system where microalgae is cultivated in transparent tubes or bags with controlled environmental conditions. Compared to open ponds, photobioreactors protect algae from invasive bacteria, maintain a high growth rate of biomass with less energy, water and land, but require high installation costs (Rajvanshi and Sharma, 2012). Many studies have compared the financial feasibility and environmental sustainability of different algae cultivation systems and findings of these studies are diverse (Jorquera et al., 2010; Norsker et al., 2011; Resurreccion et al., 2012). For instance, Resurreccion et al. (2012) find that even though microalgae bioenergy sector is still unattractive from the economic perspective, the open pond algae system is comparatively more sustainable than the photobioreactor system in terms of environmental and economic benefits. Jorquera et al. (2010) estimates that the energy ratio of both open pond and photobioreactor systems is greater than one implying the economic feasibility of both types of microalgae production system. Norsker et al. (2011) find that the production costs of microalgae biomass are respectively €4.95 and €5.96 for the open pond system and flat panel photobioreactors. Given the economic and technical advantages of open pond system, we consider the open pond system of microalgae production in this study.

Several experimental studies argue that co-digestion of manure with agricultural, residential and municipal wastes or microalgae biomass increases the productivity of bioenergy thereby reduces the cost of renewable energy production (El-Mashad and Zhang, 2010; González-Fernández et al., 2011; Macias-Corral et al., 2008; Umetsu et al., 2006; Yen and Brune, 2007). Macias-Corral et al. (2008) conduct an experimental study on biogas productivity by altering co-digestion material in the system. They find that single digestion of cow manure produces 62 m^3 of methane per ton of dry manure but co-digestion of cow manure with municipal waste produces 172 m^3 of methane per ton of dry manure. Various life cycle assessment studies on co-digestion of dairy manure with microalgae biomass have found significant increase in bioenergy productivity, but net energy use (energy output minus energy input) is lower in co-digestion algae systems than in single digestion systems because microalgae production is energy intensive (Higgins and Kendall, 2012; Mulbry et al., 2008b; Pizarro et al., 2006; Zhang et al., 2013). Nevertheless, net economic benefits from the co-digestion systems can be higher due to reduced cost of complying with environmental regulations and creation of various credits (e.g., carbon credit, nutrients credit, and tax credits). Microalgae also helps to recycle the manure nutrients so that the utilization of diary manure as nutrient supplement on microalgae production reduces the environmental, ecosystem and water quality degradation threats of dairy manure (Mulbry et al., 2008b, 2005). Thus, dairy farm would generate additional environmental and economic benefits from the adoption of basing on coupling microalgae system into the manure based anaerobic digestion system.

2 ENVIRONMENTAL REGULATION REGIME

With the fast-growing dairy industry in New Mexico since early 1980s, the challenge of properly managing dairy manure to prevent nitrate pollution of the state's scarce water resources has been emerging as a serious issue in the state. There are various environmental rules and policies regulating livestock manure management, especially for large dairy farms. In this section we provide an overview of the existing federal and state regulations.

2.1 Federal Regulations

The major Federal environmental law currently affecting animal feeding operations is the Clean Water Act (CWA)[4]. The CWA prohibits the discharge of pollutants from a point source to waters of the United States except as authorized through a National Pollutant Discharge Elimination System (NPDES) permit. It requires the U.S. Environmental Protection Agency (EPA) to establish national technology-based effluent limitations guidelines and standards (ELGs) for different categories of sources. Although agriculture has long been recognized as a nonpoint pollution source and exempted from NPDES requirements, animal production facilities (not including the adjacent lands) are easily identified and more similar to point sources. Therefore, large CAFOs with more than 1000 animal units have been historically defined as "point sources" by CWA (section 502, CWA). In the mid-1970s, EPA established ELGs and permitting regulations for CAFOs under the NPDES program, under which CAFOs were required to install acceptable technologies to improve farmstead structures and control runoff. Waste application to crop fields was exempted from the requirements because the regulations presumed that livestock manure removed from the farmstead area was handled appropriately through land application.

---

[4] Atmospheric pollutants are regulated under the Clean Air Act (CAA), but CAA currently does not recognize CAFOs for regulatory purposes. Although air pollution from CAFOs is receiving increasing attention in the academic literature, there is little or slow progress on regulatory change in practice.

Despite more than four decades of regulation of CAFOs, reports of discharge and runoff of animal waste from these large operations persist. A high correlation was found between areas with impaired surface and/or ground water due to nutrient enrichment and areas where dense livestock exist (EPA, 2003). Although this is in part due to inadequate compliance with existing regulations in the livestock sector, the recent trend of concentrating more animals within smaller geographic units contributes more to the persisting waste discharge. In response to these concerns, the U.S. Department of Agriculture (USDA) and EPA have attempted to control emissions from CAFOs since the late 1990s. In 1999, the two agencies jointly announced the Unified National Strategy for Animal Feeding Operations (hereafter Strategy), which establishes the goal that "all AFO owners and operators should develop and implement technically sound, economically feasible, and site specific comprehensive nutrient management plans (CNMPs) to minimize impacts on water quality and public health" (USDA and EPA, 1999, pp.5). The Strategy calls for both voluntary and regulatory programs, but voluntary ones (e.g., locally led conservation, environmental education, partnerships, financial assistance, and technical assistance) were mainly used at early stages to address the vast majority of AFOs. Most of the voluntary programs are executed by the Natural Resources Conservation Service (NRCS), the primary federal agency that works with private landowners to help them conserve, maintain and improve their natural resources. For example, NRCS provides technical and economic assistance to dairy farmers for secure manure management (e.g., construction of synthetic lined lagoon, nutrient management, and prescribed grazing) to help them meet the mandatory requirement of NPDES and to protect environmental quality.

In response to the increasingly severe problem of nutrient pollution, EPA published a new rule for CAFOs in 2003 to target high risk operations. This rule can be seen as a part of the regulatory program proposed by the 1999 Strategy. It expands the number of CAFOs required to seek NPDES permit coverage. One important change is that large CAFOs are required to prepare and implement site-specific nutrient management plans (NMPs) for animal waste applied to land. The guidelines for NMPs include land application rates, setbacks, and other land application best management practices (EPA, 2003). EPA finalized the rule in 2008 in response to the order issued by the U.S. Court of Appeals for the Second Circuit in Waterkeeper Alliance et al. v. EPA. There are two changes relative to the 2003 rule but the fundamental restrictions in NMPs remain the same for large CAFOs.[5] For a thorough review of federal and state regulations for water pollution from land application of animal waste, refer to Centner (2012).

EPA Region 6 directly implements the CAFO rule under the NPDES program in New Mexico.[6] The NPDES General Permit for Discharges from Concentrated Animal Feeding Operations in New Mexico (hereafter New Mexico CAFO general permit) covers any operation that meets the definition of a CAFO and discharges or proposes to discharge pollutants to waters of the country. The New Mexico CAFO general permit first became effective on September 3, 2009 and lasted for 5 years until September 2, 2014. EPA is currently proposing to reissue the New Mexico CAFO 5-year general permit, and the NMPs that are required to be submitted along with the permit application are currently available for public review and comment.[7] If effectively implemented, NMPs can significantly decrease nitrogen run-off and leaching. However, without better methods for manure disposal other than land application, NMPs increase competition for

---

[5] There are two changes in the 2008 final rule relative to the 2003 rule. First, only those CAFOs that discharge or propose to discharge are required to apply for permits; second, CAFOs are required to submit the NMPs along with their NPDES permits applications, which will then be reviewed by both permitting authorities and the public.

[6] This is different from how the CAFO program is implemented in the other states in EPA Region 6. The states of Arkansas, Louisiana, Oklahoma and Texas are authorized by EPA to implement the CAFO program in their respective states. EPA acts in an oversight and technical assistance role for these state programs.

[7] For details, refer to the EPA Region 6 CAFO program: http://www.epa.gov/region6/water/npdes/cafo/.

land capable of receiving animal manure and create additional costs for farm operators. Developing and implementing such a plan may substantially increase operating costs for dairy producers and thus hurt the dairy industry in New Mexico.

2.2 State Regulations

The New Mexico Water Quality Act (NMWQA) is the primary authority for water quality management in New Mexico. The New Mexico Water Quality Control Commission (WQCC) has been created by NMWQA under the New Mexico Environmental Department (NMED) for various duties of water quality management. WQCC establishes guidelines for the certification of federal water resources regulations and provides technical assistance to the farmers in compliance with federal regulations.

As discussed previously, EPA directly administers the NPDES permits for CAFOs in New Mexico. NMED supervises surface water quality programs in the state but does not have the power to issue NPDES permits to CAFOs. It helps EPA review the NPDES CAFO permits and make modifications as appropriate. NMED regulate dairies mainly through state groundwater regulations for dairies. According to NMED regulations, all the large dairy farms of New Mexico are required to obtain Ground Water Discharge Permits. NMED has maintained standard requirements and guidelines to issue groundwater discharge permits and monitor dairy farm manure disposal activities. The requirements include the proper application of liquid and solid dairy manures to agricultural lands, tracking off-site manure applications, soil and plant tissue sampling, monitoring well installation and groundwater sampling, provision for penalties, and enforcement actions (Lazarus et al., 2010).

As NMED’s monitoring data showed two-thirds of the state’s dairies were contaminating groundwater in 2009, the State Legislature ordered the NM Environment Department to create a dairy industry-specific rule for protecting groundwater from dairy manure. The objective is to make it easier to monitor groundwater and improve manure management practices. WQCC passed New Mexico’s first industry-specific regulations for the dairy industry in December 2010. The proposed regulations mandated various provisions in order to control water pollution from the dairy sector: a plastic liner for manure filled wastewater impoundments, minimum setbacks from important water resources such as drinking water wells, and notice to property owners within a mile radius of a proposed dairy that includes a map so the public can see where the dairy will be located in relation to residences and natural resources. Due to disputes between the administration, the dairy industry and environmental groups, the 2010 Dairy Rule was halted, the revised 2011 Dairy Rule went into effect but lacked enforcement, and a new 2015 Dairy Rule was just approved last month (May 2015). The new Dairy Rule deals primarily with how dairies manage wastewater and monitor groundwater. Large dairies in the state are required to line wastewater lagoons with two feet of compacted clay to catch manure runoff. The clay must be installed according to EPA guidelines. The liners would also need to be regularly monitored to detect nitrate contamination above the state standard. If the clay liners fail to provide adequate protection, the state could require the addition of synthetic liners. Another main rule is that wells monitoring groundwater contamination would be installed on case-by-case basis depending on the hydrogeology beneath the dairies.

3 OBJECTIVES

Our long-term goal is to better understand the advantages and disadvantages of alternative policies for controlling nonpoint source water pollution from agriculture so that we can develop better policy recommendations to reduce the pollution. Specific objectives of this project include: (1) assessing how alternative policies for controlling nitrate pollution affect net income of a typical large dairy farm in New Mexico (farm-level analysis); (2) assessing how alternative policies for controlling nitrate pollution affect New Mexico’s fast-growing dairy industry (regional analysis); and (3) identifying the most effective policy options for controlling nitrate pollution from large dairy farms while maintaining a sustainable dairy industry in New Mexico.

Objectives 1 and 3 were achieved. Objective 2 was not fully met. It would be desirable to model the spatial distribution of large dairy farms across the state with information on herd and land sizes and conduct a regional analysis, but we lack the information to do this here. We instead model a typical large dairy farm in New Mexico that accounts for herd and land size distributions and thus can be taken as an average regional analysis. The methods, data, results, implications, and recommendations pertaining to these objectives are described in the remainder of this report. Two conference presentations were made by a PhD student working on the project to disseminate results produced from this grant. The results herein, along with supplemental materials, will be submitted to a peer-reviewed journal after the submission of this report. Another metric of achievement was our participation in a multi-institutional interdisciplinary team (consists of scientists, engineers, and economists from the University of New Mexico and the University of Hawaii) to seek additional funding to continue and expand this work. Based on the work of this grant, we are currently part of the team with a pre-proposal top ranked in the internal competition for the NSF EPSCoR RII Track-2 solicitation and a full proposal submitted to NSF in February 2015.

4 METHODS

4.1 Overview

We use a combination of life cycle assessment (LCA), cost-benefit analysis (CBA), and sensitivity analysis to investigate policies for controlling nitrogen pollution from large dairy farms in New Mexico. The conceptual framework is presented in figure 7. The major output from LCA is a comprehensive assessment of environmental impacts of dairy manure management. Regulations or policies implemented to reduce these environmental impacts can either impose costs or create benefits for the dairy farms. For instance, the NMPs (a command-and-control policy) can substantially increase manure disposal cost due to increased off-site hauling while nutrients credits can provide additional income sources to the dairy farms. CBA is then conducted to evaluate the economic impacts of alternative policies. Sensitivity analysis is employed to incorporate uncertainties and risks into the model.

[Figure 7 here]

We first construct an integrated farm-level model that is suitable to investigate alternative policies for controlling nitrate pollution from a typical large dairy farm in New Mexico. Based on this typical dairy farm, we then conduct the LCA and CBA analyses of dairy manure management under three cases: direct land application of dairy manure (DLA), anaerobic digestion of dairy manure (AD), and anaerobic digestion of dairy manure coupled with microalgae cultivation (ADMC). In the DLA case, dairy manure is stored during off-season and applied to agricultural lands during cultivation periods. In the AD case, dairy manure is treated by an anaerobic digester that produces manure effluent (i.e., digested manure) and biogas. The digested manure effluent is separated into liquid and solid parts. Both of them can be directly applied to adjacent crop lands and the digested solid can be sold off-farm. The biogas is used to produce electricity. In the ADMC case, the digested liquid generated from the anaerobic digestion system is used as nutrient supplements to cultivate microalgae, which is then fed back into the digester to produce more biogas and electricity. We evaluate and compare the environmental and economic benefits of each of the three cases of dairy manure management. The DLA case is taken as the reference case so that the benefits of alternative cases can be compared against it. Compared to previous LCA studies on the topic, we add an assessment of water balance in this study. For the CBA analysis, we analyze the net benefits and economic feasibility of each case under a baseline scenario and alternative policy scenarios. We also conduct sensitivity analysis of cropland availability, rangeland availability, and policy strength to check the robustness of our results.

4.2 Model

The first step is to develop a model of a typical large dairy farm in New Mexico. The model serves as the functional unit for our LCA and CBA analyses. As previously discussed, we focus on large dairy farms with 500 or more milk cows in this study as these operations accommodate most of the dairy cows in New Mexico and pose the greatest risk to environmental quality and public health.[8] The average number of milk cows per large dairy farm (i.e., the size of a typical large dairy farm) of New Mexico is 2,892 heads (i.e., 315,183 cows divided by 109 large dairy farms) in 2012. Therefore, the functional unit of this study is defined as a typical large dairy farm consisting 2,892 milk cows.

The next step is to define system boundaries of alternative manure management cases. The boundaries we choose are “cradle to gate.” Since we focus on dairy manure management in this study, the pre-processes (e.g., dairy manure production process, dairy manure collection process,

---

[8] In 2012, total number of dairy farm in New Mexico are 410 with the milk cow number of 318,878. However, the total number of milk cows in 109 large dairy farms (with 500 or more cows) is 315,183 (USDA, 2012). This implies that about 99 percent of all the milk cows in New Mexico are concentrated in the large dairy farms.

and milk cow diets) and post-processes (e.g., consumption of produced biofuels and crops) of manure management are not included in our LCA and CBA analyses. The boundaries of DLA, AD and ADMC are shown in figures 8, 9, and 10 respectively. Dairy manure and wastewater are the flows in all the three cases, but the unit processes are different in each case. In DLA, the unit processes include the storage and direct land application of the manure. In AD and ADMC, dairy manure flows into the digester which in turn produces bio-electricity and digested effluent. The digested effluent is separated into solid and liquid, and the solid residue is sold off the farm. The liquid residue in AD is applied to cropland while in ADMC, it is directed to the microalgae cultivation pond.

[Figure 8 here]

[Figure 9 here]

[Figure 10 here]

Another important step is to define the units of measurements. Energy balances are expressed in gigajoule (gj), which is the derived unit of energy and equivalent to 278 kilowatt hours (KWH). Water balances are measured in gallons. Other environmental impacts such as eutrophication potential (ETP) and global warming potential (GWP) are measured in kilograms (kg) of phosphate (PO_4) equivalent and mega-grams (Mg) of CO_2 equivalent respectively. Mg is the derived unit of weight and is equivalent to 1,000 kg. All dollar values in the CBA part is adjusted for inflation using 2014 U.S. dollars. Other units of measurements, if used, are defined in the relevant sections, tables and figures.

5 LIFE CYCLE ASSESSMENT

LCA is an environmental decision support tool. It is used to perform quantitative assessment (or sometimes, qualitative assessment in the absence of data) of the environmental aspects of a product, activity or service throughout its life period (SAIC, 2006). Given the defined objectives, the major components of the LCA are inventory analysis, impact analysis and interpretation for policy implications and decision making. An inventory analysis is the quantification of the inputs (e.g., energy, water and other raw materials) used throughout the life cycle in the production of goods or services as well as the environmental releases (e.g., carbon dioxide and nutrients emissions) at each stage in the preparation and production cycle of the product. Based on the inventory input-output data, impact analysis is conducted. The impact analysis provides guidelines regarding environmental feasibility of producing the targeted goods or services. The interpretation component of the whole model is performed to inform decision makers regarding the information about the environmental performance of produced goods and services. Given the quantitative information on environmental performance of the goods or services to be produced and given the state of rules and regulations in the region, the interpretation of the model can informs decision-makers about the viability of conducting the activity. We follow the standard procedure to conduct the LCA.

5.1 Dairy Manure Characteristics in New Mexico

Excreted dairy manure consists of liquid and solid components containing various nutrients such as nitrogen, phosphorus, potassium and other trace elements. The amount of excretion as well as the organic and inorganic compositions of dairy manure vary depending on location, cow types, and diet. Nutrient contents also change with manure collection and storage methods (Florez-Margez et al., 2002). Cabrera et al. (2007) develop a stochastic dynamic model to predict seasonal excretion by using herd characteristics of New Mexico and find that New Mexico's dairy manure characteristics are not substantially different from the estimates of ASAE (2005) and van Horn et al. (2003). These estimates are also consistent with the findings of LPES (2013) and Van Horn et al. (1994). Given the consistency of the estimates from these previous studies, we use data from Van Horn et al. (1994) in this study and summarize the dairy manure characteristics in table 1.

[Table 1 here]

The estimated quantities of total nitrogen (TN) and total phosphorus (TP) excreted from the typical large dairy farm are 312,336 kgN/yr and 57,840 kgP/yr, respectively. Manure is applied to croplands during the cropping season and is stored in other periods. During the collection, storage and land application processes, some of the inorganic nitrogen losses through volatilization. Following Zhang et al. (2013), available nitrogen for direct land application (i.e., inorganic N available after volatilization plus 25% of organic nitrogen) in the DLA case is 27.1 kgN/cow-year and in the AD case, it is 11.4 kgN/cow-year. Therefore, for the typical large dairy farm in New Mexico, total nitrogen available for land application (TN_{land}) is 78,373 kgN/year in DLA and 32,997 kgN/year in AD.

5.2 Land in Dairy Farms of New Mexico

Dairy farms vary in the size of land they contain. Table 2 displays the distribution of land in large dairy farms of New Mexico in 2012. Over 60% of the large dairy farms in the state contain at least 202 ha (500 acres) of land and around 45% contain at least 405 ha (1000 acres). The size of land that a typical large dairy farm contains (A) is calculated by using equation (1), where i is the index for land size categories, $\aleph_i$ is the number of large dairy farms in each land size category, and L_i^{MV}

is the median value of land area in each land size category. By using data from table 2, a typical large dairy farm in New Mexico contains 391 ha of land.

$$A = \frac{\sum_{i=1}^{I} L_i^{MV} \aleph_i}{\sum_{i=1}^{I} \aleph_i} \dots\dots\dots\dots\dots (1)$$

[Table 2 here]

5.3 Major Field Crops in New Mexico

Dairy operators usually grow field crops onsite for feed. To conduct the LCA and CBA analysis of any land application, we need to simulate the typical cropping pattern of field crops in New Mexico. We also need to collect information on nitrogen requirements of different field crops to estimate the average nitrogen requirement per unit of cropland.

5.3.1 *Cropping Patterns*

Cropping patterns include crop rotations and crop arrangements within multiple crops (Pearson et al., 1995). The life cycle durations of major crops of New Mexico are reported in table 3 and the top five crops of New Mexico in 2012 in term of harvested acreage are reported in table 4. The top three field crops in New Mexico are alfalfa, wheat and corn. Alfalfa is the leading field crop and number one cash crop in New Mexico, as it is one of the highest-quality forages for milk cows. Corn and wheat are among the most flexible crops for marketing as they can be used either for grain or silage and thus help make profitable choice depending on market prices (Marsalis, 2007). In the Southwest of U.S., summer corn for silage is usually followed by winter wheat for grain so the harvest acreages of the two crops are very close; alfalfa is commonly rotated with the corn-wheat cropping system. According to table 3, the harvested acreage of alfalfa is four times of that of corn-wheat. Therefore, we assume alfalfa is rotated every four years in New Mexico, which is consistent with the literature. As a result, the field crop composition is 80% alfalfa (all year with 3-5 cuttings per year) and 20% corn-wheat (summer corn and winter wheat) for an average year.

[Table 3 here]

[Table 4 here]

The large dairy farms of New Mexico are assumed to follow this typical alfalfa-corn-wheat cropping pattern on their land. In other words, for the typical large dairy farm with 391 ha of land, alfalfa is grown on 80% of the land while summer corn and winter wheat are grown on the rest 20% of the land. The offsite croplands suitable for receiving dairy manure are also assumed to follow the same cropping pattern.

5.3.2 *Nitrogen Requirements and Evapotranspiration*

Different crops have different nitrogen and irrigation requirements. Alfalfa can obtain all the required nitrogen from its own nitrogen fixing nodules with the help of Rhizobium bacteria. However, it may require between 22-35 kgN/ha during the seeding period until the development of nitrogen fixing nodules (Caddel et al., 2001; Lindemann and Glover, 2003). Therefore, we assume the average nitrogen requirement for alfalfa is 28 kgN/ha. The recommended agronomic nitrogen application rate for wheat is 135 kgN/ha (Hossain et al., 2004). The agronomic nitrogen requirement that maximizes corn grain yield ranges from 200-240 kgN/ha so on average is 220 kgN/ha (Contreras-Govea et al., 2014; Cox and Cherney, 2001). The irrigation requirement depends on the evapotranspiration (ET) rates of crops. We collect the ET rates of alfalfa, wheat and corn in New Mexico from the Extension Center of New Mexico State University (Sammis et al., 1982, 1979). The nitrogen requirement and ET rates of alfalfa, wheat and corn are summarized in table 5.

[Table 5 here]

Following the typical cropping pattern of field crops in New Mexico, we estimate the average nitrogen requirement per unit of field crop land ($\overline{N}_{crop}$) by using equation (2), where $N_{alfalfa}$ is the nitrogen requirement rate of alfalfa, N_{wheat} is the nitrogen requirement rate of wheat, N_{corn} is the nitrogen requirement rate of corn, and α is the share of field crop land growing alfalfa ($\alpha = 0.8$). Similarly, we estimate the average ET per unit of field crop land ($\overline{ET}_{crop}$) as in equation (3), where $ET_{alfalfa}$, ET_{wheat}, and ET_{corn} are respectively ET rates of alfalfa, wheat and corn. Our calculation shows that $\overline{N}_{crop}$ is 93.4 kgN/ha and $\overline{ET}_{crop}$ is 49.4 inch.

$$\overline{N}_{crop} = \alpha N_{alfalfa} + (1-\alpha)(N_{wheat} + N_{corn}) \dots\dots\dots\dots\dots\dots\dots..(2)$$

$$\overline{ET}_{crop} = \alpha ET_{alfalfa} + (1-\alpha)(ET_{wheat} + ET_{corn}) \dots\dots\dots\dots\dots\dots\dots..(3)$$

5.4 Land Requirements of Alternative Manure Management Cases

Land is required in all the three cases of manure management. DLA requires croplands to apply the produced manure, AD requires croplands as well as lands for digester installation, and ADMC requires lands for digester installation and microalgae pond. We estimate the land requirement of each case.

5.4.1 *Land Requirement of DLA*

Spreading manure on croplands is a conventional method of dairy manure disposal. Manure contains various organic and inorganic compounds which should be applied to croplands in such a way that there would be no leaching or runoff of nutrients to water bodies and least evaporation to the atmosphere. In other words, dairy manure should be applied to croplands based on crops' nutrient requirements. The agronomic nitrogen application restriction influences land requirement for the management of produced nutrients.

The New Mexico Water Quality Control Commission (WQCC) regulates nitrogen application in the state. According to WQCC, total nitrogen applications should not exceed by more than 25% of what is reasonably expected to be removed by a harvested crop (WQCC, 2015). Since nitrogen in dairy manure is the major concern in New Mexico, we focus on nitrogen in this study and use it to calculate land requirement of each case.

We assume that dairy manure is applied to croplands based on crops' agronomic nitrogen requirements. Given the land size (A) of the typical large dairy farm and the average nitrogen requirement per unit of field crop land ($\overline{N}_{crop}$), total nitrogen that can be properly managed on the typical dairy farm (TN_{onsite}^{DLA}) is calculated as in equation (4).

$$TN_{onsite}^{DLA} = A\,\overline{N}_{crop} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots. (4)$$

Excess manure that the on-site land cannot absorb by following the agronomic nitrogen requirements should be transported to off-site field crop lands in the DLA and AD cases. The excess nitrogen that needs to be managed off-site ($TN_{offsite}$) is calculated as in equation (5), where TN_{land}^{DLA} is total nitrogen available for land application from the typical large dairy farm in the DLA case, as described in 5.1.

$$TN_{offsite}^{DLA} = TN_{land}^{DLA} - TN_{onsite}^{DLA} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (5)$$

Some of the off-site surrounding lands are not suitable to receive dairy manure as a fertilizer. In addition, some farmers may not be willing to accept dairy manure to substitute commercial fertilizer for various reasons. For instance, dairy manure may not fulfill the required nutrients requirement of a specific crop in proper proportion or might be subject to the problems of pathogens and odors. In order to calculate the total land area to be searched for the disposal of excess manure from the typical large dairy farm, we consider both the fraction of the off-site land that is suitable for receiving dairy manure (σ_1^{crop}) and the percentage of surrounding farmers that are willing to accept dairy manure (σ_2). The total land area to be searched ($\tilde{A}$) is calculated as described in equation (6).

$$\tilde{A} = \frac{TN_{offsite}^{DLA}}{\sigma_1^{crop}\sigma_2\bar{N}_{crop}} \dots\dots\dots\dots\dots\dots (6)$$

Under environmental regulations, dairy operators are required to search off-site croplands for manure spreading, if necessary, and bear all the costs of hauling the excess manure off the farm. We calculate the average hauling distance for excess manure by following Keplinger and Hauck (2006), Baerenklau et al. (2008) and Wang and Baerenklau (2015). We assume that both the land in the typical dairy farm and the total land required for manure management have the shape of a disk, with the dairy farm at the center of the two disks. The area of the inner disk is A (the land size that the typical large dairy farm contains) and the area of the outer disk is the sum of A and $\tilde{A}$. We denote the radius of the outer disk ξ_1 and the radius of the inner disk ξ_2. The average hauling distance of excess manure to off-site croplands ($\hbar_d$) is assumed to be a straight line and can be calculated as in equations (7)-(9).

$$\xi_1 = \sqrt{(A + \tilde{A})/\pi} \dots\dots\dots\dots\dots\dots (7)$$

$$\xi_2 = \sqrt{A/\pi} \dots\dots\dots\dots\dots\dots (8)$$

$$\hbar_d = \frac{1}{\tilde{A}} \int_{\xi_2}^{\xi_1} (\xi * 2\pi\xi) dr = \frac{2(\,\xi_1^3 - \xi_2^3)}{3(\,\xi_1^2 - \xi_2^2)} \ldots\ldots\ldots\ldots\ldots\ldots\ldots (9)$$

As the large dairy farms in New Mexico are mainly concentrated in five counties (Curry, Roosevelt, Chaves, Doña Ana, and Lea), we calculate the fraction of surrounding land suitable for receiving dairy manure as the ratio of the total area of field crop lands in these five counties over the total area of the five counties: σ_1^{crop} =67,455 ha/4,692,022 ha=1.4%. Following the literature, we assume off-site willingness to accept manure is 30% (Aillery et al., 2005). Results from equations (1)-(9) are summarized in table 6.

[Table 6 here]

5.4.2 *Land Requirement of AD*

In the AD case, the post-digestion manure contains the same amount of nitrogen as in the raw manure. The digested solid residue contains 30% of total nitrogen in the raw manure and is sold off the farm (Zhang et al., 2013). The liquid residue contains the rest 70% of total nitrogen in the raw manure and is applied directly to croplands. As discussed in 5.1, total nitrogen available for land application in the AD case (TN_{land}^{AD}) is 32,997 kgN/year per typical farm. Given the average nitrogen requirement per unit of field crop land equal to 93.4 kgN/ha, total land requirement of AD (A^{AD}) is 354 ha/year. Since the typical large dairy farm in New Mexico contains 391 ha of land, there is no need to search off-site land in the AD case.

5.4.3 *Land Requirement of ADMC*

In the ADMC case, land is required for microalgae cultivation. The information on land area is required to assess water balance of ADMC. We assume that microalgae is produced throughout the year and there is no need to store the manure before applying to the microalgae production system. Therefore, there is no loss of nitrogen through volatilization in the ADMC case. The the digested liquid effluent contains 70% of TN and 40% of TP in dairy manure (Zhang et al., 2013). Therefore, total nitrogen available for microalgae cultivation in the ADMC case (TN_{land}^{ADMC}) is 210,371 kgN/year and total phosphorus available for microalgae cultivation in the ADMC case (TP_{land}^{ADMC}) is 23,136 kgP/year.

Because the digested liquid effluent contains more phosphorus relative to nitrogen and only the liquid is used for microalgae production, the land requirement for microalgae production in open ponds is calculated based on the phosphorus content so that all nitrogen and phosphorus of the digested manure can be consumed by the microalgae production system. Following Zhang et al., (2013), land requirement of ADMC (A^{ADMC}) is calculated as in equation (10), where μ_1 is mass fraction of phosphorus in microalgae biomass, μ_2 is mass fraction of solid digestate, and θ is microalgae productivity (ash free dry weight) for open pond microalgae.

$$A^{ADMC} = \frac{TP_{land}^{ADMC}}{\mu_1 \mu_2 \theta} \dots\dots\dots\dots\dots\dots\dots\dots\dots..(10)$$

The parameter values are P_{admc}= 63 kgP/day (23,136 kgP/365 days), μ_1 = 0.013 (Mulbry et al., 2008a), μ_2 = 0.6 and θ = 0.0126 kg/day-m^2 (Clarens et al., 2010). The land in ADMC required to completely consume liquid phosphorus digestate is about 64 ha.

5.5 Environmental Impacts

For environmental impacts of dairy manure management, we evaluate energy balance, water balance, eutrophication potential (ETP) in terms of nutrients emissions in PO_4 equivalent, and global warming potential (GWP) in terms of GHGs emissions in CO_2 equivalent.

5.5.1 *Energy Balance*

Energy balance, which is the difference between energy output and energy input (output minus input), gives information on comparative advantages of each dairy manure management case. We evaluate the consumption (input) and production (output) of energy in each alternative case of dairy manure management. We also calculate the energy ratio (i.e., the rate of energy return per unit of energy invested) to further evaluate the feasibility of different cases. The higher the energy balance and energy ratio, the higher is the feasibility of energy production from dairy manure management.

In the DLA case, energy (e.g., diesel and petroleum oil) is needed to spread manure to the on-site croplands and to transport excess manure off-site. AD requires electricity for the operation of the digester (e.g., dilution and infrastructure operation) and heat for the maintenance of temperature for optimal biogas production. The ADMC case requires a significant amount of energy in several of its stages. Water, CO_2, and nutrients are the major inputs in the microalgae cultivation system and pumping these inputs into the open pond consumes energy in large quantity. The open pond system requires continuous circulation of nutrients with the water so that photosynthetic efficiency of the biomass is optimized, and thus electricity is continuously required to perform this operation. Energy is also needed to harvest and dewater the biomass. As the produced biomass is used for biogas production in the anaerobic digestion, the anaerobic digestion process also requires energy as in the AD case. For this study, various energy use data are collected from Pizarro at al. (2006) and Zhang at al. (2013). The input-output calculations of energy in the three cases are reported in table 7 and the results for energy balance are presented in figure 11.

[Table 7 here]

[Figure 11 here]

As shown in table 6, net energy use in the DLA case is -3,380 gj/year, which means 3,380 gj of net energy is consumed by the DLA approach of dairy manure management per year. Energy balance is 31,374 gj/year in the AD case and 15,670 gj/year in the ADMC case. Although total energy production in the ADMC case is highest among all alternative case, the energy balance in this case is about 50% less than that of the AD case.

Energy ratio is calculated as total energy output divided by total energy input. Energy ratio is also known as energy efficiency coefficient that determines the economic and technical feasibility of producing energy from given materials. A zero energy ratio of DLA indicates that DLA is completely infeasible from the energy production perspective. The energy ratio is 1.5 for ADMC, implying that 1.5 units of energy is produced per 1 unit of energy invested. The energy ratio of ADMC would seem economically feasible if it is considered in isolation as it produces 0.5 unit of surplus energy. However, it is infeasible in the current market as there are other high efficient energy production systems available (e.g., natural gas and coal). The energy ratio is 19 for the AD case, implying that it has comparatively high energy efficiency. Therefore, AD is the most economically and technically feasible system from the energy balance perspective.

5.5.2 *Water Balance*

Water is a scarce resource in New Mexico. Water scarcity is expected to increase due to climate change, population growth, and economic development. Water conservation can be partially achieved with recycling and reuse of wastewater. Apart from dairy manure, the wastewater generated from large dairy farms also contains pollutants that can harm the environment and public health (Ulery et al., 2004). Best alternative reuse of wastewater serves dual goals of water quantity conservation and water quality preservation. We examine potential reuse of wastewater on the typical large dairy farm under all the three cases of DLA, AD and ADMC. For each case, the volume of wastewater is compared to total on-site water requirement to investigate water balance. Wastewater treatment and treatment costs are beyond the scope of this study.

Dairy farms require water for supplying drinking water for the cows, cleaning farm house, collecting manure, cleaning cows and cleaning activities in milk parlor (e.g., cleaning tanks, pipelines, house floor and other equipment). As the dairy industry has been growing in New Mexico, water usage in the industry has been increasing. Water requirement of a milking cow ranges between 40-50 gallons per day per cow (Falk, n.d.). Total wastewater generated, including wastewater from the milk house, parlor and cow holding area but excluding wet manure, is around 14.7 gallons per day per milk cow (Holmes and Struss, 2009). As the typical large dairy farm in New Mexico contains 2892 cows, total wastewater generated on the typical dairy farm is 42,512 gallons per day (or 15.5 million gallons per year).

We now calculate the annual water requirement of each case. For DLA, water is required for irrigating the three field crops (alfalfa, wheat and corn) grown on-site. In addition to climate and soil quality, the efficiency of irrigation systems also influences irrigation water requirement. In New Mexico, the common method of irrigation is gravity (flood or furrow) followed by sprinklers and the average irrigation efficiency (η) is 80% (Samani et al., 2005). The total irrigation water requirement of DLA (W_{irrig}^{DLA}) is calculated as in equation (11) to be 1,620 million gallons per year.

$$W_{irrig}^{DLA} = \frac{A \cdot \overline{W}_{crop}}{\eta} \dots\dots\dots\dots\dots\dots\dots..(11)$$

In the AD case, over dilution of manure adversely affects biogas productivity and hydraulic retention time. Therefore, manure should be optimally diluted in order to maximize biogas production in the anaerobic digestion. Dairy manure as excreted contains 12% solids and 10.5% volatile solids, but digester efficiency is optimized at the concentration of 6-7% of total solids (Dennis and Burke, 2001). Generally, for every 5 kg of fresh manure, water required for manure dilution is approximately 4 gallons (An et al., 1997). The total excretion wet is about 56.7 kg/cow-day in New Mexico (see table 1) so the typical dairy farm excretes 59,851,386 kg wet manure per year. The amount of water that is required to dilute the excreted manure for anaerobic digestion (W_{digest}^{AD}) is then 48 million gallons per year. We use the same method as in the DLA case to calculate irrigation water requirement and find W_{irrig}^{AD} to be 1,465 million gallons per year. According to equation (12), the total water requirement of the AD case (W^{AD}) is 1,513 million gallons per year.

$$W^{AD} = W_{irrig}^{AD} + W_{digest}^{AD} \dots\dots\dots\dots\dots\dots..(12)$$

The total water requirement of the ADMC case consists of water requirement for the anaerobic digestion of dairy manure and water required for microalgae cultivation. The former is the same as in the AD case, with W_{digest}^{ADMC} equal to 48 million gallons per year. Microalgae slurry contains about 6.05% of total solids (Olsson et al., 2014), which is within the range of optimal concentration of total solids for digester efficiency. Therefore, no dilution is needed for the microalgae slurry before it enters the digester. For the microalgae pond, water lost through evaporation needs to be replaced daily. The amount of water required for microalgae cultivation (W_{algae}^{ADMC}) is calculated as in equation (13), where A^{ADMC} is the land area of microalgae production pond (64 ha or 644,956 m^2), D is the depth of microalgae production pond, E is evaporation loss of water from the microalgae production pond, and τ is the length of microalgae growth. Following Richardson et al. (2010), we have D=2 m, E=0.0127 m/day, and τ=365. Then total annual water requirement of the ADMC case is 903 million gallons as calculated in equation (14).

$$W_{algae}^{ADMC} = L(D + \tau E) \dots\dots\dots\dots\dots.(13)$$

$$W^{ADMC} = W_{digest}^{ADMC} + W_{algae}^{ADMC} \dots\dots\dots\dots\dots\dots..(14)$$

The water inventory data are illustrated in figure 12. The annual water requirements in DLA, AD and ADMC are 1,620, 1,513 and 903 millions of gallons respectively. ADMC is the least water consumptive case and then AD case uses less water after ADMC. The water shortage of each case is the total water collection in the typical dairy farm minus the water requirement in that case. Total wastewater collection is 16 million gallons per year. The water shortages in DLA, AD and ADMC are respectively 1605, 1498, and 887 million gallons per year. Water balance of the three cases implies that dairy wastewater is not fully sufficient for any of the three cases. However, in terms of water inventory analysis, ADMC is the least water consumptive case while AD and DLA are the highest water consumptive cases. Water demand is higher in DLA and AD due to irrigation water requirement for the croplands. The anaerobic digestion of dairy manure in both AD and ADMC case requires annual 48 million gallons of water. But, AD also requires water for crop field irrigation (1,466 million gallons per year in the typical dairy farm). Apart from water requirement for anaerobic digestion, ADMC also requires water for microalgae cultivation (824 million gallons per year in the typical dairy farm). The water balance estimates, thus, imply that ADMC is most sustainable case among all three cases of dairy manure management. Thus, given the arid and semi-arid attributes of New Mexico, ADMC case would contribute to water conservation relative to both DLA and AD cases in addition to its contribution to green energy production. If the ADMC is considered in isolation, this would require huge amount of water to commercialize the microalgae based bio-energy. However, microalgae can be grown on the wastewater from all sectors as well as saline water which would reduce the demand for fresh water in ADMC in New Mexico.

[Figure 12 here]

5.5.3 *Eutrophication Potential*

Potential emissions of nitrogen and phosphorus occur through various mechanisms like volatilization, leaching, and run-off during different stages of the manure handing process (e.g., during manure collection, storage, and application). The eutrophication potential (ETP) measures emissions of nitrogen and phosphorus. We adapt the emissions data from Zhang et al. (2013) to the large dairy farms of New Mexico.

For the ADMC case, as dairy manure is co-digested with microalgae throughout the year, there is no need to store dairy manure and thus no emissions from such processes. There can be nutrients emissions through volatilization during microalgae production process but studies have found that this type of emission is small (Cai et al., 2013; Smith et al., 2010). Following the literature, we conclude the ETP is zero in the ADMC case. The DLA and AD cases are sensitive to eutrophication potential as manure is stored and applied to the cropland in both cases. As shown in Figure 13, eutrophication potential is 87,000 kg PO_4 equivalent per year in the DLA case and 63,000 kg PO_4 equivalent per year in the AD case for the typical large dairy farm. In terms of eutrophication potential, ADMC is the most sustainable followed by AD case while DLA poses the highest risk of eutrophication.

[Figure 13 here]

5.5.4 *Global Warming Potential*

Global warming potential (GWP) consists of emissions of CO_2, nitrous oxide (N_2O), and methane (CH_4). In DLA and AD, GHGs emit during the processes of manure storage, land application and from the production of other materials that are used in the case. Substantial energy use is the major source of GWP. AD and ADMC also produce GWP from the bio-electricity production process. As in the calculations of energy balance and ETP, we adapt GWP data from Zhang et al. (2013) to the case of New Mexico based on per cow basis.

Results for GWP are presented in Figure 14. GWP is highest in the DLA case (13,000 Mg CO2-equivalnet per year) and is lowest in ADMC (9,000 Mg CO2-equivalnet per year). GWP in the AD case is 10,000 Mg CO2-equivalnet per year, which is between DLA and ADMC. These results imply that ADMC is most sustainable in terms of GWP.

[Figure 14 here]

6 COST-BENEFIT ANALYSIS

We now examine the life cycle costs, revenue and net benefits of each case under two types of scenarios: a baseline scenario and alternative policy scenarios. The baseline scenario is simulated without considering any incentive-based policies. For the policy scenarios, we simulate various state and federal policies have been adopted to control nutrients and GHGs emissions from the agricultural sector or to incentivize bioenergy production and reduction of these emissions.

Cost-benefit analysis for each case under each scenario is calculated as in equation (15), where NB is the present value of net benefit, ϑ is total revenue, $\mathfrak{C}$ is total cost, r is the discount rate and t is the index of year.

$$NB = \sum_{t=1}^{T} \frac{\vartheta - \text{Ꞓ}}{(1+r)^t} \dots\dots\dots\dots.(15)$$

Since the common lifecycle of anaerobic digesters is 20 years with steady stream of net income over the life span (Martin, 2005; Zhang et al., 2013), NB of each case is calculated for a 20-year planning period. We assume that the beginning period of all the cases is the year 2015 and the discount rate is 5%. Total revenue is the net income less the taxes, with a tax rate of 23.6% (Zhang et al., 2013). Total cost is the sum of initial outlays (also known as capital costs or initial investment) and operating and maintenance (O&M) costs. Initial outlays are discounted by the 7 years of Modified Accelerated Cost Recovery System (MACRS-Internal Revenue Service)[9]. All dollar values is adjusted for inflation using 2014 U.S. dollars.

6.1 Baseline Scenario

6.1.1 *Costs and Revenues of DLA*

In the case of DLA, initial outlays and O&M costs are associated with manure collection, handling, off-site transportation and land application. Following Zhang et al. (2013), the initial outlays of the DLA case are calculated by using equation (16), where Y is the manure land application costs (\$/cow) and x is the number of cows. Given the size of the typical large dairy farm in New Mexico, initial outlay in the DLA case is \$704.

$$Y = 1732.1x^{-0.115} \dots\dots\dots\dots\dots..(16)$$

---

[9] The MACRS is the smart tax policy that is used to depreciate the current tax burden in the United States. This policy of Internal Revenue department (IRS) allows depreciation of capital investment on a percentage basis for a specific period of time from taxable income so that tax burdens could be reduced at the beginning of the long term project. The depreciation period and rates differs by property types as defined by the IRS but the total deprecation will be the 100% of the capital investment. The case agricultural equipment and machinery and anaerobic digester lie into 7-year depreciation.

The O&M cost is the sum of costs of on-site manure land application and off-site manure hauling. The O&M costs for manure land application include the costs for labor, fertilizer, electricity, fuels, insurance and other miscellaneous items and is approximately $92/cow-year (Zhang et al., 2013). As previously discussed, the average hauling distance ($\hbar_d$) in the DLA case is 12 km. The unit costs associated with off-site hauling are shown in table 8, where the fuel cost for 12 km of hauling distance is $176/km-ha. Thus, the total hauling cost for the typical dairy farm is $18,726,400. The hauling cost of the DLA case remains the same in all scenarios (except in the sensitivity analysis of manure application to rangeland).

[Table 8 here]

Total revenue in the DLA case comes from the sale of produced crops on the farm (i.e., in 391 ha of land). Thus, revenues in the DLA case depends on the prices and quantities of produced crops during the given time span. The variation in prices and yield rates of alfalfa, wheat and corn during the period of 1990-2012 are shown in figures 15 and 16. For simplicity, we use the 2012 yield rates (bushel/ha) and per unit prices ($/bushel), as summarized in table 9. The impacts of crop price volatility are left for future research. Using the prices and yield rates of major crops and the cropland area, total revenue per typical dairy farm in the DLA case is $2,684,231/year.

[Table 9 here]

[Figure 15 here]

[Figure 16 here]

6.1.2 *Costs and Revenues of AD*

In the AD case, the initial outlay refers to all initial outlays incurred on the anaerobic digestion system (e.g., digester tank, boiler and heat exchanger, building and other materials), post digestion solid separation system (e.g., solid-liquid separator, composter, and dryer), and hydrogen sulfide treatment system. The initial outlay also accounts for utility charges, which includes the costs of power generator and gridline connection. Due to economies of scale, the initial outlay declines with the increase in the farm size (see figure 17). As digested manure is applied to agricultural lands, initial outlays also contain costs for manure collection and land application equipment. The procedure applied to calculate the manure land application is same as described in the DLA case. However, as only the digested liquid manure is applied to the agricultural land, the typical dairy farm in DLA with 2892 cows is equivalent to a large dairy farm in AD with 2,719 cows in terms of nitrogen content in the digested liquid (Zhang et al., 2013). The off-farm hauling cost is not required here as the land requirement in the AD case (354 ha) is smaller than the land owned by typical dairy farm (391 ha). The initial outlays on the anaerobic digestion system is $3,090,998 per typical dairy farm and initial outlay for manure land application is $1,914,468. Similarly, the O&M cost includes various operational costs such as maintenance, repairs, labor, fuel, and insurance. The O&M cost of the typical dairy farm in the AD case is $358,510/year.

[Figure 17 here]

Sale of bio-electricity is the major source of income in the AD case. We assume that the bio-electricity generated on the dairy farm can be fully sold back to the electric grids under mandatory policies and the sale price of electricity in the agricultural sector of New Mexico is $0.0611/KWH (Informa, 2013). As previously discussed, the annual net energy surplus per typical dairy farm in the AD case is 8,714,956 KWH.

The digested solid is also the important component for revenue generation in the AD case. The digested solid has a high use value for various reasons (EPA, 2013). Its low nutritive content attracts its use as soil conditioner (i.e., soil amendment) because there is low risk for nitrate pollution, gaseous pollution and pathogen problem when applied to the land. The high value of digested solid manure also pertains to the organic bedding material. If there is no demand for digested solid manure in the local market, it can also be easily transported to other regions where its demand is high. We assume that all the digested solids can be sold in the market and the value of digested solid manure (i.e., nutrients and fiber) is $255/cow (EPA, 2013). Dairy farm generates additional income from the sale of crops as the digested liquid is directly applied to the cropland. Calculation of crop revenue is similar to the DLA case. Total annual revenue in the AD case is $3,750,771 per typical dairy farm.

6.1.3 *Costs and Revenues of ADMC*

The parameters for initial outlays and O&M costs in the anaerobic digestion are same as in the AD case. However, as manure is co-directed with microalgae, the volume of post digestion material is higher in ADMC than in AD and thus, the cost is higher in the digester system in ADMC. The typical dairy farm in DLA with 2,892 cows is equivalent to a large dairy farm in ADMC with 5,639 cows based on initial outlays (Zhang et al., 2013). In addition to the costs introduced in the AD case, ADMC requires initial outlays and O&M costs in the microalgae cultivation system. The microalgae cultivation system contains various expenses such as pond construction, engineering, algal homogenizer, cultivation and harvesting. Initial outlays for microalgae cultivation system in the ADMC case is about $13 million and the O&M costs are about $1.5 million/year for the typical dairy farm.

As in the AD case, the major sources of income in the ADMC case are the sale of bio-electricity and digested manure. Crop revenues are not applicable in this case as there is no need to manage the digested liquid manure in the cropland. The revenues are calculated by following the procedure as in the case of AD with the same assumptions. Total annual revenue of ADMC is about $2 million.

6.1.4 *Discussions*

Comprehensive data on initial outlay, and O&M cost for DLA, AD and ADMC cases are reported in table 10. These cost data are the same for all scenarios. The total revenue data of all cases under baseline and policy scenario are reported in table 11. Using equation (15), we calculate the NB for each case under different scenarios. The NB estimates of all cases under the baselines scenario are presented in figure 18. The NB values are respectively -$156.95 million, $28.29 million and -$5.34 million in DLA, AD and ADMC. The NB is positive only in the case of AD. The negative NBs of the DLA and ADMC cases implies that these systems are not economically feasible under the baseline scenario. The NB is the lowest in the DLA case mainly due to the limitation of sufficient croplands on and surrounding the typical dairy farm such that the cost of off-site manure hauling is very high under the current NMP regulation. Higher costs and limited sources of income has caused the negative NB in the ADMC case. The high cost of ADMC is associated with high energy input in the system and thereby reducing the energy surplus for sale.

[Table 10 here]

[Table 11 here]

[Figure 18 here]

6.2 Policy Scenarios

Various state and federal policies have been adopted to control nutrients and GHGs emissions from the agricultural sector or to incentivize bioenergy production and reduction of these emissions. We call this type of policies “green policies.” One important role of these green policies is to correct market distortions due to negative externalities associated with production or consumption processes. For example, traditional fossil fuels are subject to negative externalities such as environmental pollutions and thus, may distort energy market performance. The renewable energy sector, including bioenergy production from livestock manure, is not financially competitive to the traditional fossil fuels when the negative externalities are not internalized. Financial incompetence deters the renewable energy sector to enter into the fossil fuel dominated energy market. Public policies can be an effective tool to correct market distortions and reduce pollution. In this section, we simulate both the current and prospective green policies in New Mexico to examine the effects of these policies on manure management and nitrogen control in the large dairy farms of New Mexico.

6.2.1 *Current Green Policies in New Mexico*

Various incentive and mandatory policies in the renewable for both consumers and producers are available in New Mexico. New Mexico’s renewable portfolio standard (RPS) is regulatory mandate to the investor owned utility companies to supply 20% total power sales by 2020. The RPS also mandates the rural electric cooperatives to supply 10% of total power sales by 2020. In the 20% mandated share of renewable power, the investor owned utility companies should supply no less than 30% from wind power, and no less than 20% from solar power, no less than 5% from other renewable sources (e.g., biomass, geothermal and hydropower) and no less than 3% from distributed generation. Other regulatory policies are net metering, mandatory green power options and interconnection standards. All of these regulations are intended to encourage small scale power generation by the individual consumers as well as to educate them for energy conservation. Consumers are also given the incentives to conserve energy through energy efficiency programs.

Different types of renewable energy sources are given different incentives in the state. The examples are solar market development tax credit, renewable energy production tax credit, sustainable building tax credit, geothermal heat pump tax credit, biodiesel facilities tax credit, agricultural biomass tax credit, alternative energy product manufacturers tax credit, biomass equipment & materials compensating tax deduction, and renewable electricity production tax credit. The major green energy policies are described in figure 19. Some of these policies such as renewable energy production tax credit, agricultural biomass tax credit and biomass equipment & materials compensating tax deduction also cover green energy production from the anaerobic digester and dairy manure. However, the eligibility criteria for receiving these credits vary of the types of credits. Given the set of various incentive-based policies in bio-energy sector, we choose the ‘agricultural biomass income tax credit’ for the dairy sector as this is most relevant in our case. According to this policy, the dairy farmer gets credits of $5 per ton of dairy manure and total credit limit is $5 million. This policy expires at the end of December, 2019. Thus, we include this credit from 2015-2019 in the policy analysis. In our case, the typical dairy farm gets about $0.33 million credits per year for 5 years as ‘Agricultural biomass income tax credit’. Other revenues and costs in policy analysis are the same as in baseline scenario for all cases.

[Figure 19 here]

The present value of net benefits of each case in this current policy scenario are shown in figure 20. The agricultural biomass income tax credit is not applicable to the DLA case and thus, NB of DLA remains the same as in the baseline scenario, which is about -$156.95 million. The tax credit under consideration is applicable to both AD and ADMC. NB of AD is $29.72 million in policy scenario compared to $28.29 million in baseline scenario. Similarly, NB of ADMC is -$3.90 million, compared to -$5.34 million in the baseline scenario. Under the tax credit scenario, NB of AD increases by more than $1 million from the baseline scenario. Similarly, the tax credit also reduces the negative NB of ADMC from the baseline by about $1.4 million, but it is still negative. The results imply that the current green policy in New Mexico can mitigate the cost burden of bioenergy projects but fails to make significant impact in the economic attractiveness of these projects from the baseline scenario.

[Figure 20 here]

6.2.2 *Prospective Green Policies for New Mexico*

Carbon and nutrient credits are market-based incentives that can be earned by removing or offsetting their emissions below the regulatory compliance. These credit markets are considered to be efficient tools to combat climate change, protect water quality and ecosystem as the market creates incentives to reduce greenhouse gas emissions and nitrate loading (Avi-Yonah and Uhlmann, 2009; Hoag and Hughes-Popp, 1997). Currently, California and the Regional Greenhouse Gas Initiative in the U.S. are regulating GHGs through cap-and-trade policies.[10] Some states like Virginia, Maryland, and Pennsylvania also regulate nutrient loading to maintain the nutrient loading limits of NPDES permits in the Chesapeake Bay (Branosky et al., 2011). We examine the effectiveness of nutrients and carbon credits trading that have been adopted in the other states and are potentially available in the future to the large dairy farms in New Mexico.

---

[10] National Indian Carbon Coalition (NICC): http://www.indiancarbon.org/the-carbon-credit-market.html.

The nutrient credits are earned by reducing the ETP and similarly, carbon credits are earned by reducing the GWP. The carbon and nutrient credits trading are applicable in the AD and ADMC cases. This is because the DLA is the reference case with the highest GWP and eutrophication potential relative to other two cases. The NB of DLA under this prospective policy scenario is the same as in the baseline scenario. The initial outlays and O&M costs also do not change from the baseline scenario. Under this prospective policy scenario, the only difference is the additional revenues generated from nutrients and/or carbon credits in the AD and ADMC cases. We have adapted the carbon and nutrient credits values on per cow basis from (Zhang et al., 2013).

When only nutrient credits are applied, the NBs in AD and ADMC are $35.77 million and $70.04 million respectively. In the baseline and current green policy scenario, the NB of the ADMC was negative while it has increased drastically when nutrient credits are taken into account. The NB of the AD has also increased from the baseline and current policy scenario by about $6 million. However, the negative NB of ADMC in the earlier scenario is now highest by more than 50% of the NB of the AD. ADMC has increased drastically in this case because there is no ETP in this case. Nutrient credits trading does not increase the NB of AD as this case has a high ETP.

When we consider only carbon credits as an additional income flow into the system, the NB of AD and ADMC are $28.84 million and -$4.85 million respectively. These numbers are almost the same to the baseline scenario and thus are smaller than the current green policy scenario. This is because GWP exists in all three cases despite being smallest in the ADMC case and the credits are measured relative to the DLA case. Another reason for not having significant impact of the carbon credit into the system is the minimal and fluctuating price for it ($13/cow-year). In the United States and New Mexico, the regulations are strict in controlling nutrient loading in the water source. The incentives have been adapted through various ways such as tax credits, grants and R&D investments on green energy development, the regulations are not strict in controlling the GHGs emission. Thus, our results ae consistent with these trends. That is, strict regulatory policies increase the demand for the credits to maintain the regulatory compliance by emitters and this increases the market price of the credits. Thus, when nutrient credits and carbon credits are considered together in all cases, the NBs do change much from the NBs from the only nutrient credit case. The increments from the nutrients only credits to the combined credits are less than a million dollar.

When we consider nutrients and carbon credits simultaneously, the NBs of AD and ADMC are $36.12 million and $71.22 million respectively. The results with nutrient credits and carbon credits are reported in figure 21. The CBA results under the prospective policy scenario implies that the economic competitiveness of anaerobic digestion coupled with microalgae production sustains only when nutrients credits are accounted in the analysis. The productivity of the anaerobic digestion increases when dairy manure is co-digested with microalgae. The ADMC is also relatively more environment friendly as it recycles the nutrients and emits least GWP. However, microalgae bio-energy has not achieved commercial expansion due to high system costs. The costs can be reduced by innovation in the ADMC technologies and learning by doing. Given the current state of science and technology in the microalgae sector, public policies play a vital role in providing incentives for technological innovations and reducing capital costs. The CBA estimates suggest that markets for the nutrients and carbon credits increase economic benefits of the ADMC case drastically so that the NB of ADMC is highest among all scenarios.

[Figure 21 here]

7 SENSITIVITY ANALYSIS

7.1 Cropland Availability for Dairy Manure Management

In the state of New Mexico, about 20% of dairy farm own more than 800 ha of land (USDA, 2012). We simulate the possibility that the typical dairy farm owns sufficient land (~800 ha) to manage the produced manure on-site. This means that there is no excess manure in this case and thus, there is no hauling cost to be transported to the offsite farm. Off-farm hauling cost was only applicable in the DLA case under baseline and policy scenario, and thus, the O&M costs decreases in the DLA case in the absence of offsite hauling cost. The revenue also increases for the DLA in this scenario from the baseline and policy scenarios as the onsite cropland area has increased from 391 ha to 800 ha. Using the crop prices and yield rates from table 9, the total revenue from the sale of crops in the DLA case for 800 ha of land is $5,492,032/year per a typical dairy farm. The cost and revenue for AD and ADMC remain unchanged from the baseline scenario. The CBA results for all cases under current policy scenario are reported in figure 22.

[Figure 22 here]

In this scenario, the net present values are $48.08 million, $20.29 million and -$5.34 million in DLA, AD and ADMC respectively. These results indicate that economic profits are highest in the DLA case. If a dairy farm contains sufficient cropland suitable for receiving manure, the best and least costly manure management strategy is direct land application. However, each dairy farm may not have sufficient lands to use produced manure by following agronomic N application rate. In New Mexico, only 20% of dairy farmers own more than 800 ha of land and on average, the typical dairy farm of the state owns only about 391 ha of land. This validates the argument that we discussed in the earlier scenarios that the limitation of cropland is the major reason for the economic infeasibility of the DLA case. The enforcement of implementation of environmental regulations also influence dairy farmers' decision to make the alternative best use of the manure. For instance, the lack of enforcement of NMPs in New Mexico may be one the major reasons that (over-) application of dairy manure to croplands is very common in the state.

7.2 Rangeland Availability for Dairy Manure Management

New Mexico's range land covers about the 80% of land and the rangeland lacks necessary nutrients and organic matter (Cabrera et al., 2009). Despite being limited croplands to manage the produced manure from the increasing livestock industry, the excess manure could be supplied to the nutrient deficient rangelands of the state. This helps to meet the regulatory restrictions posed to the dairy producers and improve the quality of rangeland simultaneously. In this sensitivity analysis, we assume that the surrounding rangeland and croplands are both suitable for receiving the excess dairy manure. When we consider the rangelands in the sensitivity analysis, the land area that need be searched to manage excess manure ($\tilde{A}_r$) is calculated by using equation (17), where σ_1^{crop} is the fraction of surrounding land that is suitable for receiving dairy manure for field crops farming and $\sigma_1^{rangeland}$ is the fraction of surrounding land that is suitable for receiving dairy manure for ranging. Other procedures for calculating the hauling distance and hauling costs are same as previously discussed.

$$\tilde{A}_r = \frac{TN_{offsite}^{DLA}}{\left(\sigma_1^{crop}\overline{N}_{crop} + \sigma_1^{rangeland}\overline{N}_{rangeland}\right)\sigma_2} \dots\dots\dots\dots.(17)$$

We have $\sigma_1^{rangeland}$ =80% (Cabrera et al., 2009) and from baseline scenario, σ_1^{crop}=1.4%. The agronomic N application rate for the maintenance of healthy rangeland is 168 kgN/ha-year (McFarland et al., 2007). Definitions and assumptions made for other components of hauling distance formula are the same as those in the baseline case. By using these information, the land to be searched off the farm is 416 ha per year and the hauling distance in this case is 1 km. Thus, by using the crop prices and yield rates from table 9, the total revenue in this case is $285, 5857 per year. The hauling cost in the scenario is $46/km-ha. Here, the AD and ADMC remain unchanged from while the revenues and costs are changed from the baseline scenario, due to changes in the on-site land area, off-site hauling distance and thus, the offsite hauling costs.

The CBA results of the rangeland sensitivity analysis are presented in figure 23. The NB of DLA in this case $22.8 million while the corresponding values of AD and ADMC are same as in the baseline case ($28.29 million and -$5.34 million respectively). When rangeland is included, NB of the DLA has not only turned to be positive but has increased drastically from the baseline scenario. The results of this section also augment the arguments made in the previous section. That is, if the dairy farm owns sufficient land or has sufficient land in its vicinity, and if these lands are suitable and willing to accept manure, then this not only eases the dairy farmers to dispose the produced manure but also generate positive profits from it.

[Figure 23 here]

Rangeland plays a vital role in preserving ecosystem health and sustaining the livestock industry. In the context of increasing regulatory compliance on nutrient emissions from state and federal agencies, the nutrient deficient rangeland could serve a vital role in secure management of increasing manure volumes. The rangelands owners could also generate additional incomes by earning nutrient credits through the reduction nutrients loadings in the water sources under the environmental credit trading. The rangelands are also among the major sources of carbon sequestration and thus, the rangeland farmers can also earn carbon credit with preservation of these lands. Thus, when we consider rangeland as a possible source of offsite manure management, along with the increased benefits to the rangeland farmers, it has drastically increased the net benefit of the dairy farm (from -$157 million $23 million). However, as we conduct CBA based on comparative analysis among the three cases, this increased income of DLA do not necessarily suggest that DLA is the most economically feasible case. For instance, when rangeland is included as offsite land, the NB of AD is more than that of DLA by over $5 million. However, the implication of the discussion is that looking for alternative best management strategies can benefit all the parties of the system. For example, the dairy farm reduces manure hauling costs along with maintaining the regulatory emission compliance while the nutrient deficient rangeland also gets the nutrients for free. Currently, USDA and EPA are conducting studies and discussions to enhance public knowledge on environmental credit trading and to enact it as a possible policy instrument along with the existing cap based environmental polices (EPA-USDA, 2013; Gross et al., 2008). Similar education programs are needed to increase the willingness of rangeland owners to accept manure for nutrient supplement.

7.3 Green Policy Strength

We also perform sensitivity analysis with ±25% change of the current green policy strength. The changes affect the annual revenues of AD and ADMC but not DLA. The NB estimates for this scenario are reported in figure 24. Here, ±25% change of the current green policy strength affects the NBs of AD and ADMC slightly. The NB of the ADMC is still negative. With a 25% increase in policy incentives, the NBs of AD and ADMC are about $30.08 million and -$3.54 million respectively. Thus, the NBs of AD and ADMC increases by about $1 million when the incentive is increased by 25%. When policy incentives are decreased by 25%, NBs of both AD and ADMC are decrease slightly from the status quo. As we have chosen a single green policy among a wide set of green power incentive policies, the variation in the policy strength is not effective here. For nutrients credit, even if the price is reduced by half, it still provides sufficient incentives to induce the change in manure manage practices from DLA to ADMC. Our results indicate that the current green policies in New Mexico is not strong enough and lessons can be learned from the other states that have successfully established markets of environmental credits.

[Figure 24 here]

8 CONCLUSIONS AND DISCUSSIONS

We use a combination of life cycle assessment (LCA), cost-benefit analysis (CBA), and sensitivity analysis to investigate policies for controlling nitrogen pollution from a typical large dairy farm in New Mexico. Based on this typical farm, we conduct the LCA and CBA analyses of dairy manure management under three cases: direct land application of dairy manure (DLA), anaerobic digestion of dairy manure (AD), and anaerobic digestion of dairy manure coupled with microalgae cultivation (ADMC). We assess four environmental impacts of the alternative manure management cases in the LCA analysis: energy balance, water balance, eutrophication potential (ETP), and global warming potential (GWP). We find that the ADMC case is most sustainable among all cases because of its lowest water balance, ETP (close to the AD case) and GWP. From the energy balance perspective, AD is most attractive as its net energy surplus is 50% more than the net energy surplus of ADMC. The DLA case is the least sustainable with regard to any of the environmental impacts. In the CBA analysis, we evaluate each case under a baseline scenario and alternative incentive-based policy scenarios. AD is most profitable in the baseline, tax credit, and carbon credit scenarios. ADMC is most profitable in the presence of a market for nutrient credits. This is consistent with the results from the LCA analysis, because the low ETP of ADMC enable it to generate a high level of nutrient credits when such a market exists.

We conduct sensitivity analysis to check robustness of the LCA and CBA results. When we assume that the typical dairy farm has sufficient land to manage the produced manure, the net benefit of DLA increases significantly and becomes the highest among all the cases. This partially explains why DLA is still the common approach of manure disposal in New Mexico despite its lowest profitability shown in the CBA analysis. The typical large dairy farm we model in this study contains 391 ha of land. However, around 45% of the large dairy farms in New Mexico contain at least 405 ha of land and over 20% contain more than 800 ha of land (USDA, 2012). Given the current trend of expansion and consolidation, it is possible that a higher percentage of the large dairy farms in New Mexico will have sufficient on-site croplands for manure spreading. This can be regarded as economies of scale and can be incentivized through public policy tools. On the other hand, the lack of enforcement of NMPs and the Dairy Rule in New Mexico may be another reason that land application of dairy manure is still very common in the state, as the dairy farms without sufficient on-site cropland are not enforced to transport manure off-site. This is probably due to the defining characteristic of nonpoint source emissions that they are prohibitively costly to monitor. In that case, the command-and-control type of policies like NMPs and the Dairy Rule of New Mexico might not be effective. This is also the reason why we have focused on incentive-based policies in the CBA scenarios.

Another sensitivity analysis is conducted to examine the possibility of applying excess dairy manure to rangelands of New Mexico. We find that compared to the baseline scenario, the net benefit of DLA increase significantly to 81% of the net benefit of the most profitable AD. Application of dairy manure to rangelands surrounding dairy farms can serve a dual purpose of dairy manure disposal and nutrient amendment to rangeland soil. We also perform sensitivity analysis of the strength of the current green policy in New Mexico. Our results indicate that the current green policies in New Mexico is not strong enough and lessons can be learned from the other states that have successfully established markets of environmental credits.

Our results suggest that nutrients (especially nitrogen) in dairy manure on large dairy farms of New Mexico can potentially be converted into various valuable products (e.g., nutrient supplement and renewable energy) while maintaining compliance with regulatory requirements. Incentive-based policies including subsidies (including tax credits), nutrient credits, and carbon credits are highly recommended for controlling nitrate pollution from large dairy farms while maintaining a sustainable dairy industry in New Mexico.

Below we provide a list of policy recommendations to policymakers working on water quality management programs:

- Provide subsidies for bioenergy production from dairy manure (e.g., subsidies for installation of anaerobic digesters, microalgae cultivation for digestion feed, and algal biofuel production using dairy manure and wastewater)
- Provide incentives for the consolidation of the dairy sector (e.g., tax credits and low interest loans)
- Participate in out-of-state markets for environmental credits (e.g., California’s carbon emissions trading system)
- Establish in-state markets for environmental credits (similar to Maryland’s Nutrient Trading Program)
- Education and outreach programs on alternative best manure management practices (e.g., technical assistance to dairy operators for anaerobic digestion systems and education of rangeland operator to increase their willingness to accept dairy manure)

Two caveats to consider when interpreting our results include the following. First is the assumption that the typical large dairy farm in New Mexico contains 2892 cows and 391 hectare of land. However, in practice, both the herd and land size can vary significantly. It would be desirable to model the spatial distribution of large dairy farms across the state with full information on herd and land sizes but we lack the information to do this here. We call for construction of a database of dairy CAFOs in New Mexico, probably through the Extension Center at the New Mexico State University or the New Mexico Environmental Department since the department has been keeping record of dairy farms' NPDES permit applications that already contain detailed information on each farm. Second, our results are based on deterministic crop yields and prices. However, climate change has been shown to affect crop yields and crop prices have been volatile over the past decade. A future sensitivity analysis of crop yields and prices could provide an improved assessment.

9 SUMMARY

New Mexico has ranked top in the average stocking density of large dairy farms (with 500 or more milk cows) since 2002 and the state's average stocking density was up to 3000 milk cows per farm in 2012. Another characteristic of the dairy sector in New Mexico is that most cows are concentrated in a small agricultural area. The dairy sector has been an economic development driver in Southern New Mexico and has a significant economic impact on the region and the state. However, the large dairy farms in New Mexico lead to challenges in proper manure management.

In this study, we use a combination of life cycle assessment (LCA), cost-benefit analysis (CBA), and sensitivity analysis to investigate policies for controlling nitrogen pollution from large dairy farms in New Mexico. We first construct an integrated farm-level model that is suitable to investigate alternative policies for controlling nitrate pollution from a typical large dairy farm in

New Mexico. Based on this typical dairy farm, we then conduct the LCA and CBA analyses of dairy manure management under three cases: direct land application of dairy manure (DLA), anaerobic digestion of dairy manure (AD), and anaerobic digestion of dairy manure coupled with microalgae cultivation (ADMC). Four environmental impacts of the alternative manure management cases are assessed in the LCA analysis and net benefits of each case are evaluated in the CBA analysis under a baseline scenario and different incentive-based policy scenarios. We also conduct sensitivity analysis of cropland availability, rangeland availability, and policy strength to check the robustness of our results.

Our results suggest that nutrients (especially nitrogen) in dairy manure on large dairy farms of New Mexico can potentially be converted into various valuable products (e.g., nutrient supplement and renewable energy) while maintaining compliance with regulatory requirements. We recommend incentive-based policies including subsidies (including tax credits), nutrient credits, and carbon credits for controlling nitrate pollution from large dairy farms while maintaining a sustainable dairy industry in New Mexico. Education and outreach programs on alternative best manure management practices are also recommended. Given the ongoing consolidation in the dairy industry both within and beyond New Mexico’s borders, our results can inform local, state, and federal policymakers working on water quality management programs.

10 REFERENCES

Addiscott, T.M., 1996. Fertilizers and nitrate leaching. Issues in Environmental Science and Technology (United Kingdom).

Aillery, M., Gollehon, N., Johansson, R., Kaplan, J., Key, N., Ribaudo, M., others, 2005. Managing manure to improve air and water quality. US Department of Agriculture, Economic Research Service.

An, B.X., 2002. Biogas technology in developing countries: Vietnam case study, in: Proceedings Biodigester Workshop. University of Agriculture and Forestry.

An, B.X., Rodriguez, L., Sarwatt, S.V., Preston, T.R., Dolberg, F., 1997. Installation and performance of low-cost polyethylene tube biodigesters on small-scale farms. World Animal Review (FAO).

ASAE, A.S. of A.E., 2005. D384. 2, Manure Production and Characteristics. ASABE, St. Joseph, MI (March 2005).

Avi-Yonah, R.S., Uhlmann, D.M., 2009. Combating global climate change: Why a carbon tax is a better response to global warming than cap and trade. Stanford Environmental Law Journal 28.

Baerenklau, K.A., Nergis, N., Schwabe, K.A., 2008. Effects of Nutrient Restrictions on Confined Animal Facilities: Insights from a Structural-Dynamic Model. Canadian Journal of Agricultural Economics/Revue canadienne d'agroeconomie 56, 219–241.

Beddoes, J.C., Bracmort, K.S., Burn, R.B., Lazarus, W.F., 2007. An analysis of energy production costs from anaerobic digestion systems on US livestock production facilities. Washington, DC: US Department of Agriculture.

Branosky, E., Jones, C., Selman, M., 2011. Comparison tables of state nutrient trading programs in the Chesapeake Bay watershed. World Resources Institute, Washington, DC.

Brennan, L., Owende, P., 2010. Biofuels from microalgae—a review of technologies for production, processing, and extractions of biofuels and co-products. Renewable and sustainable energy reviews.

Cabrera, V.E., Hagevoort, R., Solís, D., Kirksey, R., Diemer, J.A., 2008. Economic impact of milk production in the state of New Mexico. Journal of dairy science 91, 2144–2150.

Cabrera, V.E., Mathis, C.P., Kirksey, R.E., Baker, T.T., 2007. NM-Manure: A Seasonal Prediction Model for Manure Excretion by Dairy Cattle in New Mexico. Agricultural Experiment Station, College of Agriculture and Home Economics, New Mexico State University.

Cabrera, V.E., Stavast, L.J., Baker, T.T., Wood, M.K., Cram, D.S., Flynn, R.P., Ulery, A.L., 2009. Soil and runoff response to dairy manure application on New Mexico rangeland. Agriculture, Ecosystems & Environment 131, 255–262. doi:10.1016/j.agee.2009.01.022

Caddel, J., Stritzke, J., Berberet, R., Bolin, P., Huhnke, R., Johnson, G., Kizer, M., Lalman, D., Mulder, P., Waldner, D., others, 2001. Alfalfa production guide for the southern Great Plains. E-826. Online: http://alfalfa. okstate. edu/pub/alfalfa-production/guide. pdf (Accessed: 19 June 2009 108.

Cai, T., Park, S.Y., Li, Y., 2013. Nutrient recovery from wastewater streams by microalgae: Status and prospects. Renewable and Sustainable Energy Reviews 19, 360–369. doi:10.1016/j.rser.2012.11.030

Cantrell, K.B., Ducey, T., Ro, K.S., Hunt, P.G., 2008. Livestock waste-to-bioenergy generation opportunities. Bioresource technology 99, 7941–53. doi:10.1016/j.biortech.2008.02.061

Centner, T.J., 2012. Regulating the land application of manure from animal production facilities in the USA. Water Policy 14, 319.

Clarens, A.F., Resurreccion, E.P., White, M.A., Colosi, L.M., 2010. Environmental Life Cycle Comparison of Algae to Other Bioenergy Feedstocks. Environ. Sci. Technol. 44, 1813–1819. doi:10.1021/es902838n

Contreras-Govea, F.E., Marsalis, M., Lauriault, L., 2014. Corn Plant Density Effects on Silage Quality, Guide A-416 (No. Guide A-416). Cooperative Extension Service, College of Agricultural, Consumer and Environmental Sciences , New Mexico State university.

Cox, W.J., Cherney, D.J., 2001. Row spacing, plant density, and nitrogen effects on corn silage. Agronomy Journal 93, 597–602.

Demirer, G.N., Chen, S., 2005. Two-phase anaerobic digestion of unscreened dairy manure. Process Biochemistry 40, 3542–3549. doi:10.1016/j.procbio.2005.03.062

Dennis, A., Burke, P.E., 2001. Dairy waste anaerobic digestion handbook. Environmental Energy Company 6007.

EIA, U., 2013. Annual energy outlook 2013. US Energy Information Administration, Washington, DC.

Ellabban, O., Abu-Rub, H., Blaabjerg, F., 2014. Renewable energy resources: Current status, future prospects and their enabling technology. Renewable and Sustainable Energy Reviews 39, 748–764. doi:10.1016/j.rser.2014.07.113

El-Mashad, H.M., Zhang, R., 2010. Biogas production from co-digestion of dairy manure and food waste. Bioresource Technology 101, 4021–4028. doi:10.1016/j.biortech.2010.01.027

EPA, 2013. U.S. Dairy Industry's Report National Market Value of Anaerobic Digester Products [WWW Document]. Innovation Center for U.S. Dairy, 2013 AgSTAR National Conference, informa economics. URL http://www.epa.gov/agstar/documents/conf13/National%20Market%20Value%20of%20Anaerobic%20Digestion%20Products,%20Jerry%20Bingold.pdf (accessed 5.21.15).

EPA, 2003. National pollutant discharge elimination system permit regulation and effluent limitation guidelines and standards for concentrated animal feeding operations (CAFOs); final rule (2003) (No. 68(29)). Federal Register.

EPA-USDA, 2013. USDA, EPA Partnership Supports Water Quality Trading To Benefit Environment, Economy [WWW Document]. URL http://yosemite.epa.gov/opa/admpress.nsf/ec5b6cb1c087a2308525735900404445/41888687a8e96fdb85257c36005830d4!opendocument (accessed 6.24.15).

EPA, U.S.E.P.A., 2000. National Water Quality Inventory: 1998 Report to Congress. EPA-841-R-00-001. Office of Water Washington DC.

Falk, D.E., n.d. Fresh Water Needs for Dairy Farms, Extension Dairy Specialist, University of Idaho [WWW Document]. URL http://www.oneplan.org/Stock/DairyWater.asp (accessed 5.30.15).

Florez-Margez, J.P., Flynn, R.P., Lindemann, W.C., Remmenga, M., 2002. Total nitrogen content of dairy manures in New Mexico. Agricult. Exp. Sta. Bull 785.

Goldemberg, J., 2006. The promise of clean energy. Energy Policy 34, 2185–2190. doi:10.1016/j.enpol.2005.03.009

González-Fernández, C., Molinuevo-Salces, B., García-González, M.C., 2011. Evaluation of anaerobic codigestion of microalgal biomass and swine manure via response surface methodology. Applied Energy, Special Issue of Energy from algae: Current status and future trends 88, 3448–3453. doi:10.1016/j.apenergy.2010.12.035

Gross, C.M., Delgado, J.A., McKinney, S.P., Lal, H., Cover, H., Shaffer, M.J., 2008. Nitrogen Trading Tool to facilitate water quality credit trading. Journal of Soil and Water Conservation 63, 44A–45A. doi:10.2489/jswc.63.2.44A

Hannon, M., Gimpel, J., Tran, M., Rasala, B., Mayfield, S., 2010. Biofuels from algae: challenges and potential. Biofuels 1, 763–784.

HCD-CWR, 2011. Crop Water Requirements (CWR) [WWW Document]. Hammond Conservancy District (HCD). URL http://hammondcon.org/cropwaterrequirements.html (accessed 5.26.11).

Higgins, B.T., Kendall, A., 2012. Life Cycle Environmental and Cost Impacts of Using an Algal Turf Scrubber to Treat Dairy Wastewater. Journal of Industrial Ecology 16, 436–447. doi:10.1111/j.1530-9290.2011.00427.x

Hoag, D.L., Hughes-Popp, J.S., 1997. Theory and practice of pollution credit trading in water quality management. Review of Agricultural Economics 19, 252–262.

Hossain, I., Epplin, F.M., Horn, G.W., Krenzer, E.G., 2004. . Wheat production and management practices used by Oklahoma grain and livestock producers (No. BB-818). Oklahoma Agricultural Experiment Station, Departments of Agricultural Economics, Animal Science, and Plant and Soil Sciences, Division of Agricultural Sciences and Natural Resources, Oklahoma State University.

Informa, economics inc., 2013. National Market Value of Anaerobic Digester Products. Prepared For: innovation center for us dairy.

Jorquera, O., Kiperstok, A., Sales, E.A., Embiruçu, M., Ghirardi, M.L., 2010. Comparative energy life-cycle analyses of microalgal biomass production in open ponds and photobioreactors. Bioresource Technology 101, 1406–1413. doi:10.1016/j.biortech.2009.09.038

Keplinger, K.O., Hauck, L.M., 2006. The economics of manure utilization: model and application. Journal of Agricultural and Resource Economics 414–440.

Klavon, K.H., 2011. Design and Economics of Plug-Flow, Small-Scale Anaerobic Digesters for Temperate Climates.

Lazarus, J., Hagevoort, R., Ratcliff, C.D., 2010. Dairy technical and regulatory guidance manual for New Mexico.

Lazarus, W.F., 2014. University of Minnesota, Department of Applied Economics, Decision Tools [WWW Document]. URL http://faculty.apec.umn.edu/wlazarus/tools.html (accessed 5.19.15).

Lindemann, W.C., Glover, C.R., 2003. Nitrogen Fixation by Legumes, Guide A-129. Las Cruces, NM: New Mexico State University Extension.

LPES, 2013. Livestock and Poultry Environmental Stewardship Curriculum Lessons - eXtension:LESSON 12 Feeding Dairy Cows to Reduce Nutrient Excretion [WWW Document]. URL http://www.extension.org/pages/8964/livestock-and-poultry-environmental-stewardship-curriculum-lessons (accessed 5.31.15).

Macias-Corral, M., Samani, Z., Hanson, A., Smith, G., Funk, P., Yu, H., Longworth, J., 2008. Anaerobic digestion of municipal solid waste and agricultural waste and the effect of co-digestion with dairy cow manure. Bioresource technology 99, 8288–93. doi:10.1016/j.biortech.2008.03.057

Marsalis, M.A., 2007. Small Grain Silages for New Mexico (No. Circular 630). Cooperative Extension Service; College of Agriculture and Home Economics; New Mexico State University.

Martin, J.H., 2005. An evaluation of a Mesophilic, modified plug flow anaerobic digester for dairy cattle manure. Eastern Research Group, Inc. EPA Contract No. GS 10F-0036K Work Assignment/Task Order.

McFarland, M.J., Vasquez, I.R., Vutran, M., Schmitz, M., Brobst, R.B., Greenhalgh, L., 2007. Rangeland Restoration Using Biosolids Land Application. Water Practice 1, 1–12. doi:10.2175/193317707X243382

Mulbry, W., Kondrad, S., Buyer, J., 2008a. Treatment of dairy and swine manure effluents using freshwater algae: fatty acid content and composition of algal biomass at different manure loading rates. J Appl Phycol 20, 1079–1085. doi:10.1007/s10811-008-9314-8

Mulbry, W., Kondrad, S., Pizarro, C., Kebede-Westhead, E., 2008b. Treatment of dairy manure effluent using freshwater algae: algal productivity and recovery of manure nutrients using pilot-scale algal turf scrubbers. Bioresource technology 99, 8137–8142.

Mulbry, W., Westhead, E.K., Pizarro, C., Sikora, L., 2005. Recycling of manure nutrients: use of algal biomass from dairy manure treatment as a slow release fertilizer. Bioresource Technology 96, 451–458. doi:10.1016/j.biortech.2004.05.026

NASS, 2013. Agricultural Statistics 2013. National Agricultural Statistics Service (NASS), U.S. Department of Agriculture (USDA), Washington, DC.

NASS, 1994. Agricultural Statistics 1994. National Agricultural Statistics Service (NASS), U.S. Department of Agriculture (USDA), Washington, DC.

NMED, 1998. Groundwater water quality assessment. New Mexico Environment Department.

Norsker, N.-H., Barbosa, M.J., Vermuë, M.H., Wijffels, R.H., 2011. Microalgal production — A close look at the economics. Biotechnology Advances 29, 24–27. doi:10.1016/j.biotechadv.2010.08.005

Olsson, J., Feng, X.M., Ascue, J., Gentili, F.G., Shabiimam, M.A., Nehrenheim, E., Thorin, E., 2014. Co-digestion of cultivated microalgae and sewage sludge from municipal waste water treatment. Bioresource Technology 171, 203–210. doi:10.1016/j.biortech.2014.08.069

Pearson, C.J., Norman, D.W., Dixon, J., 1995. Sustainable dryland cropping in relation to soil productivity. Food & Agriculture Org.

Pizarro, C., Mulbry, W., Blersch, D., Kangas, P., 2006. An economic assessment of algal turf scrubber technology for treatment of dairy manure effluent. ecological engineering.

Powlson, D.S., Addiscott, T.M., Benjamin, N., Cassman, K.G., de Kok, T.M., van Grinsven, H., L'hirondel, J.-L., Avery, A.A., Van Kessel, C., 2008. When does nitrate become a risk for humans? Journal of environmental quality 37, 291–295.

Rajendran, K., Aslanzadeh, S., Taherzadeh, M.J., 2012. Household biogas digesters—A review. Energies 5, 2911–2942.

Rajvanshi, S., Sharma, M., 2012. Micro Algae: A Potential Source of Biodiesel. Journal of Sustainable Bioenergy ….

Resurreccion, E.P., Colosi, L.M., White, M.A., Clarens, A.F., 2012. Comparison of algae cultivation methods for bioenergy production using a combined life cycle assessment and life cycle costing approach. Bioresource technology 126, 298–306. doi:10.1016/j.biortech.2012.09.038

Richardson, J.W., Outlaw, J.L., Allison, M., 2010. The economics of microalgae oil.

SAIC, S.A.I.C., 2006. Life-cycle assessment: principles and practice. Scientific Applications International Corporation, National Risk Management Research Laboratory, Office of Research and Development, US Environmental Protection Agency.

Samani, Z., Sammis, T., Skaggs, R., Alkhatiri, N., Deras, J., 2005. Measuring on-farm irrigation efficiency with chloride tracing under deficit irrigation. Journal of irrigation and drainage engineering 131, 555–559.

Sammis, T.W., Gregory, E.J., Kallsen, C.E., 1982. Estimating evapotranspiration with water-production functions or the Blaney-Criddle method [Cotton, alfalfa, corn, barley]. Transactions of the ASAE [American Society of Agricultural Engineers].

Sammis, T.W., Hanson, E.G., Barnes, C.E., Fuehring, H.D., Gregory, E.J., 1979. Consumptive use and yields of crops in New Mexico.

Sanford, G.R., Posner, J.L., Hadley, G.L., 2009. Economics of hauling dairy slurry and its value in Wisconsin corn grain systems. J. Agric. Food Environ. Sci 3, 1–10.

Shafiee, S., Topal, E., 2009. When will fossil fuel reserves be diminished? Energy policy 37, 181–189.

Smith, V.H., Sturm, B.S.M., Denoyelles, F.J., Billings, S.A., 2010. The ecology of algal biodiesel production. Trends in ecology & evolution 25, 301–9. doi:10.1016/j.tree.2009.11.007

Ulery, A.L., Flynn, R., Parra, R., 2004. Appropriate preservation of dairy wastewater samples for environmental analysis. Environmental monitoring and assessment 95, 117–124.

Umetsu, K., Yamazaki, S., Kishimoto, T., Takahashi, J., Shibata, Y., Zhang, C., Misaki, T., Hamamoto, O., Ihara, I., Komiyama, M., 2006. Anaerobic co-digestion of dairy manure and sugar beets. International Congress Series, Greenhouse Gases and Animal Agriculture: An Update. Proceedings of the 2nd International Conference on Greenhouse Gases and Animal Agriculture, held in Zurich, Switzerland between 20 and 24 September 2005 1293, 307–310. doi:10.1016/j.ics.2006.03.025

USDA, 2012. United States Department of Agriculture. Census of Agriculture. National Agricultural Statistics Service [WWW Document]. URL http://www.nass.usda.gov/Statistics_by_State/New_Mexico/Publications/Annual_Statistical_Bulletin/bulletin12.asp (accessed 5.20.15).

USDA, EPA, 1999. Unified national strategy for animal feeding operations. USDA and USEPA, Washington, DC.

USDA-NASS, 2014. United States Department of Agriculture-National Agricultural Statistics Service. State Agricultural Overview, New Mexico. [WWW Document]. URL http://www.nass.usda.gov/Quick_Stats/Ag_Overview/stateOverview.php?state=NEW%20MEXICO (accessed 6.26.15).

USDA-NASS, 2010. United States Department of Agriculture-National Agricultural Statistics Service. Usual planting and harvesting dates for U.S. field crops. Agricultural handbook number 628. [WWW Document]. URL http://usda.mannlib.cornell.edu/usda/current/planting/planting-10-29-2010.pdf

US EPA, O., 2015. Livestock Anaerobic Digester Database [WWW Document]. URL http://www2.epa.gov/agstar/livestock-anaerobic-digester-database (accessed 6.24.15).

Van Horn, H.H., Newton, G.L., Nordstedt, R.A., French, E.C., Kidder, G., Gratez, D.A., others, 2003. Dairy Manure Management: Strategies for Recycling Nutrients to Recover Fertilizer Value and Avoid Environmental Pollution.[Circ. 1016]. Gainesville, FL: Univ. of Florida Coop. Ext. Serv.

Van Horn, H.H., Wilkie, A.C., Powers, W.J., Nordstedt, R.A., 1994. Components of dairy manure management systems. Journal of Dairy Science 77, 2008–2030.

Wang, J., Baerenklau, K.A., 2015. How Inefficient Are Nutrient Application Limits? A Dynamic Analysis of Groundwater Nitrate Pollution from Concentrated Animal Feeding Operations. Appl. Econ. Perspect. Pol. 37, 130–150. doi:10.1093/aepp/ppu023

WQCC, 2015. New Mexico Administrative Code, 2015. GROUND AND SURFACE WATER PROTECTION, New Mexico Water Quality Control Commission, 20.6.2 NMAC (12-1-95 as amended through 1/15/2001). [WWW Document]. URL http://164.64.110.239/nmac/parts/title20/20.006.0002.htm (accessed 5.21.15).

Yen, H.-W., Brune, D.E., 2007. Anaerobic co-digestion of algal sludge and waste paper to produce methane. Bioresource Technology 98, 130–134. doi:10.1016/j.biortech.2005.11.010

Zhang, Y., White, M.A., Colosi, L.M., 2013. Environmental and economic assessment of integrated systems for dairy manure treatment coupled with algae bioenergy production. Bioresource technology 130, 486–494.

11 TABLES

Table 1: Dairy manure characteristics in New Mexico

Dairy Manure Excretion and Nutrients	Unit	Value
Total Excretion wet	kg/cow-day	56.7
Total Dry Matter	kg/cow-day	6.9
Water Content	kg/cow-day	49.8
Volatile Solids	kg/cow-day	573
Total Nitrogen[a]	kg/cow-day	0.296
NH_3-N[a]	kg/cow-day	0.112
Total Phosphorus[a]	kg/cow-day	0.054

[a] *Total N, ammonia as N (NH_3-N), and total P concentrations are for total manure (i.e., solids plus liquids).*

Source: Van Horn et al. (1994)

Table 2: Land area in dairy farms with 500 or more milk cows in New Mexico

Land size category (acres)	Median value of land size (acres)	Number of farms	Percentage of farms
1 – 9	5.0	1	0.9%
10 - 49	29.5	1	0.9%
50 - 69	59.5	1	0.9%
70 - 99	84.5	7	6.4%
100 – 139	119.5	4	3.7%
140 – 179	159.5	6	5.5%
180 – 219	199.5	6	5.5%
220 – 259	239.5	6	5.5%
260 – 499	379.5	11	10.1%
500 – 999	749.5	18	16.5%
1,000 - 1,999	1499.5	26	23.9%
2,000 or more	2000.0	22	20.2%

Source: USDA (2012)

Table 3: Planting and Harvesting Dates of New Mexico Crops

Crop	Usual planting dates			Usual harvesting dates		
	Begin	Most active	End	Begin	Most active	End
Beans, dry edible	15-May	May 20 - Jun 1	15-Jun	15-Aug	Sep 1 - Sep 30	15-Oct
Corn for grain	15-Apr	Apr 20 - May 10	20-May	25-Sep	Oct 1 - Oct 30	20-Nov
Corn for silage	15-Apr	Apr 20 - May 10	20-May	1-Sep	Sep 10 - Oct 1	1-Nov
Cotton, all	10-Apr	Apr 20 - May 10	20-May	10-Oct	Oct 25 - Nov 30	20-Dec
Hay, alfalfa	(NA)	(NA)	(NA)	1-May	(NA)	20-Oct
Hay, other	(NA)	(NA)	(NA)	1-May	(NA)	20-Oct
Peanuts	10-May	May 15 - May 25	1-Jun	1-Oct	Oct 10 - Oct 30	10-Nov
Potatoes, fall	20-Apr	Apr 25 - May 5	10-May	1-Sep	Sep 25 - Oct 10	20-Oct
Sorghum for grain	15-May	May 20 - Jun 15	10-Jul	15-Oct	Oct 20 - Nov 15	15-Dec
Sorghum for silage	10-May	May 20 - Jun 10	20-Jun	5-Sep	Sep 15 - Oct 10	1-Nov
Wheat, winter	25-Aug	Sep 10 - Sep 24	15-Oct	15-Jun	Jun 20 - Jul 10	15-Jul

Source: USDA-NASS (2010)

Table 4: Top five crops of New Mexico in term of harvested acreage

Crop	Acreage (hectare)
Alfalfa[a]	138,820
Wheat for grain, all	35,412
Winter wheat for grain	34,979
Corn for silage	33,130
Pecans, all	16,726

[a] *Forage-land used for all hay and haylage, grass silage, and greenchop.*

Source: USDA-NASS (2014)

Table 5: Nitrogen requirement and evapotranspiration rates of major field crops in New Mexico

	Crop	Unit	Average	Source
Nitrogen requirement	corn[a]	kgN/ha	220	(Cox and Cherney, 2001)
	wheat	kgN/ha	135	(Hossain et al., 2004)
	alfalfa[b]	kgN/ha	28	(Caddel et al., 2001; Lindemann and Glover, 2003)
Evapotranspiration	corn	inch	30	(HCD-CWR, 2011)
	wheat	inch	25	(HCD-CWR, 2011)
	alfalfa	inch	48	(HCD-CWR, 2011)

[a] *The minimum and maximum nitrogen requirement of corn are respectively 200 and 240 kgN/ha. The average is 220 kgN/ha.*

[b] *The minimum and maximum nitrogen requirement of alfalfa are respectively 22 and 35 kgN/ha. The average is 28 kgN/ha.*

Table 6: Characteristics of a typical large dairy farm in New Mexico

Variable	Definition	Unit	Value
Baseline			
H	Number of milk cows	Head	2892
A	Land area contained in the typical large dairy farm	Hectare (ha)	391
α	The share of field crop land growing alfalfa	Fraction	0.8
$\overline{N}_{crop}$	The average nitrogen requirement for all crops per unit of crop land	kgN/ha	93.4
σ_1^{crop}	The off-site crop land suitable for receiving dairy manure	Fraction	0.014
σ_2	The percentage of surrounding farmers that are willing to accept dairy manure	Fraction	0.3
TN_{land}^{DLA}	The total nitrogen available for land application from the typical large dairy farm	kgN/year	78,373
TN_{onsite}^{DLA}	The total nitrogen that can be properly managed on the typical dairy farm	kgN/year	36,746
$TN_{offsite}^{DLA}$	The excess nitrogen that needs to be managed off-site the typical large dairy farm	kgN/year	41,627
$\tilde{A}$	The offsite land area to be searched to haul the excess manure	ha	106,400
ξ_1	The radius of the outer disk	km	18
ξ_2	The radius of the inner disk	km	1.2
$\hbar_d$	The average hauling distance of excess manure to off-site croplands	km	12
Sensitivity Analysis of Rangeland Availability			
$\tilde{A}_r$	The offsite land area to be searched to haul the excess manure	ha	416
ξ_1	The radius of the outer disk	km	1.6
ξ_2	The radius of the inner disk	km	1.2
$\hbar_d$	The average hauling distance of excess manure to off-site croplands	km	1

Table 7: Energy input, output and net surplus (gj/year-farm) in alternative dairy manure management cases

	DLA	AD	ADMC[a]
Total Energy input	**3,380**	**1,739**	**31,803**
On-farm manure land application[b]	629	265	0
Off-farm manure hauling[b]	2,635	0	0
Algae cultivation[c]	0	0	6,976
Anaerobic digestion			
Electricity	*0*	*521*	*7,899*
Heat	*0*	*405*	*846*
Infrastructure burden[d]	116	549	16,081
Total Energy output	**0**	**33,113**	**47,473**
Energy Net Surplus[e]	**-3,380**	**31,374**	**15,670**
Energy Ratio[e]	**0**	**19.0**	**1.5**

[a] *Assume that co-digested solid manure (digestate manure from microalgae and dairy manure loading) is sold off farm and the digested liquid manure is used for microalgae production which does not require energy input for land application.*

[b] *Energy use for on-farm manure land application and off-farm transportation. Data for off-farm manure hauling is adapted from Sanford et al. (2009).*

[c] *Energy use in a microalgae cultivation system such as water pumping, nutrient supply and mixing, CO_2 pumping, and biomass harvesting and dewatering.*

[d] *The infrastructure burden accounts for annual infrastructure energy burden (assume life time of 20 years of anaerobic digester equipment and manure application equipment).*

[e] *Energy Net Surplus is equal to energy output minus energy input. Energy ratio, also known as energy return on energy invested, is defined as total energy output divided by total energy input.*

Data Source: Lazarus (2014); Zhang et al. (2013)

Table 8: Energy use and cost in manure hauling

Distance	Diesel use[a]	Fuel cost[b]
(km)	(gallon/km-ha)	($/km-ha)
1	12	46
2	14	54
3	15	58
4	17	65
5	20	77
6	22	85
7	25	96
8	28	108
9	32	123
10	36	139
11	41	156
12	46	176
13	52	199
14	59	225
15	66	255

[a] *One gallon of diesel is equivalent to 0.15 GJ of energy.*

[b] *U.S. energy information administration, 2014 annual average price for rocky mountain region of the United States, EPA: (http://www.eia.gov/dnav/pet/pet_pri_gnd_dcus_r40_a.htm). Diesel price is $3.85 per gal.*

Source: Data are adapted from (Sanford et al., 2009)

Table 9: Yield rates and prices of major field crops in New Mexico

	Crop	Unit	Average
Yield	corn	bushel/ha	432
	wheat	bushel/ha	420
	alfalfa	bushel/ha	59
Price	corn	\$/bushel[a]	7.42
	wheat	\$/bushel	7.73
	alfalfa	\$/bushel	7.00

[a] *One bushel is equivalent to 27.2 kg.*

[*] *All dollar values are in 2014 dollars.*

Data source: USDA (2012)

Table 10: Initial outlay and operating and maintenance (O&M) costs for DLA, AD and ADMC in the baseline and policy scenarios

	Unit	DLA	AD	ADMC	Source
O&M Cost					
Manure land application					
Manure on-farm application[a]	*$/year*	270,380	254,157	0	Zhang et al. (2013)
Manure off-farm hauling[b]	*$/year*	18,726,400	0	0	
Anaerobic digestion					
Engine overhaul & spare engine cost	*$/year*	0	80,850	80,850	Lazarus (2014)
Digester sludge cleanout	*$/year*	0	6,930	6,930	Lazarus (2014)
Labor cost for routine O&M	*$/year*	0	5,023	5,023	Lazarus (2014)
Oil changes & other routine O&M	*$/year*	0	11,550	11,550	Lazarus (2014)
Algae cultivation system[c]	*$/year*	0	0	1,328,802	Zhang et al. (2013)
Total O&M cost	***$/year***	**18,996,780**	**358,510**	**1,433,155**	
Initial outlays (or Capital Cost)[d]					
Manure land application					
Manure on-farm application	*$*	2,036,667	1,914,468	0	Zhang et al. (2013)
Anaerobic digestion					
Digester system	*$*	0	2,560,008	3,303,459	Lazarus (2014)
Post-digestion solids separation	*$*	0	229,617	271,157	Lazarus (2014)
Hydrogen sulfide (H2S) treatment	*$*	0	111,221	131,342	Lazarus (2014)
Utility requirements	*$*	0	190,152	224,552	Lazarus (2014)
Algae cultivation system					
Infrastructure and equipment	*$*	0	0	5,400,267	Zhang et al. (2013)
Algae homogenizer	*$*	0	0	687,472	Zhang et al. (2013)
Miscellaneous[e]	*$*	0	0	2,700,133	Zhang et al. (2013)
Total initial outlay (capital cost)	***$***	**2,036,667**	**5,005,466**	**12,718,382**	

[a] *Includes O&M costs for electricity, fuel, fertilizer, labor and overhead, insurance etc. We assume that O&M costs are constant over the lifecycle of each case.*

[b] *Hauling cost (i.e., offsite manure transportation cost) for typical dairy farm is calculated by authors. In this case, we assume that the off-farm crops are same as in the on-farm (i.e., alfalfa, wheat Corn). When rangeland is considered along with alfalfa, wheat and corn for off farm management of excess manure, the annual hauling cost is $19,136/year.*

[c] *Electricity, fertilizer, labor and overhead, insurance, maintenance etc.*

[d] *Capital costs, also defined as initial outlays are the lifecycle costs of DLA, AD and ADMC. We assume the lifecycle of each case is 20 years* (Martin, 2005; Zhang et al., 2013). *The capital costs are depreciated by using seven years Modified Accelerated Cost Recovery System (MACRS-Internal Revenue Service)* (Zhang et al., 2013) *in the calculation of net present values.*

[e] *Start-up, engineering, etc.*

** All dollar values are in 2014 dollars. All zero (0) values reported in the table indicate 'not applicable'.*

Table 11: Total annual revenue for DLA, AD and ADMC in the baseline and policy scenarios

	Unit	DLA	AD	ADMC	Reference
Baseline Scenario					
Sale of crops[a]	$/year	2,684,231	2,430,224	0	
Sale of bioelectricity	$/year	0	571,125	818,787	Zhang et al. (2013); Informa (2013)
Sale of digestate[b]	$/year	0	749,422	1,124,134	EPA (2013)
Total Revenue	$/year	2,684,231	3,750,771	1,942,921	
Policy Scenario[c] (Prospective Green Policies for New Mexico: carbon and nutrient credits)					
Sale of crops	$/year	2,684,231	2,430,224	0	
Sale of bioelectricity	$/year	0	571,125	818,787	Zhang et al. (2013); Informa (2013)
Sale of digestate[b]	$/year	0	749,422	1,124,134	EPA (2013)
Sale of nutrients credits (N)	$/year	0	783,573	7,986,263	Zhang et al. (2013)
Sale of nutrient credits (P)	$/year	0	1,793	3,615	Zhang et al. (2013)
Sale of carbon credits (CO_2)	$/year	0	37,148	50,931	Zhang et al. (2013)
Total	$/year	2,684,231	4,573,285	9,983,730	

[a] *Revenue from the sales of crops (alfalfa, wheat and corn) are calculated by using information from table 9 for 391 ha of land in DLA and 354 ha land in AD.*

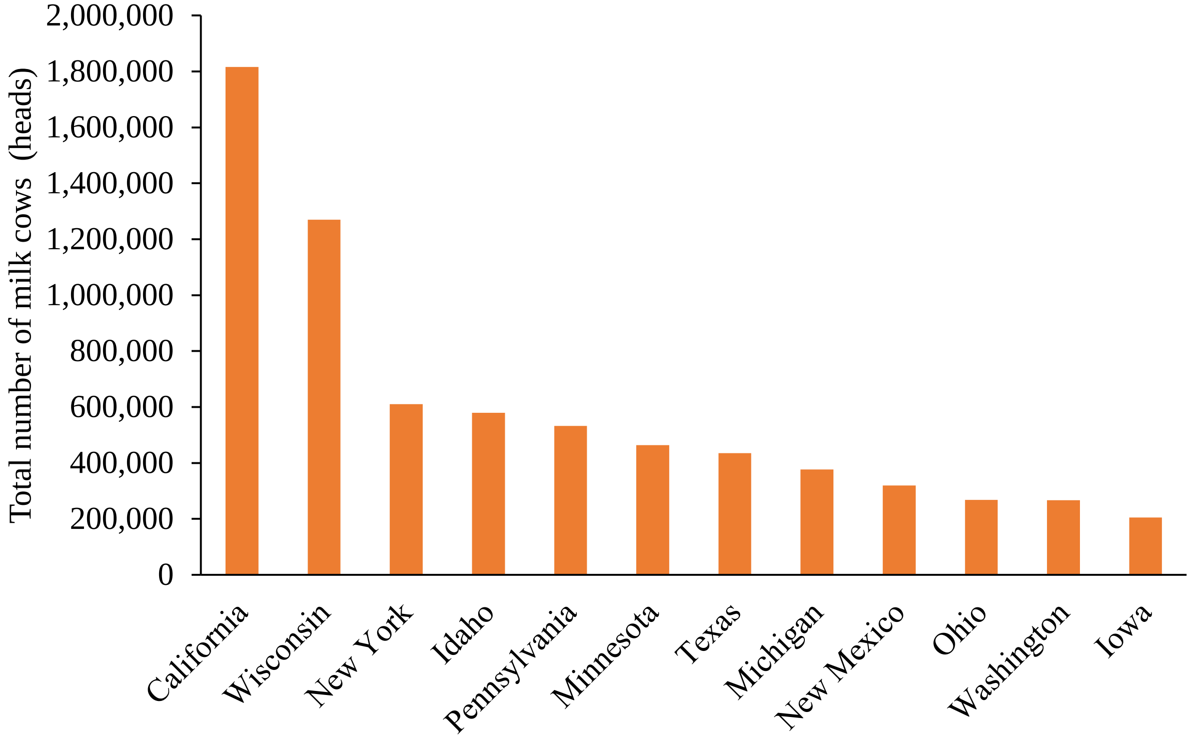
[b] *Digested solid manure such as nutrients and fiber.*

[c] *For current Green Policies in New Mexico, we have chosen 'Agricultural biomass income tax credit' as this green energy policy is most relevant in the context of this research (bio-energy production from dairy manure by the dairy farmer). More information about the policy is explained in the text.*

** All dollar values are in 2014 dollars. All zero (0) values reported in the table indicate 'not applicable'.*

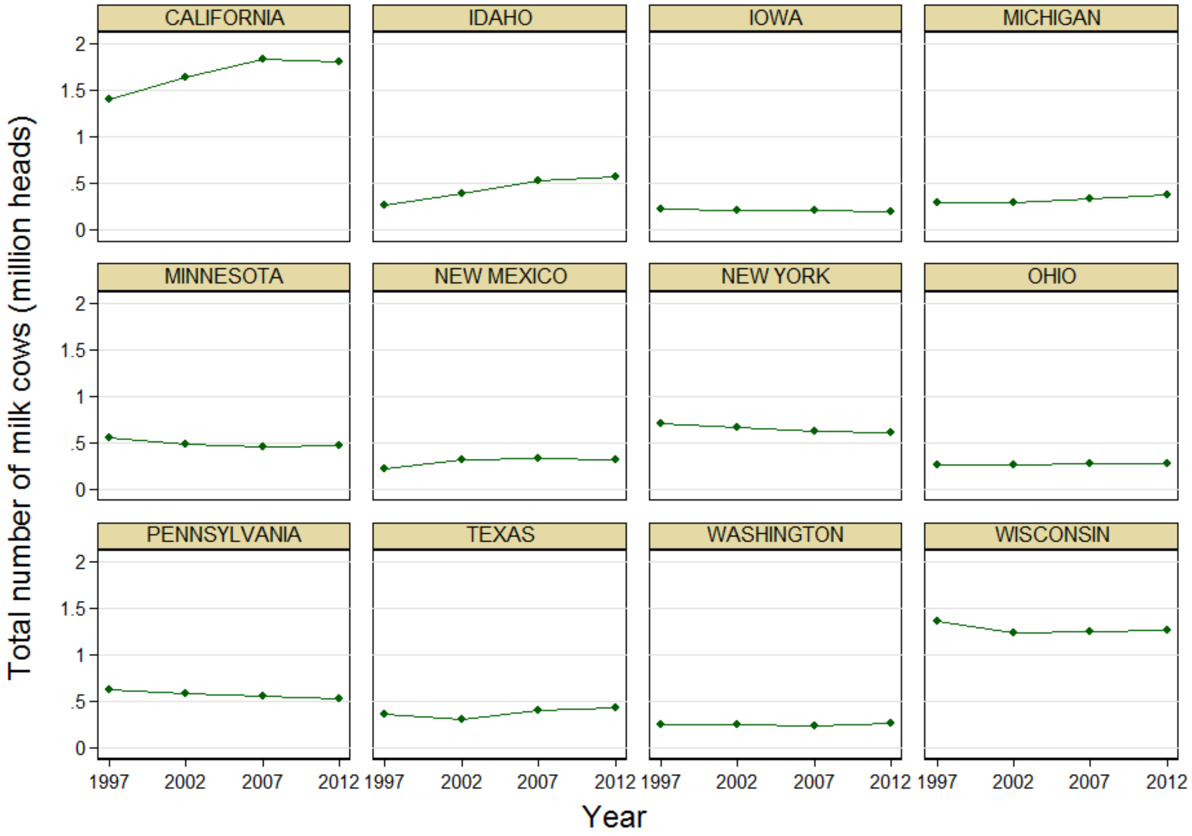
12 FIGURES

Figure 1: Total number of milk cows in top twelve dairy states in 2012



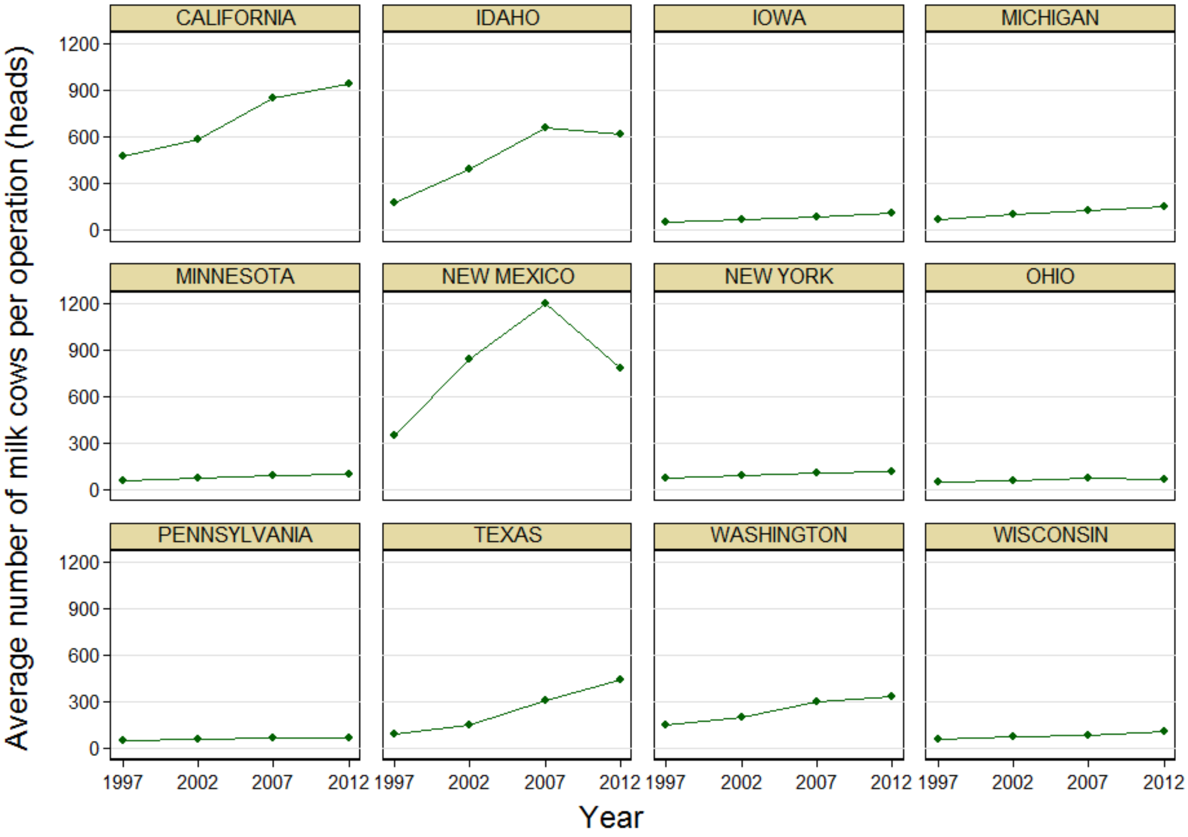
Data source: USDA (2012)

Figure 2: Total number of milk cows in top twelve dairy states from 1997 to 2012



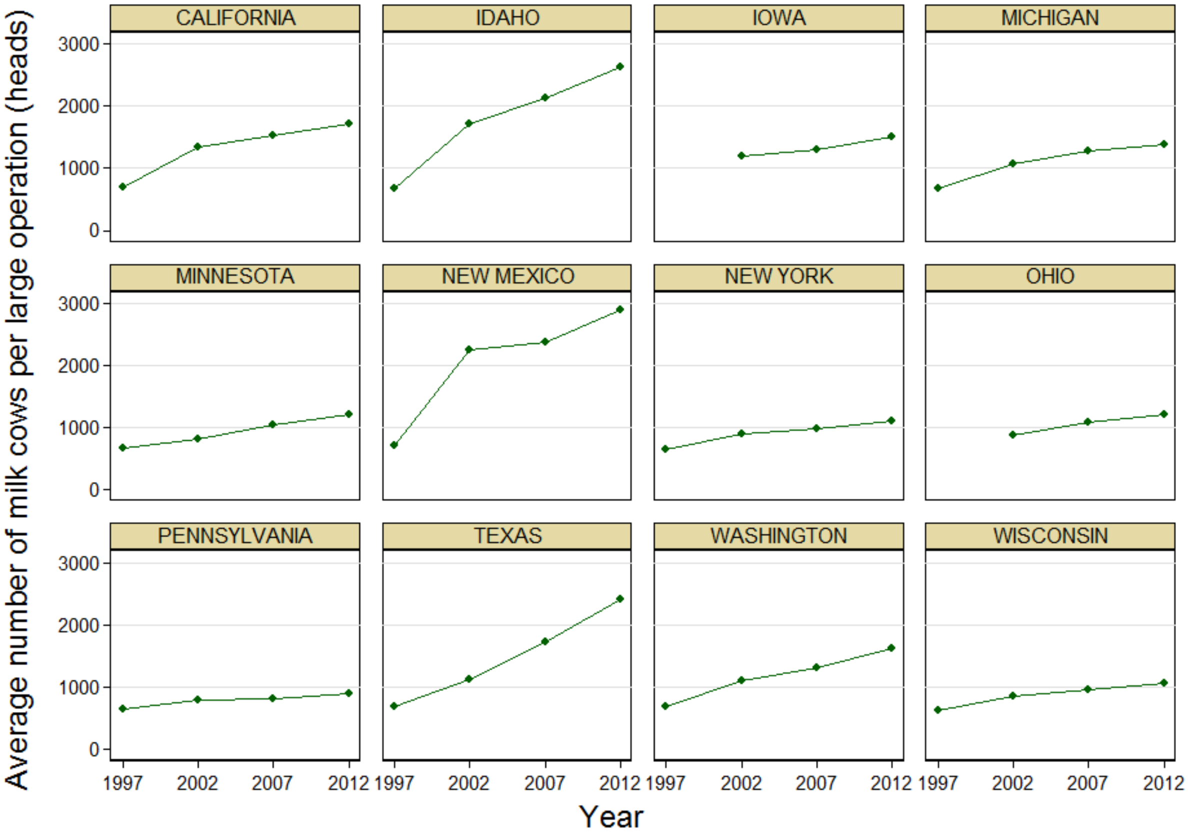
Data source: USDA (2012)

Figure 3: Average stocking density of milk cows in top twelve dairy states from 1997 to 2012



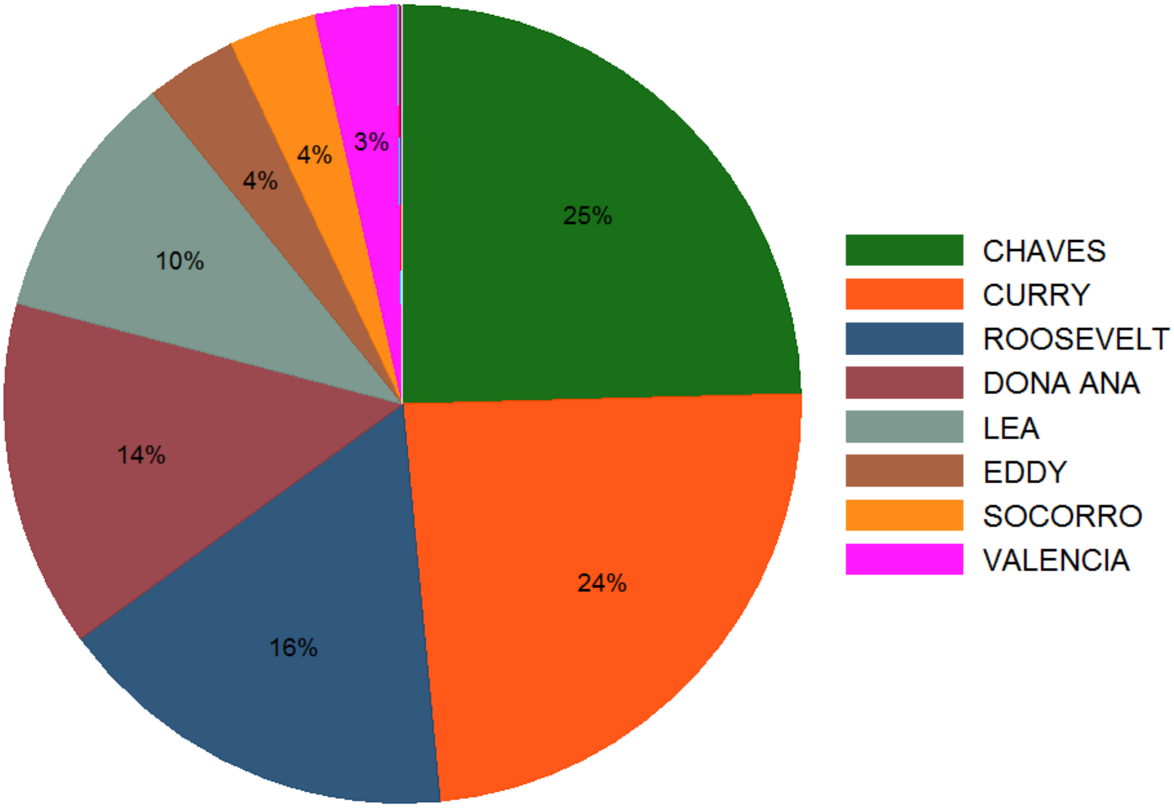
Data source: USDA (2012)

Figure 4: Average stock density of milk cows on large dairy farms (with 500 or more milk cows) in top twelve dairy states from 1997 to 2012



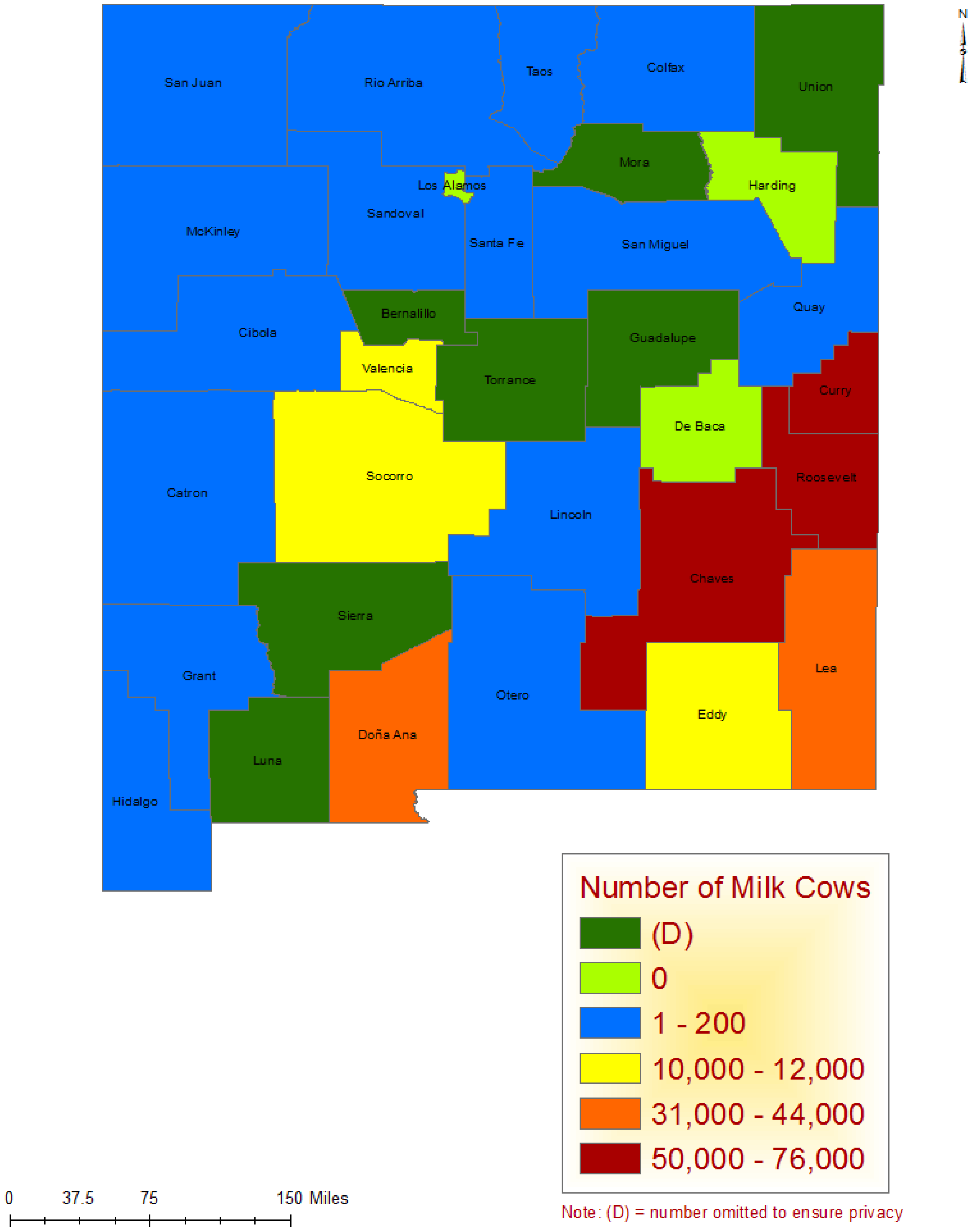
Data source: USDA (2012)

Figure 5: Composition of milk cows in New Mexico in 2012 at the county level



Data source: USDA (2012)

Figure 6: Number of milk cows in New Mexico in 2012 at the county level



Note: (D) = number omitted to ensure privacy

Data source: USDA (2012)

Figure 7: Conceptual framework of a combination of life cycle assessment, cost-benefit analysis and sensitivity analysis for controlling nitrogen pollution from large dairy farms of New Mexico

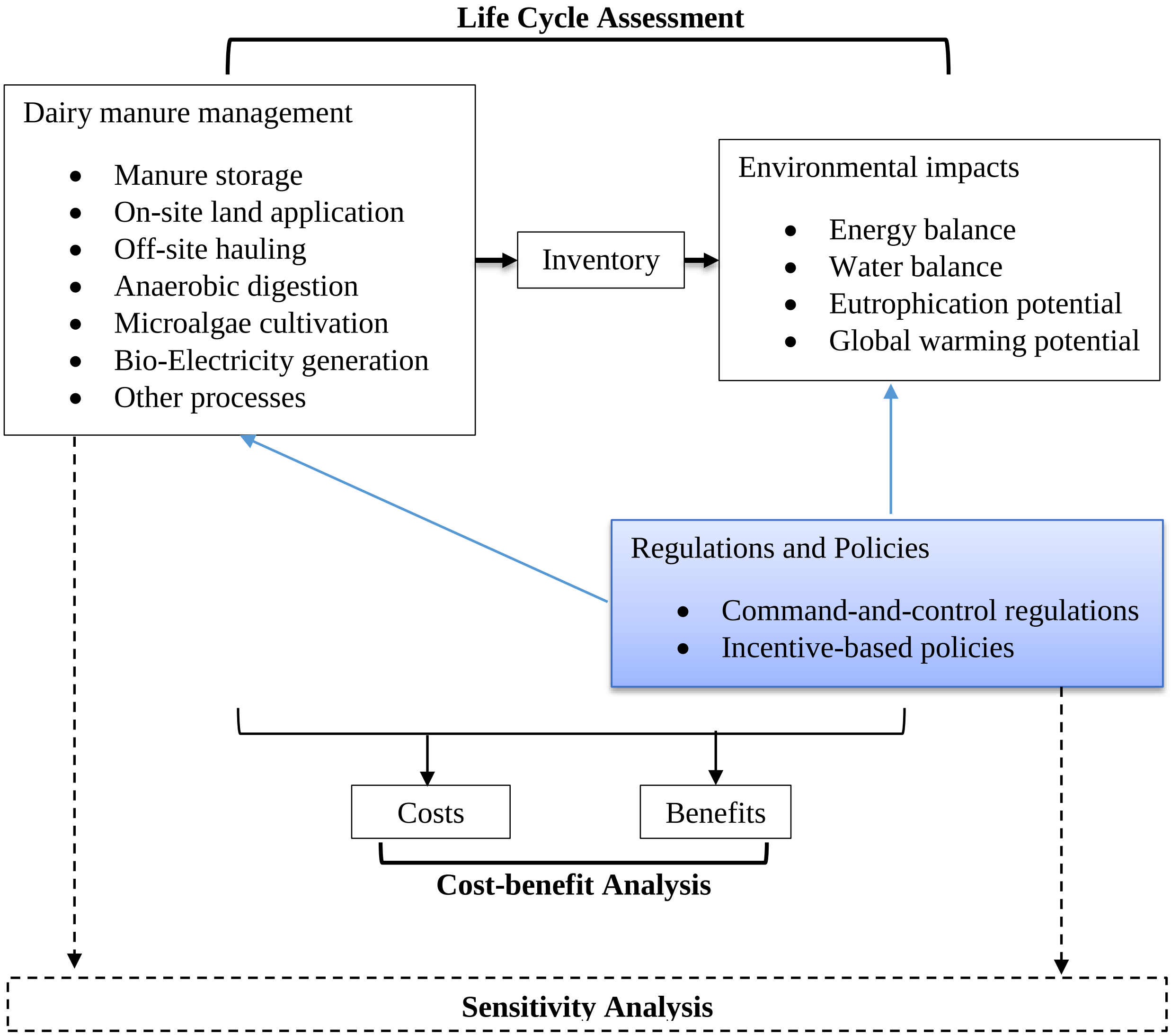
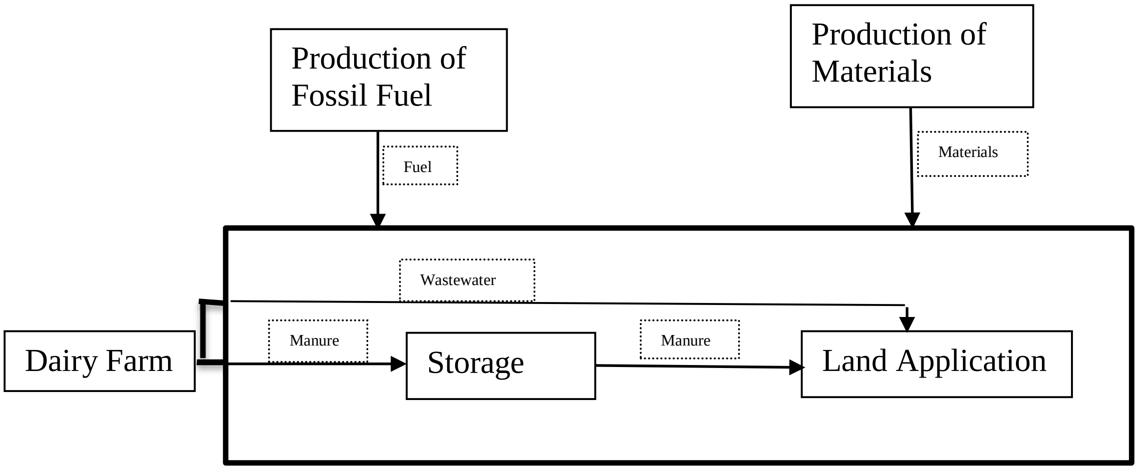
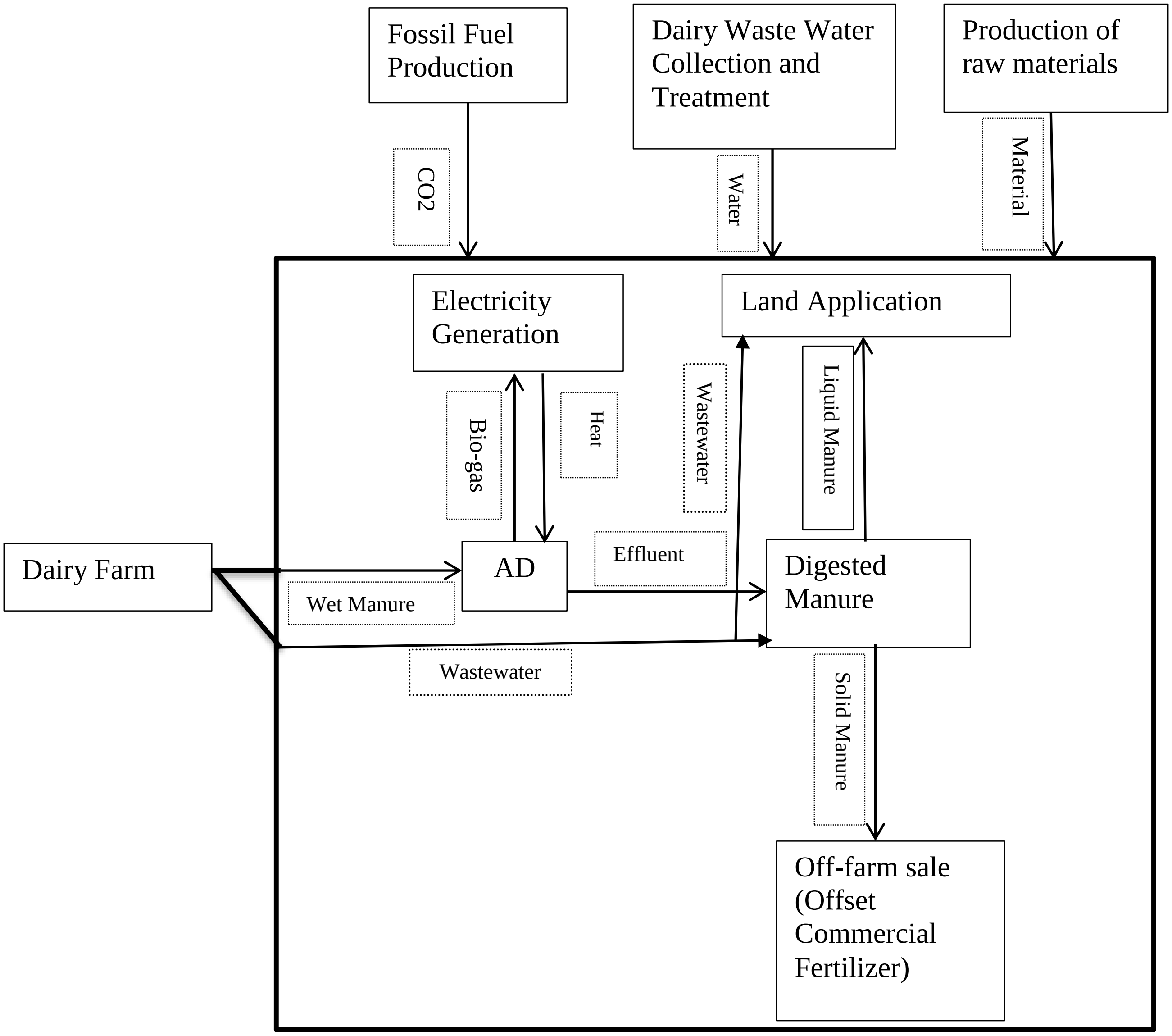


Figure 8: LCA boundary of direct land application (DLA)



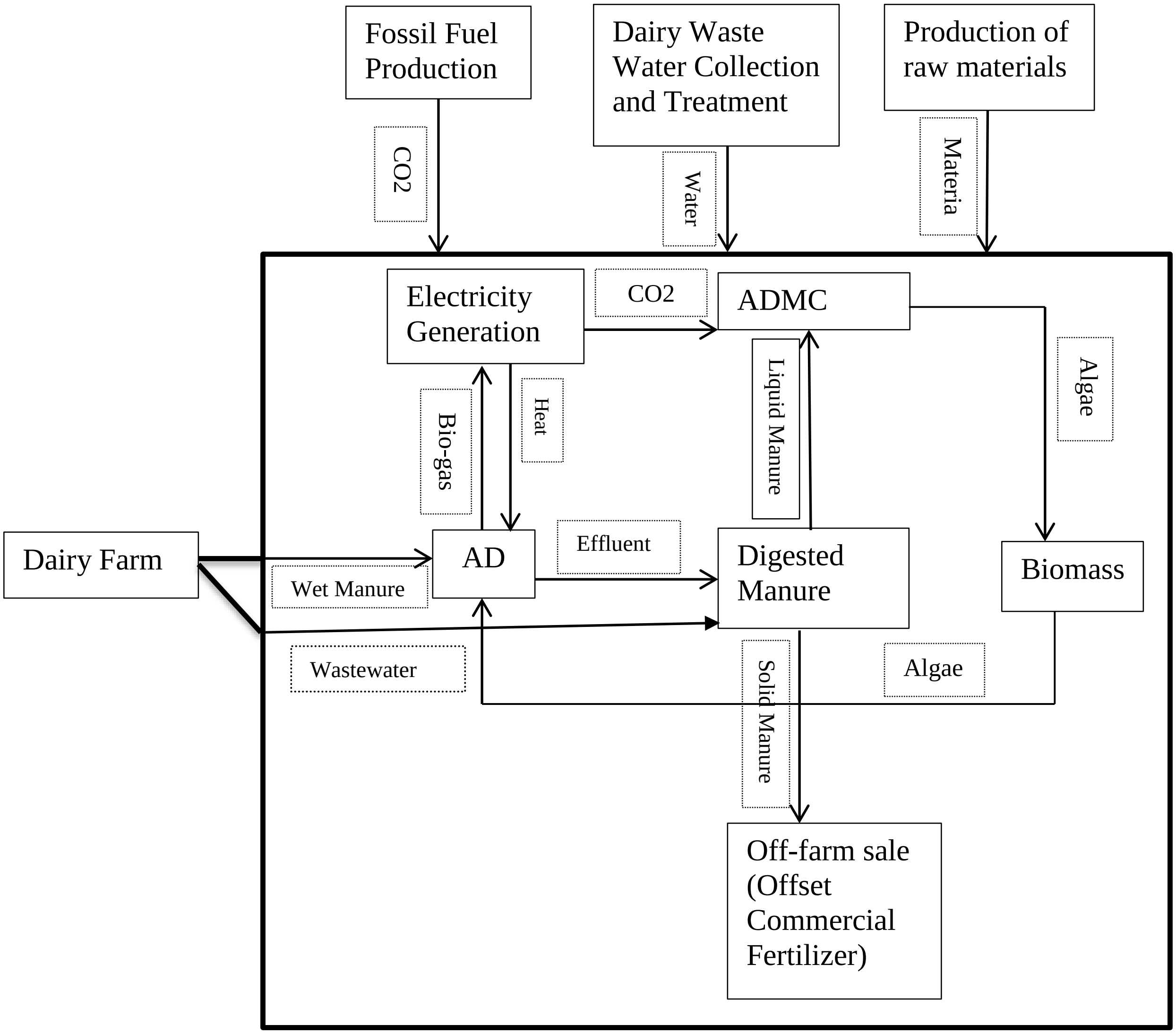
Note: The thick solid rectangular box is the system boundaries, the thin solid rectangular boxes indicate the unite processes, the dotted boxes are the material flows, and arrow lines indicate the direction of the respective material flows in the unit processor.

Figure 9: LCA boundary of anaerobic digestion (AD)



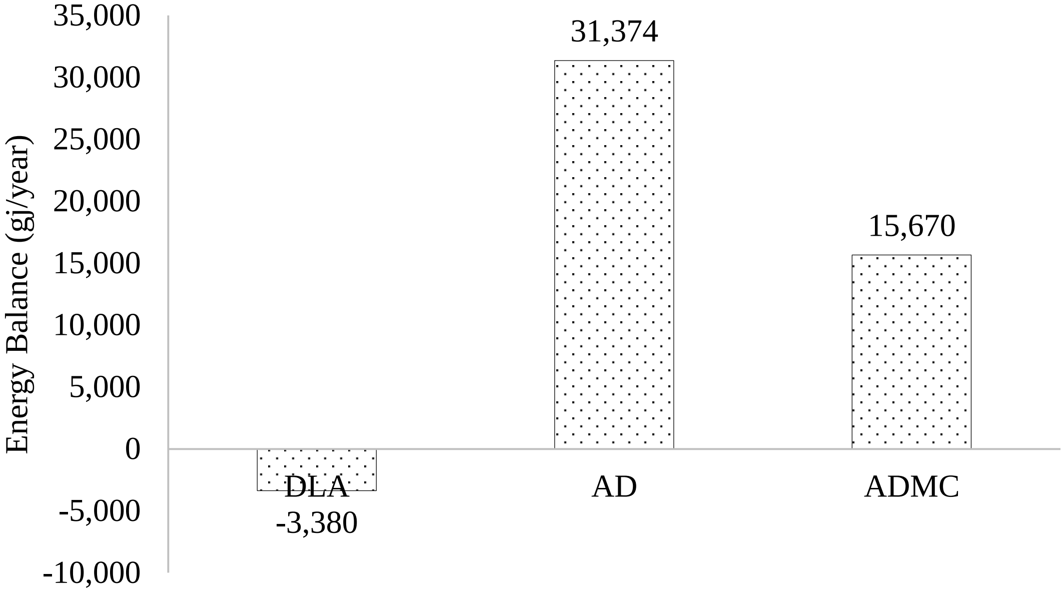
Note: The thick solid rectangular box is the system boundaries, the thin solid rectangular boxes indicate the unite processes, the dotted boxes are the material flows, and arrow lines indicate the direction of the respective material flows in the unit processor.

Figure 10: LCA boundary of the anaerobic digestion of dairy manure coupled with microalgae cultivation (ADMC)



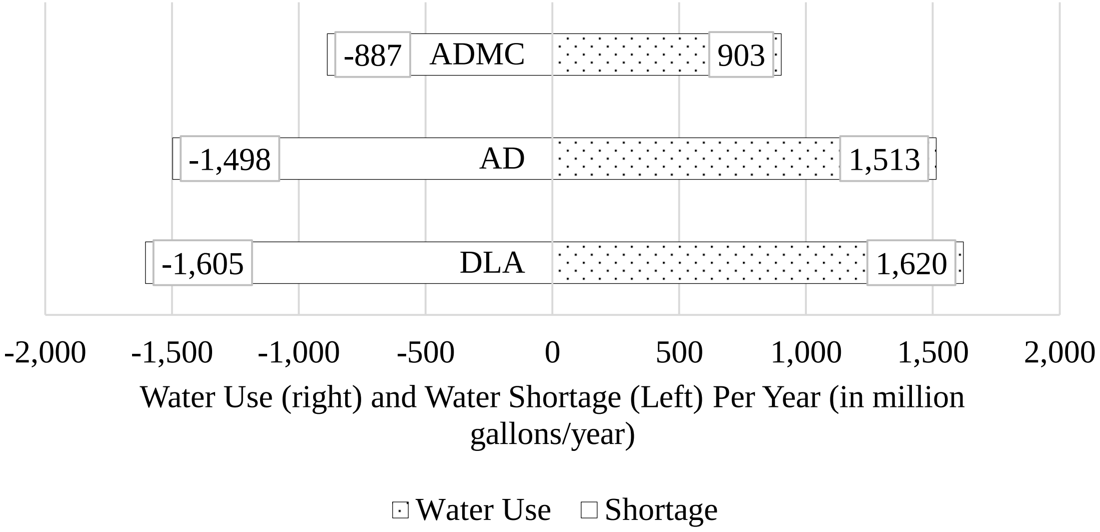
Note: The thick solid rectangular box is the system boundaries, the thin solid rectangular boxes indicate the unite processes, the dotted boxes are the material flows, and arrow lines indicate the direction of the respective material flows in the unit processor.

Figure 11: Energy balance in the DLA, AD and ADMC cases under LCA



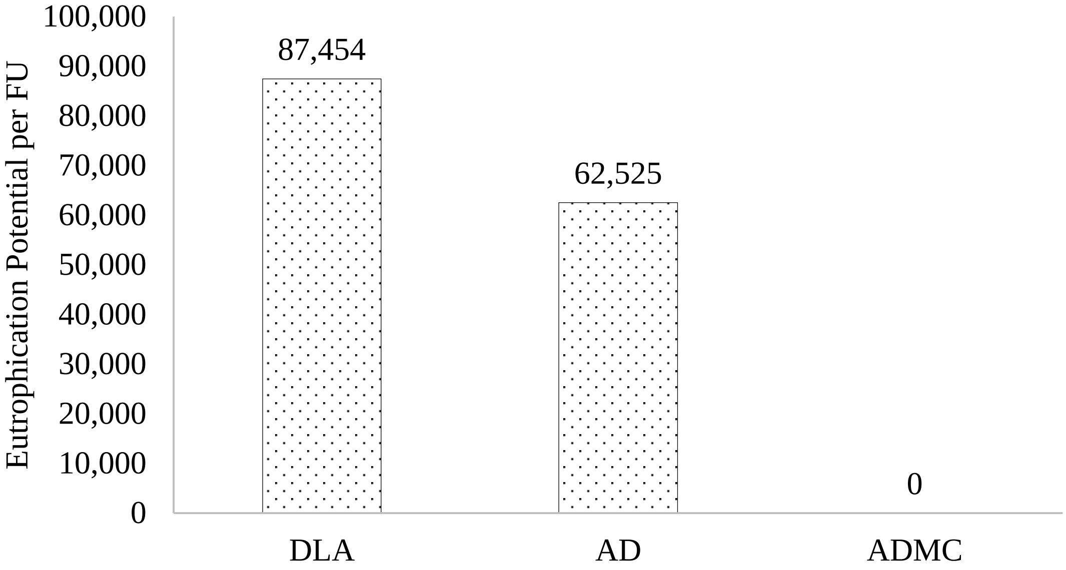
Note: We define energy balance (gj/year) as the difference between annual energy output and annual energy input in each case as indicated in the graph. These outputs are based one functional unit in the defined system boundary of each case. Energy balance less than zero indicate net energy consumption and energy balance greater than zero indicate net energy generation.

Figure 12: Water usage and water shortage in the DLA, AD and ADMC cases under LCA



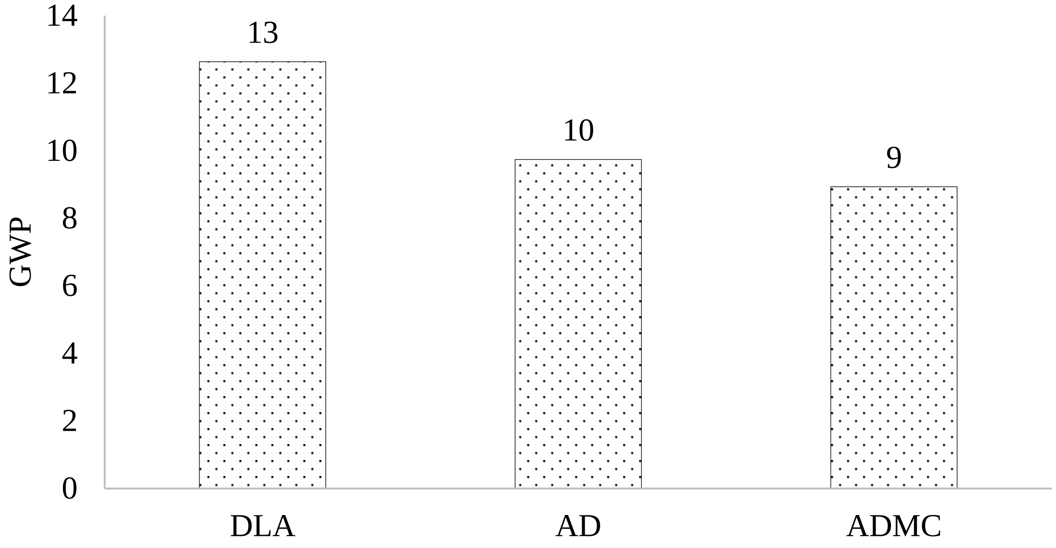
Note: Water shortage is defined as the difference between total wastewater collection in the typical dairy farm and total water requirement in each scenario, and is shown on the left side of the figure. Water use the total water requirement, and is shown on the right side of the figure. The wastewater collection in a typical dairy farm is 16 million gallons per year.

Figure 13: Eutrophication Potential (kg PO4-eq/year) in DLA, AD and ADMC cases under LCA



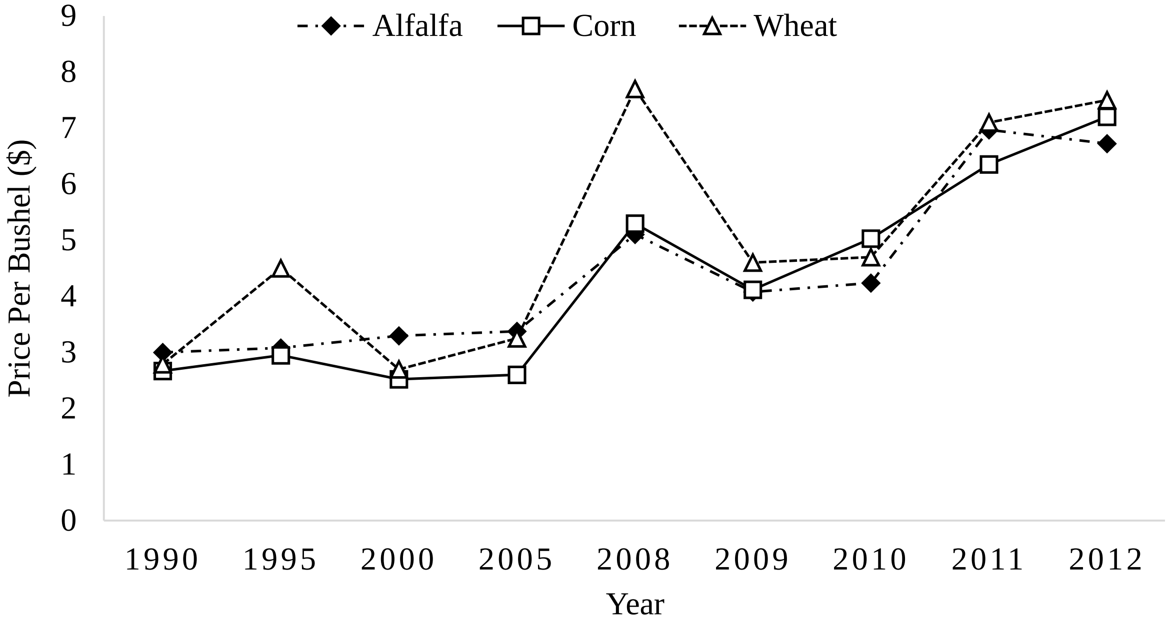
Note: The graph shows the eutrophication potential per functional unit per year in the defined system boundary of each case. Eutrophication potential greater than zero indicate the net outcome from the system boundary of each case and eutrophication potential less than or equal to zero indicate no eutrophication in system boundary of given activity.

Figure 14: Global Warming Potential (in 1000 Mg CO2-equivalent per year) in the DLA, AD and ADMC cases under LCA



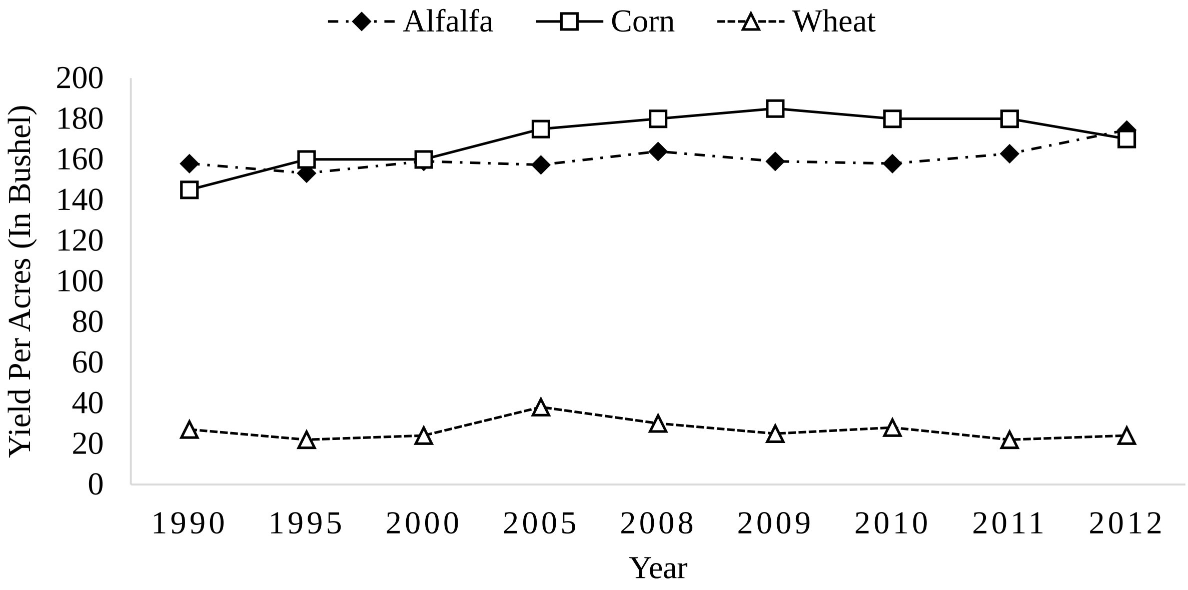
Note: GWP in CO2-equivalent per year are for one functional unit for the given defined system boundary of each case. Mg is the megagram, and equivalent to 1000 kg. Positive values of GWP indicate the net GWP in the defined system boundary and zero n negative GWP indicate no GWP in the given boundary.

Figure 15: Prices of alfalfa, wheat and corn per bushel (in dollar)



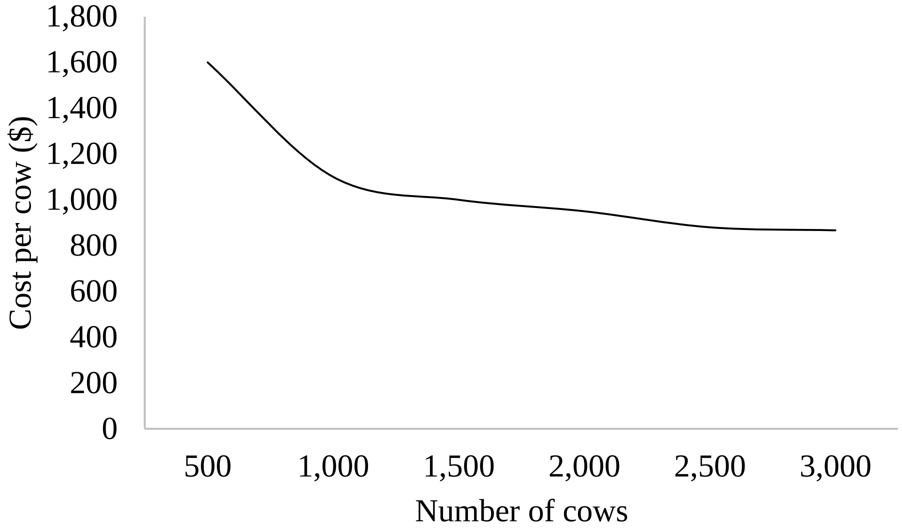
Data Source: USDA (2012)

Figure 16: Alfalfa, wheat and corn yield per acres (in bushel)



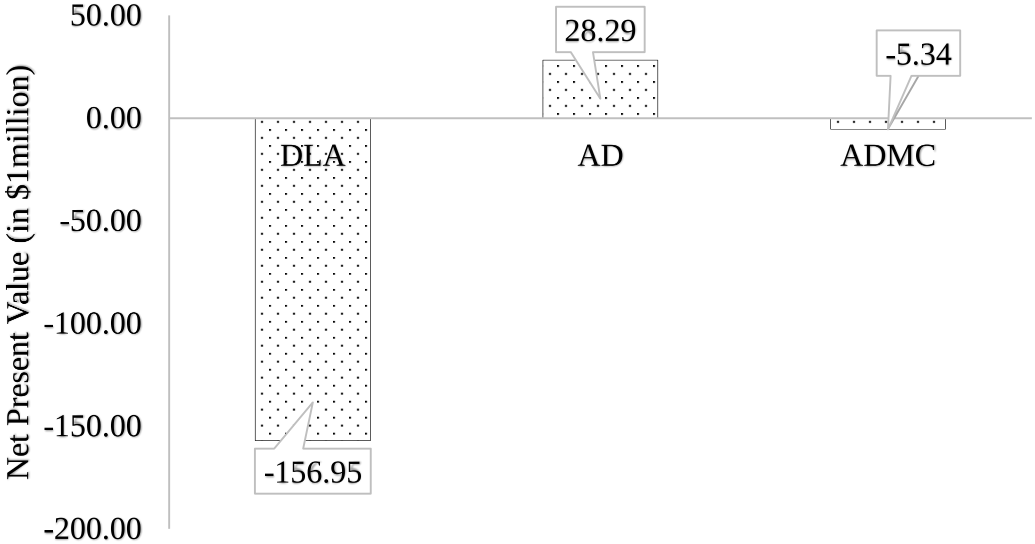
Data Source: USDA (2012)

Figure 17: Initial outlay of anaerobic digestion per cow based on farm size



Source: Lazarus (2014)

Figure 18: Net benefits of DLA, AD and ADMC under the baseline scenario



Note: The NBs shown in the graph are for one functional unit in the defined system boundary of each case under the baseline scenario. By Definition, the Positive NBs indicate net return by performing and negative NBs indicate net loss. In the comparative analysis, the one which has highest NB will be economically feasible in our case. These definitions also applies to all other graphs of NB of all scenarios.

Figure 19: Selected biofuel policies and regulations in the state of New Mexico

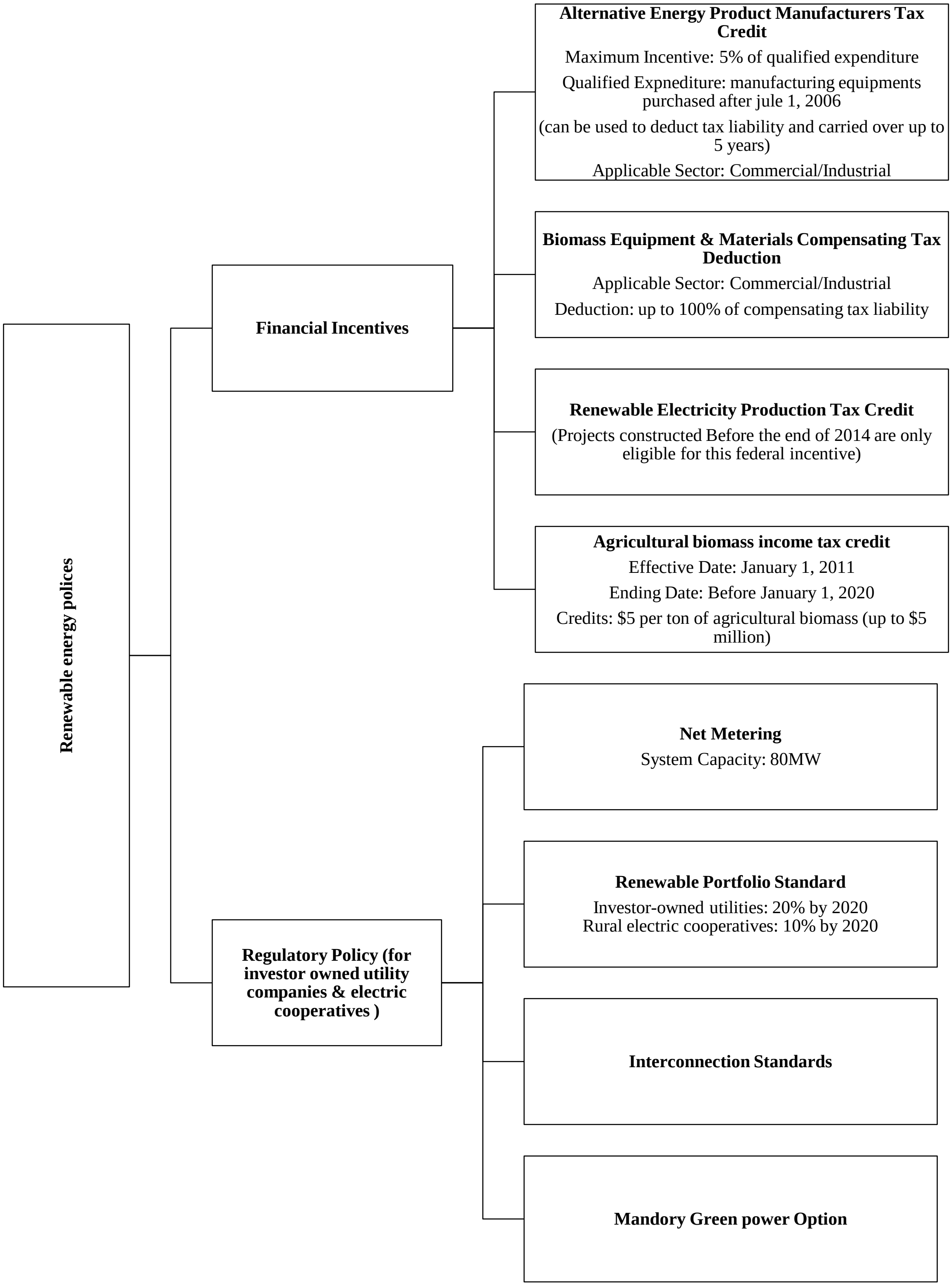
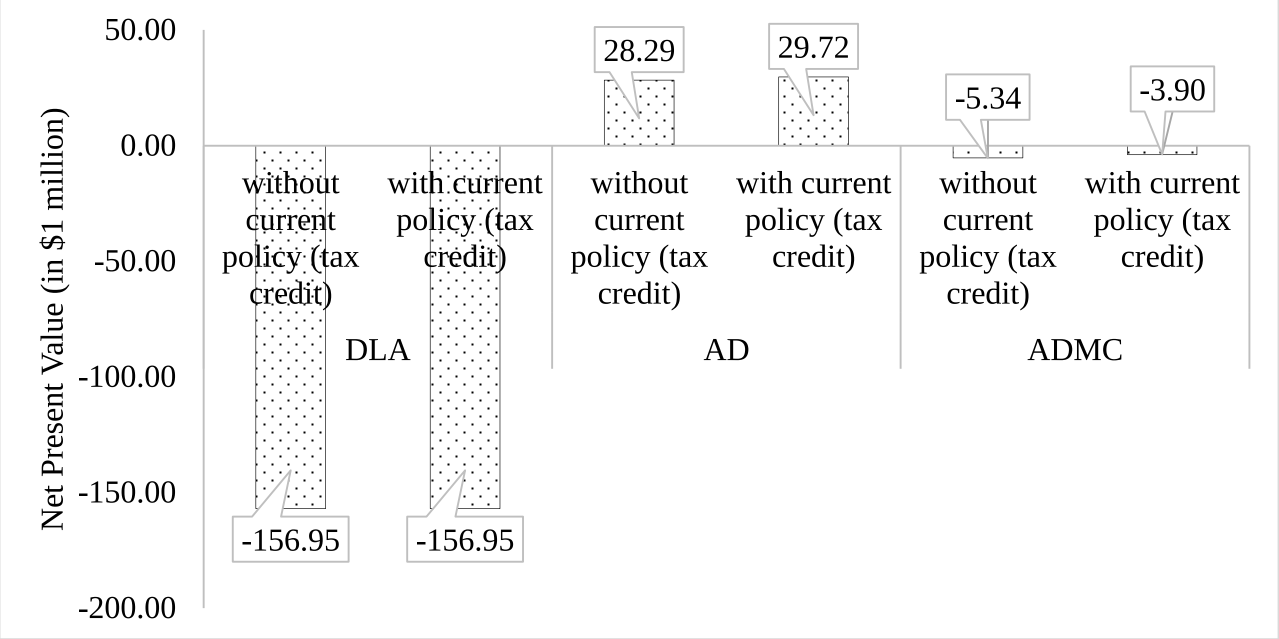
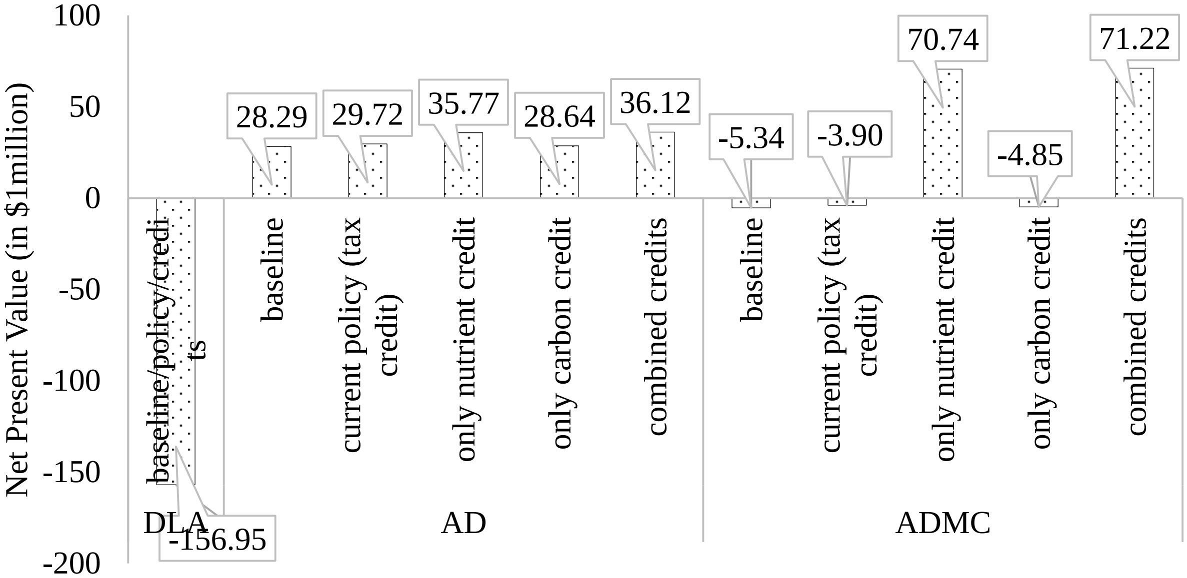


Figure 20: Net benefits of DLA, AD and ADMC under current green energy policy scenarios



Note: The NBs shown in the graph are for one functional unit in the defined system boundary of each case under the policy scenario. Positive NBs indicate net return by performing and negative NBs indicate net loss. To illustrate the effectiveness of current green energy policies in New Mexico, we have chosen 'Agricultural biomass income tax credit' as this green energy policy is most relevant in the context of this research (bio-energy production from dairy manure by the dairy farmer). The NBs of DLA case are constant under policy and without policy scenarios because the chosen green energy policy does not apply to the DLA case.

Figure 21: Net benefits of DLA, AD and ADMC under nutrient and carbon credits scenario



Note: The NPV remains constant over the policy scenarios here. All the policies such as current policy (tax credit) and prospective policies (nutrient credit and carbon credit) are indecently applied to the baseline scenarios. The combined credit indicate when the carbon and nutrient credits are applied together to the baseline scenario.

Figure 22: Net benefits of DLA, AD and ADMC if the typical dairy farm owns more than 2000 acres of land

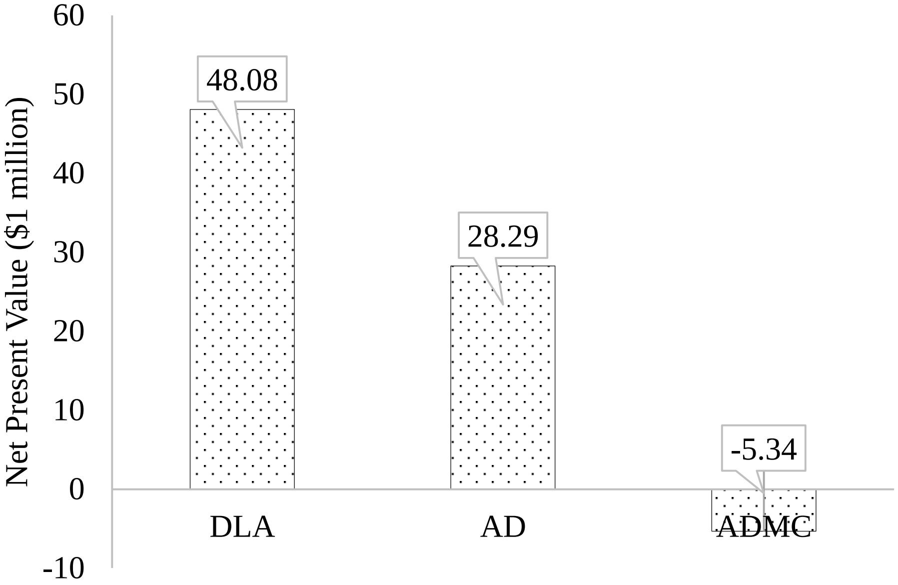


Figure 23: Net benefits of DLA, AD and ADMC under rangeland inclusion case

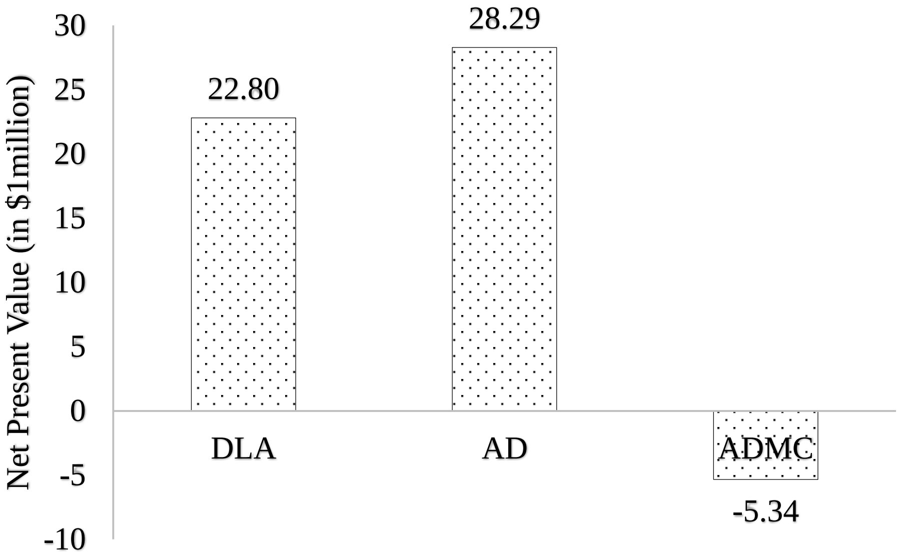
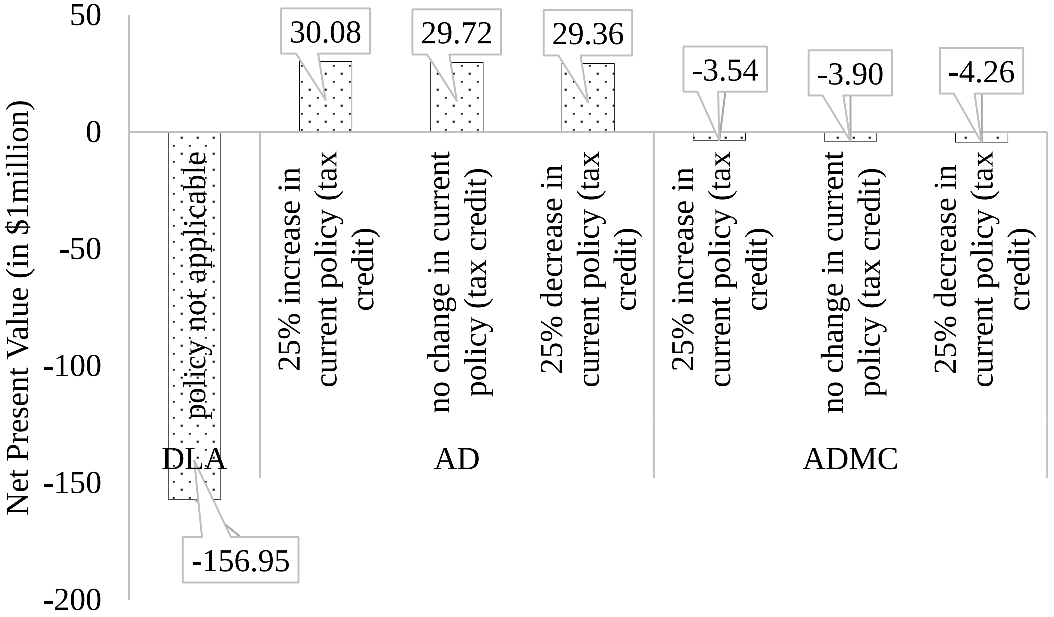


Figure 24: Net benefits of DLA, AD and ADMC under sensitivity analysis of policy scenarios (current green policy)



Note: The NBs shown in the graph are for one functional unit in the defined system boundary of each case under the sensitivity analysis of current green policy scenario. Positive NBs indicate net return by performing and negative NBs indicate net loss. As current green policy is not applicable in the DLA case, the sensitivity analysis of the current green policy also does not apply to the DLA case.