CONCENTRATED ANIMAL FEEDING OPERATIONS, ENVIRONMENTAL QUALITY AND PUBLIC HEALTH

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by

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DISSERTATION

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DEDICATION

To my family and friends who have always been there.

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ABSTRACT

Using dairy farm data, this dissertation investigates the environmental and health implications of concentrated animal feeding operations (CAFOs) in New Mexico. It seeks to answer three primary research questions: (1) the relationship between environmental justice indicators and proximity to dairy farms; (2) the overall health consequences of dairy air pollutants; and (3) the viability of implementing an anaerobic digester (AD) system as a potential solution to externality concerns while maintaining dairy farm economic sustainability.

The first study demonstrates that foreign-born populations and Hispanics disproportionately experience emissions from CAFOs, with living near dairy farms or in areas with elevated ammonia levels linked to lower family income, fewer high school graduates, and higher poverty rates. These findings provide insights to inform policy decisions aimed at reducing environmental injustice, benefiting policymakers, stakeholders, and activists dealing with similar challenges in other regions.

The second study quantified the health damages caused by dairy air pollutants. The study determined that increased PM2.5 concentrations from dairy farm emissions resulted in 12.41 annual deaths, equivalent to $129 million in monetary terms. The primary pollutant responsible for these health damages was found to be ammonia, contributing 99.38% of the damages through its transformation into secondary PM2.5. This research is one of the first to quantify and monetize health costs related to dairy farms and suggests the need for expanded research to include other livestock types and geographical regions.

The third study evaluated potential solutions to address these challenges. We assessed the cost and revenue parameters of various AD systems and environmental incentive regimes, focusing on configurations with fiber and nutrient separation due to their large private and social benefits. Recommendations were provided to policymakers on how to address challenges such as high initial capital costs and the lack of markets for co-products to optimize net benefits for both private and public parties.

In conclusion, CAFOs impose substantial human health costs and contribute to global greenhouse gas emissions. However, an integrated approach utilizing AD systems can address both local pollution and global climate change concerns. Policymakers can foster the implementation of such systems through grants, low-interest loans, and assistance in establishing markets for AD co-products. Future research should include geographical extension of studies, lifecycle assessments of CAFOs, identification of optimal locations for dairy farms, comparative studies of large farms versus traditional farming methods, and investigations on the impact of further government regulations on dairy farm operations. This comprehensive assessment of environmental, health, and socioeconomic impacts of CAFOs will inform more sustainable and equitable policy decisions.

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Chapter 1: Introduction

The phrase "Get big or Get out" extends beyond mere motivational rhetoric; it reflects the stark reality faced by small-scale livestock operations in the US. The advantages of economies of scale enable larger farms to attain higher profits, leaving smaller farms susceptible to market pressures. As a result, many commercial livestock producers and dairies are left with two choices: i) shutting down or ii) consolidating into concentrated animal feeding operations (CAFOs). While CAFOs offer certain societal benefits such as job creation and food security, they also pose environmental risks through the generation of substantial waste that can disrupt human health and the ecosystem.

This dissertation identifies and investigates the environmental and health issues related to CAFOs, as well as proposes and assesses one possible solution to the identified issues. The three pieces in this dissertation are linked by a common thread of dairy farms in New Mexico. The first study examines the environmental justice concerns of dairy farms, explicitly comparing the growth of the dairy sector with the changes in demographic compositions. The second study calculates the health damages of dairy farms by measuring emissions and transportation of dairy-borne pollutants, their conversion to particulate matter (PM), and the impact of concentration changes on human health. The third study examines anaerobic digester (AD) systems as a possible solution to the aforementioned issues, exploring various alternatives and opportunities accessible to farmers.

Studies indicate that the adverse environmental externalities related to CAFOs disproportionately affect areas with high poverty rates and significant minority populations, resulting in environmental injustice. In Chapter 2 of this dissertation, we explore the distribution of environmental justice indicators for exposure to large dairy farms in New Mexico. We employ two independent sets of indicators—environmental justice and exposure indicators—constructed using demographic data, dairy farm data, and high-resolution satellite data of ammonia concentrations and explore their relationships. Three measures of pollution exposure: count-based, buffer-based and actual ammonia concentrations are used to assess disparities. Similarly, seven different environmental justice indicators are compared across time and space to examine their relationship with the consolidation of dairy farms. Results indicate that foreign-born populations and Hispanics disproportionately experience emissions from CAFOs. We also found that living near dairy farms or in areas with elevated ammonia levels is correlated to a lower family income, fewer high school graduates, and higher poverty rates. Census tracts with dairy farms have had better economic outcomes in the past 30 years. This suggests that dairy farms may have created jobs and uplifted rural communities. We recommend future research to supplement proxy measures of environmental threats with actual exposure data, explore unexamined geographic regions and sources of environmental threats, and adopt innovative measures and methodologies for identifying and understanding perceived environmental threats' extent and distribution. This study's findings inform policy decisions aimed at reducing environmental injustice, benefiting policymakers in New Mexico and stakeholders and activists in other regions confronting similar challenges.

Areas surrounding CAFOs have high concentrations of pollutants such as ammonia, hydrogen sulfide, methane, PM, and volatile organic compounds. Some of these pollutants can transform into secondary PM, which has been linked to heart diseases, lung diseases, cancer, and congenital disabilities. However, relatively few studies have analyzed the dispersion and transformation of these pollutants or calculated their impact on human health in monetary terms.

Chapter 3 of this dissertation aims to address this gap by quantifying the total health damage resulting from changes in PM concentration. The study focuses on the increased concentration of PM2.5 resulting from emissions of primary PM2.5 and ammonia from large dairy farms. To achieve this, the study utilizes data on the location and number of animals in dairy farms, emission factors, the InMAP Source-Receptor Matrix for each pollutant, population data, and the value of statistical life (VSL). The study estimates the total health damages, the monetary value of these damages, their distribution across impact locations, and the marginal damages per livestock at the emission location. The results show that the increased concentration of PM2.5 from dairy farm emissions causes 12.41 annual deaths in New Mexico, which equals $129 million. The primary pollutant responsible for these health damages is ammonia, contributing 99.38% of the damages through its conversion to secondary PM2.5, whereas the primary PM2.5 emitted from dairy farms contributes only 0.62%. The study also provides county-level estimates of the monetary value of health damages, which vary between $468 and $1634 across different counties and have higher values in areas with high population density. The study recommends future research to expand the study area to include the entire US and a wider range of CAFO categories such as swine, beef, and broiler operations to provide a more comprehensive understanding of the consolidation in CAFOs. Policymakers should consider both the economic benefits of CAFOs and their potential externalities when formulating incentive-based policies that address externalities without hurting the farmers' bottom line.

The livestock industry is a significant contributor to greenhouse gas emissions. However, regulations intended to penalize or directly control emissions are met with substantial opposition and may lack economic logic. Consequently, incentive-based policies may be more effective in addressing these challenges. AD systems are a solution with the dual benefits of reducing greenhouse gas emissions and generating revenue. The AD system can also reduce ammonia emissions with nutrient separation technology, ultimately mitigating particulate matter formation in the atmosphere. Chapter 4 of this dissertation evaluates the bioenergy potential of a range of dairy farms in New Mexico and assesses the viability of two alternative technologies under four different scenarios. The technology components assessed in this study include an AD unit, combined heat, and power (CHP) unit, compressed natural gas (CNG) unit, fiber separation unit, and nutrient separation unit. The chapter compares the net present value of each system, considering costs, revenues, and environmental incentives. The results show that AD systems that produce electricity and co-products such as fiber and nutrients, and also avail environmental credits, have the highest net present value. The study also analyzes the net social benefits of the AD system, which sometimes exceed the private benefits. The government can incentivize the adoption of AD systems and internalize the positive externalities they create by offering tax breaks, subsidies, low-interest loans, and grants. To enhance the voluntary adoption of this technology, it is crucial to reframe the narratives surrounding AD systems from being perceived as burdensome “white elephants” to lucrative "cash cow" enterprises. Ultimately, the viability of any AD system relies on the existence of a vibrant market for its valuable co-products.

Chapter 2: Disproportionate Effects of CAFOs on Disadvantaged Communities: A Case Study of Dairy Farms

2.1 Introduction

The livestock sector in the United States (US) underwent significant structural change in the mid-twentieth century, resulting in an increasing concentration of agricultural production in fewer and larger farms (Mallin, 2000). Many smaller farms were forced out of business or relegated to the status of hobby farms because of the decline in their competitiveness and contribution. The poultry industry started this consolidation trend in the 1950s, followed by swine operations in the Midwest in the 1970s, and has since been adopted by the dairy industry (Martin et al., 2018). An analysis of midpoint sales and inventory values of seven major livestock commodities (broilers, fed cattle, hogs, egg layers, turkeys, beef cattle, and dairy cows) between 1987 and 2012 shows that all of them experienced some consolidation, but hogs and dairy operations experienced the largest growth in inventory size of 3,233% and 1,025%, respectively (MacDonald et al., 2018). This consolidation has established CAFOs as the most economically successful form of animal agriculture in the US. CAFOs are defined by the US Environmental Protection Agency (USEPA) as animal feeding operations that maintain more than 1,000 animal units on-site for more than 45 days per year, or have between 300 and 1,000 units and are designated a CAFO by the state (Browner et al., 2001). One animal unit is defined as a 1000-pound animal, often a beef cow at market weight. However, smaller facilities may also be considered CAFOs based on their potential to discharge pollutants into the US water bodies.

Thus, CAFO designation considers not only the size of the facility but also waste containment and disposal practices.

Supply-side considerations, such as economies of scale, favorable policies, improved disease control, advanced genetics, labor-saving technologies and market power have driven the consolidation trend in the livestock industry (MacDonald et al., 2018). Concurrently, the growing and increasingly prosperous global population has amplified demand for livestock products, creating a favorable market environment for consolidated producers. According to projections, the global population is estimated to reach 9.7 billion by 2050, doubling the demand for livestock products (FAO, 2018; Rojas-Downing et al., 2017). This combination of supply and demand side factors has led to significant benefits for producers and consumers, including lower prices and greater access to international markets for a wider range of livestock products. Nevertheless, despite their increased production efficiency, CAFOs pose substantial negative externalities. As farms shift towards larger operations, they specialize in a limited set of crops or livestock species/stages. In 2015, 37% of all livestock in the US were raised on farms with no crop production, up from 22% in 1996 (MacDonald et al., 2018). The rising volume of animal waste and the lack of adequate on-site crop production for nutrient assimilation has raised significant environmental and public health concerns, emphasizing the need for robust animal waste management (Ghimire et al., 2021).

Animal waste primarily consists of manure and other organic matters such as urine, unconsumed animal feed, and occasionally animal remains such as blood and carcasses. These wastes contain various chemical compounds and radicals, including hydrocarbons, nitrates, phosphates, sulfates, and ammonium (USEPA, 2004). While these amendments can serve as nutrients for crops in moderate amounts, excessive levels can result in soil degradation and water pollution.

Furthermore, these compounds can volatilize into gaseous molecules and particulate matter (PM), negatively impacting ambient air quality over a large area. The increasing focus on rapid turnovers and razor-thin profit margins has led CAFOs to use substances previously unutilized in animal husbandry, such as antibiotics to prevent disease spread in close-quartered animals, natural and synthetic hormones to boost growth, and metals like As, Cu, and Zn to preserve feed freshness and enhance growth (USEPA, 2004). The release of these substances into the environment can result in numerous negative consequences, including the eutrophication of waterways, loss of biodiversity, the transmission of antibiotic-resistant bacteria, and the outbreak of water-borne, air-borne and zoonotic diseases (Hribar, 2010). Additionally, the potential effects of some of these substances and pathogens on the environment, other animals and humans are not entirely understood (USEPA, 2004).

Ambient air pollution is a major environmental health concern linked to CAFOs. Emissions from CAFOs mainly come from the decomposition of manure during its handling, storage, and application. Animal movements and fossil fuel combustion during transportation and heating activities related to animal farming can also contribute to air pollution (Hribar, 2010; P. Walker et al., 2005). Ammonia is a prevalent air pollutant generated by CAFOs, and its volume of emission and intensity of effect are of particular concern (USEPA, 2004). Over 90% of the world's ammonia emissions come from agriculture, with cattle farming being one of the major contributors (Plautz, 2018). Ammonia is a potent irritant of the upper respiratory tract, and prolonged exposure can result in burns to the eyes and skin, persistent cough, chronic lung disease, blindness, and even death (Hribar, 2010; National Research Council, 2008). Recent evidence suggests that ammonia significantly contributes to PM production (Maas & Grennfelt, 2016). In some regions, more than half of the formation of atmospheric PM can be attributed to the interaction of ammonia with other atmospheric pollutants (Plautz, 2018; UNECE, 2021). The presence of ammonia in the air explains why PM concentrations have not reduced as rapidly as expected in the US, despite declines in nitrogen oxide and sulfur dioxide emissions (EMEP, 2016). Ammonia is directly or indirectly responsible for 61,000 premature fatalities worldwide (Ma et al., 2021a). Given the almost exclusive association of ammonia emissions with agricultural operations and the evidence indicating its susceptibility to convert into PM2.5 and PM10, ammonia emissions or concentrations can be used as a reliable proxy to estimate the air pollution and health impacts from CAFOs, especially in regions with intensive livestock production and minor crop production. Studies have shown a critical issue regarding the negative externalities associated with CAFOs: their adverse impacts are not uniformly distributed across society. Specifically, CAFOs tend to be concentrated in areas characterized by high poverty rates and substantial minority populations resulting in environmental injustice (J.-Y. Son, Muenich, et al., 2021).

Environmental injustice refers to the unequal distribution of environmental threats and negative externalities among different socioeconomic groups or communities, with disadvantaged or vulnerable people, such as low-income communities and communities of color, frequently being the most affected (Mohai & Saha, 2006). It occurs when one group or community faces the negative impacts of environmental pollution, degradation, or other environmental damages while another group or community benefits from the actions that create these harms (Kelly-Reif & Wing, 2016). Environmental injustice is frequently attributable to economic and political power discrepancies, resulting in uneven access to decision-making processes and environmental resources. Epidemiological and socioeconomic research has examined the disparity in CAFO-induced pollutants' distribution and impacts over the years (Carrel et al., 2016; Hall et al., 2021;

Ogneva-Himmelberger et al., 2015; J.-Y. Son, Muenich, et al., 2021). However, there is no well-accepted approach to assess the wide-ranging and multi-faceted nature and implications of environmental injustice related to CAFOs.

This study aims to investigate environmental justice outcomes related to large dairy farms on vulnerable populations using various measures of environmental inequity. While previous studies have largely focused on the distributional impact of environmental threats from the hog and poultry operations in the Midwest and Eastern US, our study specifically examines the impact of large dairy farms in the western US. This is a critical area of investigation, given the ongoing consolidation in the dairy industry and the potential for concentrated pollution in areas with many dairy farms. We chose New Mexico as our case study because it has one of the country's most significant dairy farm consolidations and is a minority-majority state with a high proportion of Hispanic and Native American residents (Census Bureau, 2023a; USDA, 2019). Given New Mexico's distinct demographic composition, history of oppression and segregation primarily along ethnic lines compared to racial lines in many other states (Melzer et al., 2011), the traditional understanding of environmental injustice might not hold true, necessitating new investigations. To achieve our objective, we performed a spatio-temporal comparison of seven different environmental justice indicators before and after dairy intensification, using three different measures of exposure to dairy farms.

We contribute to literature in at least three ways. First, to our knowledge, this is the first study to examine the environmental disparities related to dairy farms systematically. Second, in addition to traditional environmental justice indicators, we applied a relatively new indicator, i.e., the Index of Concentration at the Extremes (ICE), to evaluate environmental injustice outcomes related to CAFOs. While traditional measures such as percentages, means, medians, isolation indices, segregation indices, and dissimilarity indices only provides a one-dimensional measure of either privileged or deprived group, the ICE measure offers a broad-spectrum diagnosis to explain gaps in adverse health outcomes and exposure to environmental harms as it considers both deprived and privileged socioeconomic groups in one measure (Chambers et al., 2019). Finally, we used both direct and indirect measures of population exposure. Previous studies relied on the count of animals or a buffer-based count of animals as indirect proxies for exposure. We directly used high-resolution actual ammonia concentration to measure population exposure. Overall, our study provides a comprehensive understanding of the distributional impact of environmental threats from large dairy farms on vulnerable populations, offering insights that can inform policy decisions to reduce environmental injustice.

2.2 Literature Review

Numerous studies have documented the disproportionate burden of environmental externalities faced by marginalized communities concerning industrialization, militarism, and consumer practices (Mohai et al., 2009). While earlier research focused on racial disparities in toxic waste site exposure, recent studies include newer indicators such as income, education level, and immigration status. Other sources of environmental burdens, such as factories, CAFOs, and disaster-prone areas, have also been added to the scope of research. Despite some evidence regarding the role of income-based market forces, structural racism is frequently cited as the primary cause of environmental inequality (Mohai et al., 2009).

CAFOs have garnered significant attention from environmental justice researchers in recent years due to their connection to marginalized populations who work in or live near these farms and the scale of pollution potential of these large farms, comparable to that of big cities. Studies on CAFOs have shown that they are more commonly located in areas with extreme poverty and substantial minority populations, and disparate siting and residential sorting are identified as two of the main mechanisms contributing to the disparity (Banzhaf et al., 2019; Mohai & Saha, 2015). Carrel et al. (2016) investigated the environmental justice scenario of hog CAFOs in Iowa, focusing on the potential clustering of these operations in specific areas of the state. Using spatial regression techniques, they examined the relationship between swine CAFO concentration and conventional environmental justice indicators such as poverty rate, population density, percentage of non-white residents, and percentage of population without college education at the census block group level. The study identified regions and watersheds with significant swine CAFO concentrations, but the density of hog population was not correlated with the prevalence of low-income and minority race/ethnicity communities. The authors recommended a more nuanced assessment of environmental injustice, highlighting the importance of both "downstream" and "upstream" approaches to understanding the numerous factors responsible for the environmentally unjust landscape of the Iowan swine production industry. Moreover, the authors emphasized the role of high-quality, publicly accessible data for the accurate assessment of injustice.

Himmelberger et al. (2015) focused on air pollution modeling and environmental justice analysis related to hog farming in North Carolina. The authors used CALPUFF air pollution model to estimate how far air pollutants from CAFOs spread and how much they exposed nearby communities to CAFO-related emissions. The study also investigated the relationship between the demographic composition of hot spot regions with high ammonia concentrations. The study found that air pollution from CAFOs harmed low-income communities and persons of color more than other groups. This was evident from the average increase of 2.5 to 3 times in ammonia levels in hotspot areas over ten years, as the simulated data from the CALPUFF model revealed. In addition, the authors urged academics and professionals in public health to investigate and diagnose the potential adverse health effects of prolonged ammonia exposure in other high-risk areas across the nation. The study suggested that future studies employ air pollution dispersion models and fine-scale demographic data to understand better the impacts of CAFOs on the health and quality of life of impacted populations.

Son et al. (2021) examined how the environmental justice indicators related to exposure to CAFOs in North Carolina were distributed. The authors used a combination of Geographic Information Systems and statistical methods to analyze the spatial distribution of CAFOs and their proximity to communities using eight different demographic and socioeconomic indicators: percentage of Hispanic, Non-Hispanic Black, and Non-Hispanic White; median household income; poverty rate; percentage of the population with less than high school education; residential isolation index for Non-Hispanic Black; and residential isolation index for those without a college degree. Two approaches were employed to assign exposure to CAFOs per ZIP code. The count approach, also known as the unit-hazard coincidence approach, used the simple count of CAFOs within each ZIP code. On the other hand, the buffer approach determined the total number of CAFOs in each ZIP code using the percentage of area overlapped by 15 kilometers (9.32 miles) buffer drawn around each CAFO. The study found that those with lower economic status and the people of color were more likely to reside in neighborhoods with CAFOs, leaving them more exposed to pollution and health risks. The results highlight the significance of considering the consequences of CAFOs on marginalized communities and argue for an equal allocation of environmental burdens.

These studies have significantly highlighted the disproportionate distribution of environmental hazards related to CAFOs, particularly swine operations in states east of the Mississippi River. Recent studies have increasingly used advanced analytical methods, including Geographic Information Systems, to uncover these relationships. While distance-based methods provide additional support for claims of environmental injustice identified through earlier broader spatial analyses, actual measures of environmental harm are needed to reflect the damage done to society accurately. Moreover, ambiguity remains regarding the persistence and magnitude of effects across various racial and socioeconomic indicators, necessitating multidimensional measures of injustice. Most research on this topic has been cross-sectional, demonstrating inequality only at a single time point. However, longitudinal research can provide more nuanced insights and establish causal links by tracking the consistency or shifts in these effects over time. As a result of cross-disciplinary debates and the topic's growing policy significance, environmental justice studies now cover a more comprehensive range of techniques, explanatory theories, epistemologies, and perspectives drawn from the social, economic, and historical spheres (Agyeman et al., 2016).

The key contribution of this study is twofold: expanding the scope for the environmental justice literature to include large dairy farms in the Southwestern US and making methodological contributions to the literature. We have expanded the scope of environmental justice literature to include dairy farms and the Southwestern US. The findings from this study will be helpful not only to New Mexico but also to other states in the Southwest which are concurrently experiencing a surge in dairy farm consolidation and significant demographic shifts. In terms of methodology, the study employs three measures of pollution exposure - count-based, buffer-based, and the actual concentration of a major pollutant (ammonia) - to assess the disparity. In our context, exposure refers to the extent of contact between individuals or populations and hazardous substances, dairy farm emissions. The count-based and buffer-based methods employ proximity to the pollution sources as an indirect measure of exposure. However, the actual concentration of the pollutants and, ultimately the exposure may depend on factors such as wind speed, direction, and other meteorological conditions. Conversely, the concentration of ammonia is a direct measure of gauging harm, as it quantifies exposure to the pollutant that can impact human health, both in its primary form and secondarily through its transformation into PM. The study also establishes a case for including satellite data in environmental justice analysis, providing a more complete and reliable measure of environmental harm, especially in areas where pollution monitoring stations are scarce or out of commission. Furthermore, this study conducts a comparative analysis over time and space that captures both the pre-and post-trend corresponding with the growth of dairy farms in the state, allowing for a better understanding of how present-day disparities emerge. By using a multidimensional measure of inequity (ICE), the study presents a more inclusive and nuanced picture of environmental justice. Overall, this study fills a gap in the literature by examining the distribution of environmental hazards concerning dairy farms and providing new insights into effective measures of environmental threats to account for distributional issues.

2.3 Data

This study employed three different data sources to construct two independent sets of indicators: Environmental Justice Indicators and Exposure Indicators. The indicators related to environmental justice were created using the decennial Census and American Community Survey (ACS) data. Exposure indicators were subdivided into two categories: direct and indirect measure of exposure. Farm-level CAFOs data and satellite data of ammonia concentrations were used to create exposure related indicators.

2.3.1 Data for Environmental Justice Indicators

We used census tract level variables obtained from 1990 Census data and 2019 American Community Survey (ACS) data to evaluate the environmental disparities by several environmental justice indicators. All the census tracts in New Mexico are considered as the study region to make a comparison between dairy producing and non-dairy producing census tracts. The 1990 census data used in our study is a standardized version consistent to the 2010 census tract boundaries and maintained as Longitudinal Tract Database by Brown University (Census Bureau, 2023b; Logan et al., 2014). The ACS data used in our study is based on 2015-2019 5-year estimates and maintained by the Census Bureau and was extracted using Tidy Census package in R (Census Bureau, 2023a; R core team, 2022; K. Walker & Herman, 2023). 1990 marks as the earliest census year before the rapid proliferation of dairy farms in New Mexico, similarly 2019 ACS year is the last ACS year with census tract boundaries consistent to the 2010 census tract boundaries.

The validity of environmental justice research can also depend on the geographic scale of the analysis (Chakraborty & Maantay, 2011). In our study, we have used census tract as the unit of spatial analysis for various reasons. Census tracts are relatively smaller in size than counties therefore provide a larger sample size for analysis and yet provide socio-demographic information at a detailed level not available for census blocks. Similarly, census tracts have a reasonably consistent population size averaging 4,000 people and a relatively stable boundary for year-to-year statistical data comparisons. Census tract boundaries generally follow visible and identifiable features and, therefore can be accounted as a neighborhood for the purpose of sociodemographic research.

We use seven indicators to assess the environmental disparities related to the dairy farms: percentage of Hispanic, percentage of non-Hispanic White, percentage of foreign born, percentage of adults with education less than high school diploma, percentage living below the poverty line, Indices of Concentration at the Extremes for race (ICE-race), median household income and median home value. These indicators were chosen based on the practices of similar studies performed in other state as well as based on their relevance to dairy producing regions of New Mexico. For instance, several environmental justice studies use percentage of African American population as one of the indicators. However, New Mexico's tiny African American population makes any analysis statistically weak. Similarly, the native American population of New Mexico do not lie nearby dairy production regions therefore are excluded from the analysis although they belong to the socioeconomically underprivileged group.

The ICE indicator reveals the extent to which residents of a given area are concentrated into groups at the extremes of deprivation and privilege. The ICE indicator ranges from -1 to 1, where -1 indicates that 100% of the population is concentrated in the most deprived group, and a value of 1 indicates that 100% of the population is concentrated in the most privileged group (Krieger et al., 2016; Massey & Crouter, 2001). In this study, we use ICE for race due to the lack of complete data for other variables. The formula for calculating ICE will be introduced in the methodology section.

Table 1 provides summary statistics of the ICE for race indicator for the years 1990 and 2019. The ICE score in New Mexico ranged from -1 to 0.73 in 2019 and from -0.91 to 0.83 in 1990, with standard deviations of 0.39 and 0.42, respectively. The relatively large standard errors are indicative of significant heterogeneity in racial and ethnic distribution. Negative values of medians indicates that more than half of New Mexico census tracts have census tracts with disproportionately larger Hispanic population compared to non-White population. Similarly, a minimum ICE score being very close to -1 indicates that there are census tracts with a 100 percent Hispanic population. The ICE score in itself does not indicate any form of environmental injustice, but it does point towards considerable residential segregation. The relationship between ICE and the exposure indicators will reveal whether there is disproportionate assortment of population in dairy concentrated regions.

Table 2.1: Summary statistics of the Index of Concentration at the Extremes (ICE) for race across New Mexico

Year	*Mean*	*Median*	*Min*	*Max*	*Standard deviation*
2019	-0.08163	-0.35	-1.00	0.74	0.39
1990	0.13	-0.20	-0.91	0.83	0.42

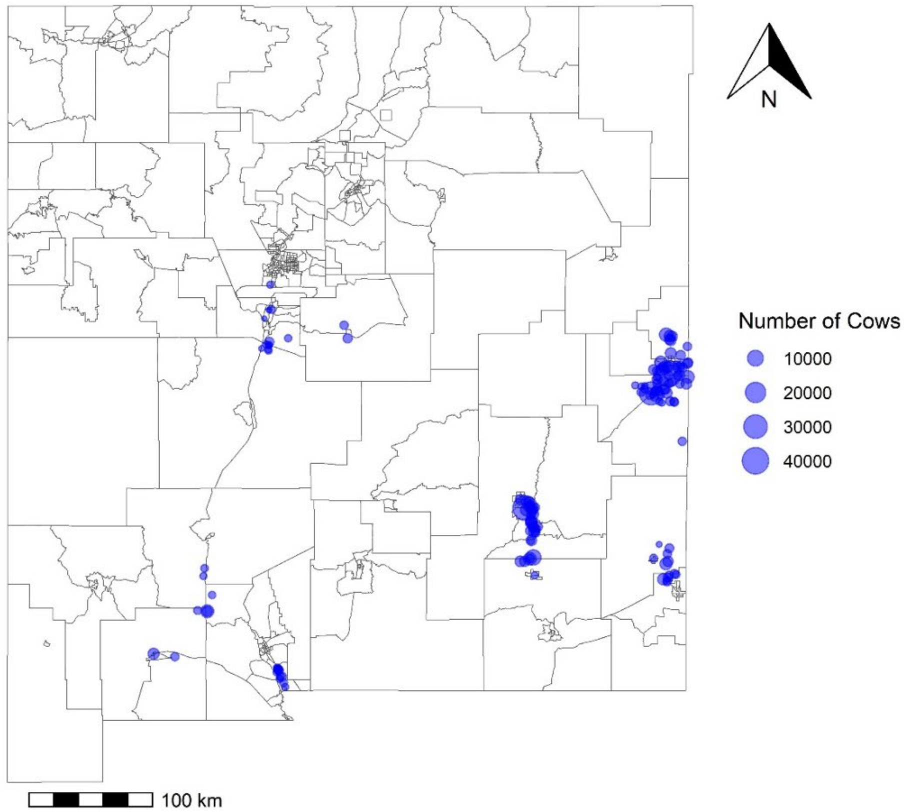
2.3.2 Data for Exposure Indicators

The dairy farm data was obtained from the wastewater discharge permit records maintained by New Mexico Environment Department. Data included facility names, permit number, permit status, farm location, start year and the total discharge volume in gallons per day for farms operating through May 2020. The dairy farm data helps us to create the indirect measure of dairy farm exposure which uses proximity or distance from dairy farms as the explanatory variable.

First, the data was cleaned, and appropriate indicators were created using the available information. Information about the total number of cows per farm was unavailable in the dataset. Total cows per farm was therefore estimated by dividing the discharge volume of each farm (gallons/day) by 40 (gallons/day/cow), the average direct water use per cow per day in a New Mexican dairy farm. Direct water use consists of water used for drinking and cleaning purposes of cows in a farm. This value was based on information provided by a contact at the New Mexico Environment Department (N. McDuffie, personal communication, 2020), and is within the range of values, 30-55 gallons/day/cow, as reported by other studies (Guerrero et al., 2012; Matlock et al., 2013). Dairy farm addresses were manually cleaned and geocoded to their appropriate latitude and longitude using “Geocode by Awesome table” google sheet add-on package. This information was then combined with demographic data and shape files to produce a spatial dataset at the census tract level for further analysis. The study employed the WGS84 UTM zone 42N projection, a commonly used coordinate system for mapping and analyzing spatial data in the southwestern United States, including New Mexico. This uniform framework enables us to measure distances, areas, and other geographic features within the state consistently and reliably. It can also facilitate the smooth integration and comparison of our findings with other related studies and datasets utilizing the same coordinate system.

The actual measurement of ammonia concentration across the state was used to quantify the direct exposure to dairy borne pollutants. The satellite data of ammonia concentration was obtained from Van Damme et al., (2018) which consists of 9 years of data from 2008-2016 at a spatial resolution of 0.01° x 0.01°. Figure 1 visualizes the distribution of two distinct exposure variables concerning the large dairy farms of New Mexico. Panel A is the proportional circle representation of large dairy farms in NM. The diameter of the circle represents a dairy farm's size. The majority of the dairy farms in terms of number and size are concentrated in the Eastern and southeastern parts of the state. Panel B depicts the ammonia concentration across NM based on satellite imagery data collected by Infrared Atmospheric Sounding Interferometer-European Space Agency. Van Damme et al. (2018) reprocessed and reanalyzed this data in their time series assessment of global ammonia concentrations trend. The map shows considerable heterogeneity in the distribution of ammonia concentration and the higher ammonia concentration region neatly aligns with the intensity of dairy farming in the state.

A)


N
Number of Cows
10000
20000
30000
40000
100 km

B)

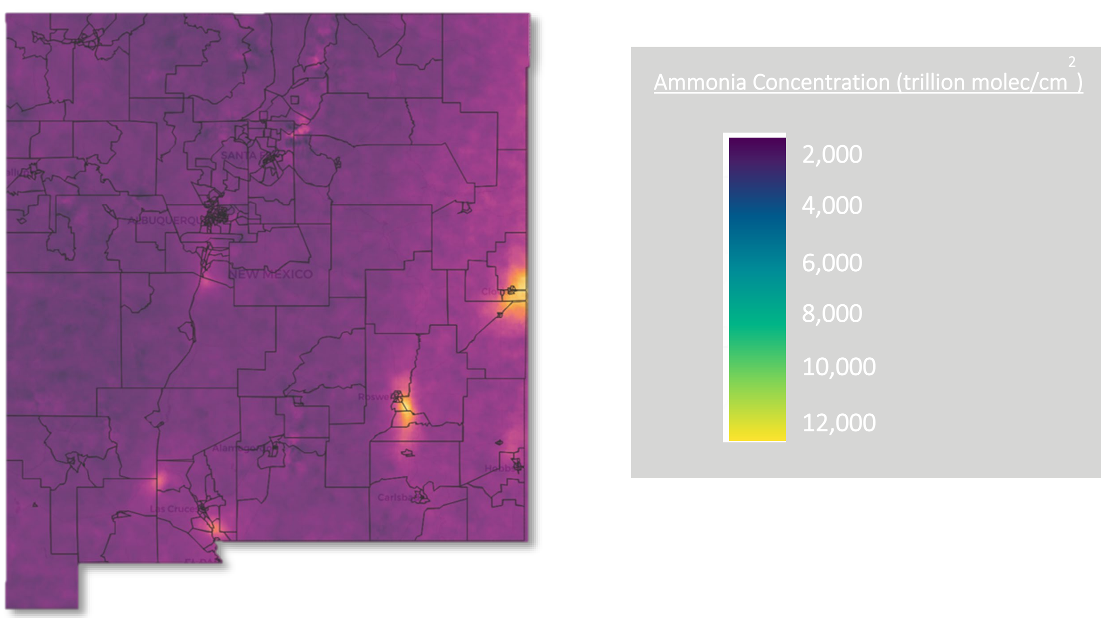

NEW MEXICO
Ammonia Concentration (trillion molec/cm^2)
2,000
4,000
6,000
8,000
10,000
12,000

Figure 2.1*: A) Proportional circle representation of large dairy farms in New Mexico (2020) B) Ammonia concentrations in New Mexico averaged across 2008-2016 as measured by Infrared Atmospheric Sounding Interferometer-European Space Agency.*

The descriptive statistics for the exposure measurements are summarized in Table 2. The count indicator, which indicates the total number of cows in a census tract, ranged from zero to 64,340, with an average of 622. However, when the buffer indicator was used, which calculates the total number of cows based on the fraction of three-mile circular buffers around farms intersected by the census tract boundary, the distribution of cows in the state became less extreme. The third exposure indicator, ammonia concentration, had a heterogeneous range, varying from 1,120 trillion to 12,280 trillion molecules per square centimeter. The maximum concentration was over 11 times higher than the minimum concentration. On average, the state had an ammonia concentration of 1,228 trillion molecules per square centimeter. The distribution of ammonia concentration across the state was highly skewed, with most of the state at moderate levels and a few hotspots with significantly elevated concentrations.

Table 2.2: Summary statistics of exposure indicators (n=499)

Statistics per tract	*# Cows based on count*	*# Cows based on 3 miles buffer*	*Ammonia concentration (trillion molecules cm-2)*
Mean	623	612	2,820

St. Dev.	4,373	3,786	1,680
Min	0	0	1,120
Percentile (25)	0	0	1,950
Percentile (75)	0	0	2,920
Max	64,340	49,124	12,280

2.4 Methodology

2.4.1 Creating Environmental Justice Indicators

Demographic data from the Census Bureau was utilized to create seven Environmental Justice indicators, including percentage of non-Hispanic white, percentage of Hispanic, percentage of foreign-born residents, percentage of population below high school education, median household income and median home value. We also created an additional EJ indicator, Index of Concentration at the Extremes (ICE) for race.

The percentage of a certain demographic in a census tract was calculated using 1990 Census and 2019 ACS data using equation (1):

$$\eta_i = \frac{Z_i}{T_i} \tag{2.1}$$

where η_i is the percentage of a certain demographic group in a geographic region i, Z_i is the number of populations from that specific demographic group in a geographic region i, and T_i is the total population.

An Index of Concentration at the Extremes (ICE) for race was constructed using census tract level race and ethnicity data. ICE measures the geographical social polarization of privileged and deprived social groups. In our calculation, the privileged and disadvantaged populations are Non-Hispanic White and Hispanic, respectively. ICE is calculated using equation (2):

$$ICE_i = \frac{A_i - P_i}{T_i} \tag{2.2}$$

where A_i is the number of privileged population (non-Hispanic White) and P_i is the number of deprived population (Hispanic).

2.4.2 Creating Exposure Indicators

In this study, we used three different exposure indicators to measure how CAFOs affect various population groups. The first two indicators, count-based and buffer-based, used a density- or distance- based approach to quantify the exposure. The third indicator, a direct measure of exposure, made use of satellite data to quantify actual exposures to the population.

The classification of census tracts as either dairy or non-dairy is based solely on 2020 dairy farm data, despite environmental justice indicators being derived from two different census or ACS years. This method enables us to trace the census tracts with high dairy farm concentrations back in time, allowing for a historical comparison of their differences. Additionally, this approach helps us determine if dairy farm operators strategically chose to consolidate in particular census tracts. Although dairy farms were present in New Mexico prior to the 1990s, the trend of consolidation became significantly more pronounced after this period.

The count-based method, also known as the unit-hazard coincidence method, is commonly used to measure the total number of animal units inside the administrative boundary of a geographic region. The count-based number of cows in a census tract is calculated using equation (3):

$$v_i = \sum_{j=1}^{J} n_{ij} \tag{2.3}$$

where, v_i represents the count-based number of cows in census tract i; n_{ij} represents the number of cows in CAFO j; and J is the number of CAFOs physically located within the census tract.

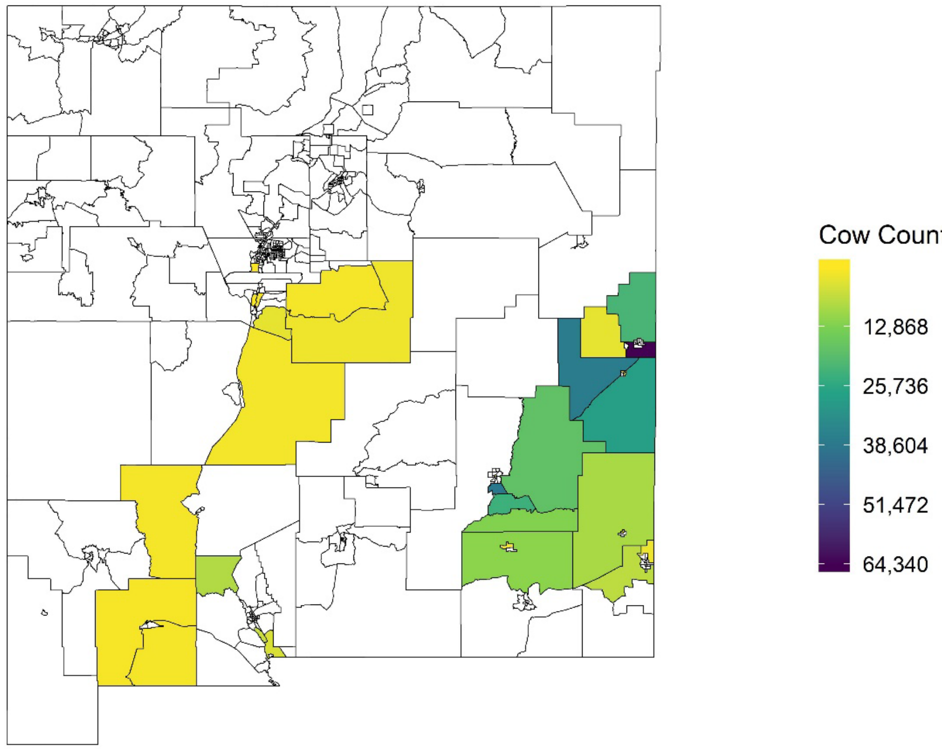
Despite its convenience, the count-based method can misidentify exposed and unexposed population groups when certain CAFOs are located near the border of a geographic region. This is because CAFOs situated at the edge of a geographic region may be exclusively assigned to their host region, even though their negative impacts may also be experienced in nearby regions. A buffer-based method is recommended to overcome this limitation. Specifically, this method involves drawing a certain distance radius around a CAFO and assigning a proportional weight to each geographic region based on the portion of the circular buffer within that region. Then, by multiplying this weight by the total number of animal units in the CAFO, we can calculate the buffer-based number of animal units per geographic region. The buffer-based number of cows in a tract can be estimated using equation (4):

$$\tau_i = \sum_{j=1}^{J} \theta_j n_{ij} \tag{2.4}$$

where, τ_i represents the buffer-based number of cows in census tract i; θ_j represents the percentage area of the circular buffer surrounding CAFO j that falls within census tract i.

Figure 2 illustrates how the distribution of dairy cows changes when different counting methods are utilized. There are 499 census tracts in New Mexico, 35 of which have at least one major dairy farm, leaving 464 census tracts without large dairy farms. However, when the number of cows in each census tract is rearranged based on the 3-mile buffer, the number of census tracts with major dairy farms climbs to 85, while the other 413 census tracts are located at a significant distance from the large dairy farms. Similarly, the expansion of dairy farms footprint into nearby census tracts due to the buffer has also led to a decrease in dairy cow density in existing census tracts. The 3-mile buffer was established in light of recent studies that show the highly localized nature of CAFO emissions and the resulting health effects (Mirabelli et al., 2006).

A) Count based cows per census tract



B) Buffer based cows per census tract

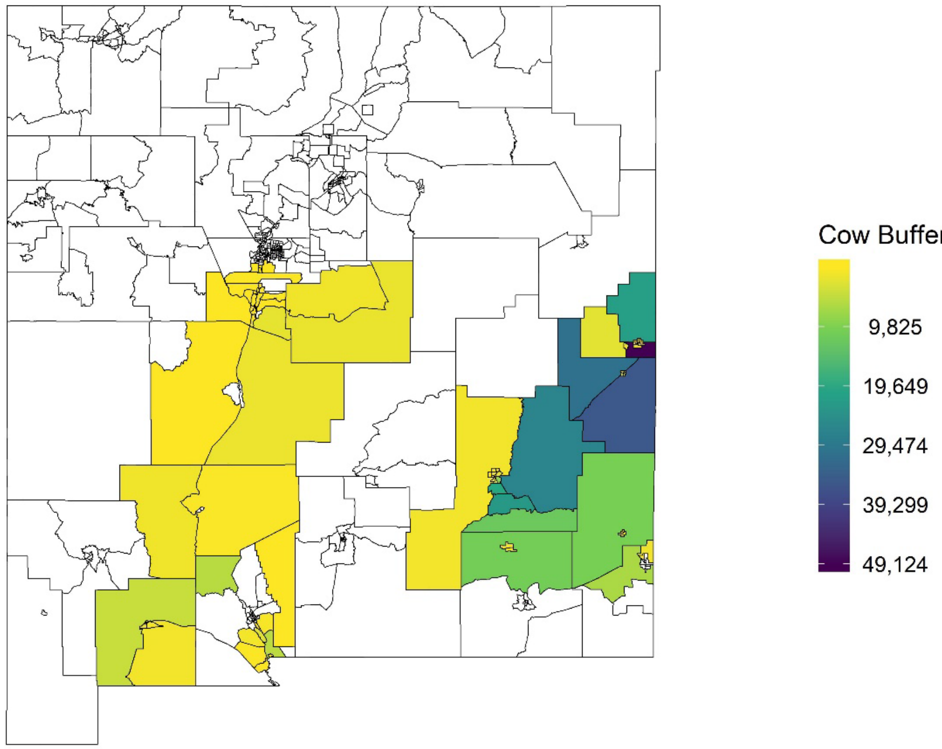


Figure 2.2: A) Map of New Mexico showing total number of dairy cows per census tract B) Map of New Mexico showing total number of dairy cows per census tract based on the 3-miles buffer apportionment.

Similarly, we created a direct measure of exposure based on the actual concentration of ammonia as shown in Figure 1b. The satellite data of Ammonia concentration at a resolution of 0.01 degrees was averaged across census tract to create a comparable variable across a consistent spatial scale. For instance, consider a census tract i, the average ammonia concentration in the tract can be estimated using equation (5):

$$\mu_i = \frac{\sum_{k=1}^{K} r_{ik} c_{ik}}{\sum_{k=1}^{K} c_{ik}} \tag{2.5}$$

where, μ_i represents the area-weighted average of raster values for census tract i, r_{ik} represents the raster value for a specific cell k $i$ntersecting census tract i, and c_{ik} represents the fraction of the cell's area covered by census tract i. A raster value represents a particular attribute, such as ammonia concentration. A cell refers to a single, square, or rectangular area within the larger grid of the map. The spatial resolution of the data dictates the location and size of a cell. For instance, at a resolution of 0.01 degrees, a cell covers an area of roughly 1.56 square kilometers or 1.11 km × 1.41 km in New Mexico.

2.4.3 Assessing Disproportionate Exposure

We begin our statistical analysis by calculating the descriptive statistics for each exposure indicator. Then, a proportionate circle representation map of the major dairies in New Mexico is created. Using Van Damme et al. (2018) data, we also generate a map of the ammonia concentration throughout New Mexico. Next, a column graph is created depicting the average value of environmental justice indicators across dairy and non-dairy census tracts for the years 1990 and 2019. We use a buffer-based number of cows per census tract to construct column graphs. Finally, a Spearman rank correlation analysis is performed to determine the relationship between each exposure indicator and environmental justice indicators. One advantage of using Spearman rank correlation is that it does not restrict the distribution of explanatory and dependent variables.

To assess the relationships between average ammonia concentrations and the environmental justice indicators for each census tract, we used Spearman's correlation coefficient. Spearman's rank correlation is a nonparametric statistic that transforms variable values to rankings before computing correlations as in equation (6). The value of ρ lies between 1 (a perfect direct correlation) and -1 (a perfect inverse correlation). The closer ρ is to 1, the greater the monotonic association, whereas close to 0 implies no correlation between the two variables.

$$\rho = 1 - \frac{6\sum d^2}{n(n^2-1)} \tag{2.6}$$

Where:

ρ = Spearman's rank correlation coefficient

d = R(X) – R(Y) is the differences between the rankings of two observations.

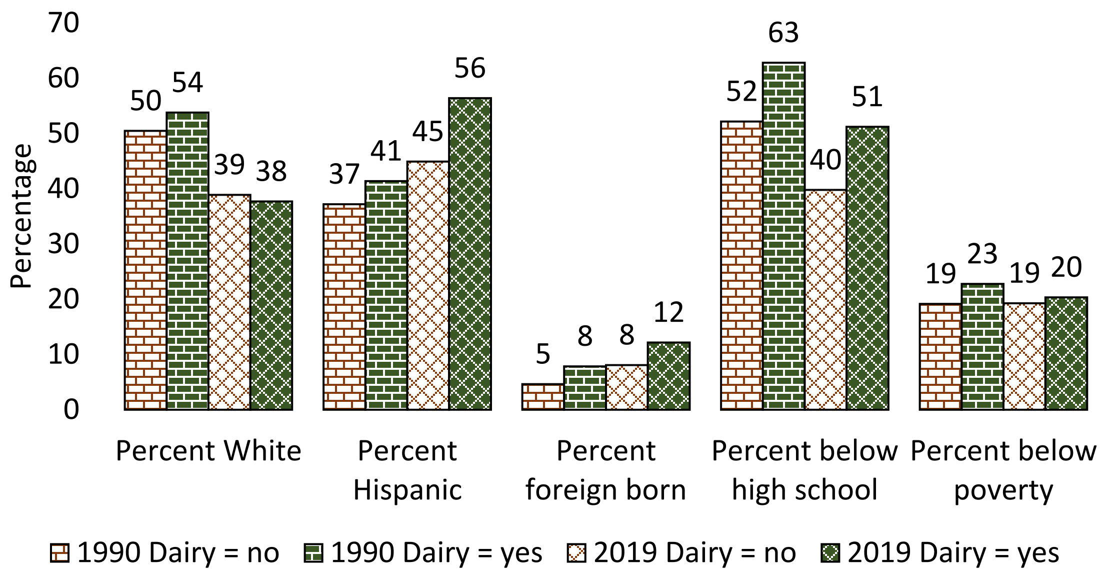
n = the number of observations

2.5 Results

Figure 3 compares the mean values of seven Environmental Justice indicators in dairy and non-dairy census tracts between 1990 and 2019. Panel A depicts the graph for socioeconomic factors expressed in percentage terms, whereas Panel B depicts the graph for dollar-denominated variables adjusted for 2019 dollars. In 1990, New Mexico had fewer and smaller dairies with less impact on health and the environment. By 2019, large dairies had already entered and expanded in New Mexico and had been reported to have a disproportionate impact on the health and environment of neighboring communities. The dairy vs non-dairy distinction for census tracts in

2019 and 1990 is based on 2019 numbers, the only year out of which comprehensive and reliable dairy data is available. In other words, a 1990 dairy census tract may or may not have contained large dairy farms in 1990, but it is home to large dairy farms in 2019. Similarly, the 1990 non-dairy census tract did not have large dairy farms in 2019 but may or may not have had large dairy farms in 1990.

A) Environmental Justice Indicators in percentage values



B) Environmental Justice Indicators in dollar terms

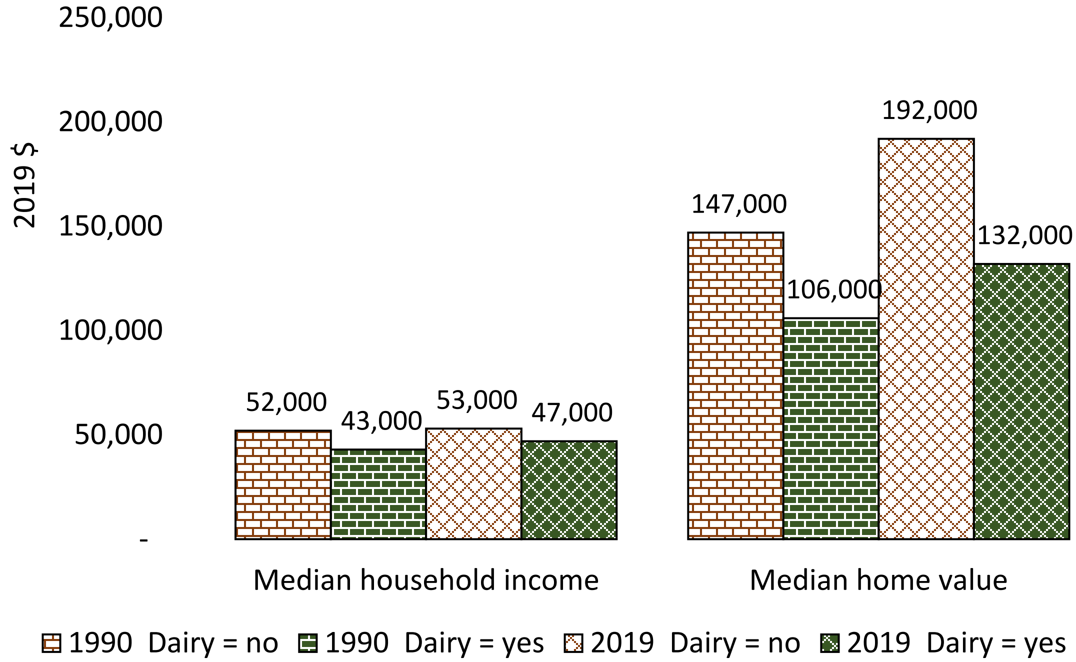


Figure 2.3: Distribution of environmental justice indicators for census tracts with and without dairy farms in 2019, compared to the same census tracts in 1990 A) shows the percentage indicators, while B) shows the dollar-denominated indicators.

The results show that the share of non-Hispanic Whites in census tracts has been going down steadily over the last 30 years. A higher percentage of Hispanics live in dairy census tracts than in non-dairy census tracts. Similarly, dairy census tracts have had consistently higher poverty levels, lower median incomes, and lower median home values in both the periods. However, poverty rates have been declining at a higher rate in the dairy census tracts compared to non-dairy census tracts which have not seen much improvement over the last three decades. The notably lower values of most environmental justice indicators across the dairy census tracts in 1990 suggests that dairy farms may have strategically selected these regions for consolidation due to economic or political factors. However, the relatively higher economic growth in dairy regions over the past three decades highlights the potential economic benefits of dairy farms in rural areas, suggesting a complex interplay between environmental impact and economic development.

Table 3 shows the correlation between exposure and environmental justice indicators for 1990 and 2019. The correlational analysis validates the visual evidence presented in Figure 3. In 2019, the association between the percentage of Hispanic residents and the level of exposure to dairy farms or ammonia in a census tract was stronger than in 1990, as measured by the correlation coefficient of all exposure indicators. In fact, the count and buffer indicators do not indicate any statistically significant correlation between the percentage of Hispanic population and large dairy farms in a census tract in 1990. Similarly, the correlation test using the ammonia concentration indicators shows a weakly positive association between the percentage of Hispanics and ammonia concentration in 1990 which becomes moderately positive in 2019. Similarly, the percentage of non-Hispanic whites exhibits an opposite pattern, which had a marginally positive correlation with the dairy presence in 1990, which becomes marginally negative and statistically insignificant in 2019. This suggests a greater immigration rate, a higher birth rate, or a lower death rate among the Hispanic population in the dairy census tract, or a higher emigration rate, a lower birth rate, or a higher death rate among the non-Hispanic population in the dairy census tract, or a combination of both. However, without granular individual-level data, no conclusions can be made.

Table 2.3: Correlation between exposure indicators and environmental justice indicators for 1990 and 2019

	Count		Buffer		Ammonia	
Year	1990	2019	1990	2019	1990	2019
% White	0.06	0.02	0.05	-0.02	0.11***	-0.08
% Hispanic	0.04	0.11***	0.07	0.19***	0.22***	0.43***
% foreign born	0.18***	0.18***	0.20***	0.23***	0.45***	0.46***
ICE for race	0.00	-0.06	-0.01	-0.12***	-0.03	-0.29***
% below high school	0.18***	0.24***	0.23***	0.27***	0.04	0.15***
% below poverty	0.14***	0.08*	0.16***	0.06	-0.01	0.02

Median household income	-0.13***	-0.05	-0.17***	-0.10	0.01	-0.03
Median home value	-0.21***	-0.16***	-0.27***	-0.24***	-0.08*	-0.12***

Note: * , **, and *** denote statistical significance at the 0.05, 0.01, and 0.001 levels, respectively.

Similarly, ICE for race does not seem to be a significant determinant of exposure based on the count method. However, when we look at the buffer indicator from 2019, we can see a greater spatial concentration of the deprived group (Hispanic) in the region surrounding dairy farms. This disproportionately higher spatial polarization is even more evident if we examine the ammonia concentration indicator from 2019. The absence of a statistically significant spatial polarization in 1990, and the subsequent notable spatial polarization in 2019, with a disproportionate proportion of the deprived group exposed to higher ammonia levels, suggest that it is improbable to be a coincidental occurrence.

There is also a positive association between the degree of exposure and the percentage of a census tract's population with less than a high school diploma. The percentage of foreign-born individuals in a census tract is also highly correlated with the intensity of pollution exposure for all three exposure indicators. The median value of home is also lower in census tracts with higher concentration of dairy cows or higher ammonia concentration. However, the association between the percentage of the population below the poverty line and the median household income does not appear to be consistent across the exposure indicators. While both the magnitude and direction of the association between income and poverty rate with the exposure indicators appear to be as expected for indirect exposure indicators, the evidence for the relationship between ammonia exposure and poverty or income is not established. Observing the temporal trends in the count and buffer measures, we can deduce that the median household income and poverty rates have improved over time. However, no significant association can be drawn when we observe the same trend for the association with ammonia concentration data.

2.6 Discussion and Conclusion

We employed GIS and spatial statistical tools to investigate the association between the distribution of CAFOs in New Mexico and several socioeconomic indicators that would indicate the existence or absence of environmental injustice. The findings indicate that disadvantaged demographic groups are overrepresented in dairy-concentrated regions and disproportionately exposed to dairy-borne pollution. Over the past three decades, the percentage of Hispanics has increased significantly across dairy-producing regions while the population of non-Hispanic Whites has fallen.

This study's results are similar to the findings of a small number of studies analyzing environmental injustice in CAFO siting in relation to the Hispanic population, which reveal a larger percentage of Hispanic people in communities near CAFOs (Horton, 2012; Lenhardt & Ogneva-Himmelberger, 2013; J. Son & Bell, 2022; J.-Y. Son, Muenich, et al., 2021). Hispanics are New Mexico's largest ethnic group; therefore, it stands to reason that their population would be larger than in other states independent of CAFOs. However, despite their larger overall presence, Hispanics are disproportionately represented in census tracts with CAFOs.

Hispanic immigrant employees are more likely to be employed in CAFO operations due to a possible match between their skill sets and the nature of the employment (Arcury & Marín, 2009; Imhoff, 2010; Lenhardt & Ogneva-Himmelberger, 2013). To corroborate this, we conducted a correlation analysis and observed a statistically significant association between the proportion of foreign-born inhabitants in a census tract and the presence of CAFOs. The degree of this correlation increases when we move from the indirect exposure indicator to the direct exposure indicator. This also supports the claims of previous studies that the immigrant population may not only be inconvenienced by living close to CAFOs but may also be doubly exposed due to working in the CAFOs (Lenhardt & Ogneva-Himmelberger, 2013). However, the percentage of the foreign-born population in dairy concentrated census tracts has stayed steady over time, suggesting that technical advancements in dairy techniques may have decreased the need for immigrant laborers. Future research is needed to explore the causality.

The findings also show that most of New Mexico's dairies are located in economically disadvantaged areas with low median household income, a lower percentage of high school graduates, median home values, and a higher percentage of the population living under the poverty line. This conclusion is comparable with previous studies conducted in dairy, poultry and swine-concentrated regions (Wilson et al 2002, Son et al. ER 2021, Hall et al 2021). A lower value for each of these socioeconomic indicators is correlated with rurality. It should not be construed as a cause or consequence of the existence of large dairy farms unless there is conclusive data to support such an interpretation. In fact, our longitudinal analysis of the data reveals that census tracts containing dairy farms have had stronger socioeconomic progress over the last three decades, indicating that dairy farms may be instrumental in creating wealth and employment opportunities in impoverished areas.

New Mexico is among the top ten states for dairy production and has the largest average dairy herd size. Consequently, there are issues regarding air, water, and soil pollution, as well as the annoyances from odor and the loss of aesthetic appeal in the areas near large dairy farms. Furthermore, as a significant body of research demonstrates, disadvantaged groups are likely to bear the brunt of these nuisances. This is one of the first studies to analyze the distributional concerns of large dairy farms in the southwestern United States within the setting of a majority-minority state. We have also provided a few methodological contributions to studying environmental justice across time and space. We have compared the findings from before and after the proliferation of dairy farms to determine how these farms have altered the demographic landscape of these regions.

Similarly, we have used seven environmental justice indicators to examine the disparities. To our knowledge, this is the first study to employ the Index of Concentration at the extremes as one of the environmental justice indicators to examine the environmental justice concerning the CAFO facilities. Furthermore, we have allowed future research to utilize satellite-derived pollutant concentration data as a direct measure of pollution exposure instead of proxy measures such as the actual count of the facilities or area-weighted count of the facilities or animal units. The findings of this study underscore the need to integrate health and environmental equity considerations into the policy framework not only to policymakers in the state of New Mexico but also to stakeholders and activists in other regions experiencing the same predicament.

When addressing problems of environmental injustice, it is necessary to consider the efficiency-equity trade-off by evaluating costs and possible benefits. Additionally, we must use care to prevent inciting another type of injustice or inequality while solving one. Currie et al. (2020) found that throughout the previous two decades, initiatives such as the US Clean Air Act that prioritize the remediation of the most polluted regions had the most impact on closing the racial disparity in pollution exposure. Thus, we can argue that a renewed emphasis on the best nutrient management practices, the recognition of ammonia as one of the primary pollutants, and the implementation of prevention and abatement measures could help us achieve the dual objectives of reducing overall pollution levels and reducing existing inequities. Ammonia is responsible for more than half of the nitrogen deposition and particulate matter formation in and around high livestock density regions (UNECE, 2021). Co-benefits of ammonia abatement might also be achieved from the more effective nitrogen absorption by plants, as well as reduced co-emissions of other toxins and pollutants resulting in a positive impact on air, water and soil quality, as well as climate, and biodiversity. The societal benefits of decreasing ammonia levels seem to surpass the costs of inactivity; hence, reducing ammonia levels is not just a moral obligation but also an economic argument.

Despite its documented ecological and human health consequences, USEPA does not regulate ammonia as a criteria air pollutant. Satellite observations and ground-level measurements have shown North America to be a zone of intense ammonia emissions (Yao & Zhang, 2019). This occurs at a time when the majority of air pollutants and PM 2.5 precursors, such as NOx and SO2, have seen significant emission reductions throughout the US (Currie et al., 2020). The European Union (EU), whose stricter air pollution regulations have not hampered economic development, may serve as a model for the US. While the GDP of the EU expanded by 32% between 2000 and 2017, agricultural ammonia emissions declined by 10% (European Commission, 2021). To decrease risks to human, animal, and ecosystem health, the most current Zero Pollution Action Plan under the European Green Deal has specifically targeted ammonia reduction from intensive livestock operations (European Commission, 2021). In addition, this new initiative aims to promote fairness and equality by monitoring trends, disparities, and inequalities in the distribution of pollutants regularly and by formulating intervention strategies at EU, national, and local levels (European Commission, 2021). Canada has also classified gaseous ammonia as a Schedule 1 toxin under the Canadian Environmental Protection Act in 1999. It has adopted various national restrictions to limit its emissions, particularly from the agricultural sector (UNECE, 2021). Efforts have been made by the US government to address equity concerns related to environmental harm exposure such as Executive Order 12898 by President Clinton in 1994 and Executive Order 13985 by President Biden in 2021. However, to effectively promote environmental justice, stricter pollutant regulations may be necessary as marginalized communities are often the most impacted. Therefore, the US should consider following the lead of the EU and Canada by developing more comprehensive policies to control ammonia emissions from agricultural sources and promote equity in pollutant distribution.

The choice and efficacy of interventions to reduce ammonia emissions may vary depending on local conditions and farming practices. A range of physiochemical processes such as membrane filtration (Zarebska et al., 2015), photocatalysis (Altomare et al., 2012), air stripping (Yao & Zhang, 2019), ion exchange (Gurreri et al., 2020), wet scrubbing (Hadlocon et al., 2015), chemical precipitation (Cerrillo et al., 2015), and electrodialysis (L. Shi et al., 2018) have demonstrated technical feasibility (S. Shi et al., 2022). In addition, biological-based techniques such as activated sludge(Montes et al., 2015), biochar adsorption (Kizito et al., 2015) and microalgae production (Joshi & Wang, 2018), have also shown promise. Covering manure during storage and switching to low-emission manure application methods like pumping manure onto grasslands or agricultural land may result in measurable reductions in ammonia emissions for regions that have never implemented any ammonia abatement practices. However, reactive nitrogen can enter the environment through various pathways, not just ammonia emissions. The leaching of nitrate into water sources as well as the emissions from agricultural land as nitrogen oxides are some other ways nitrogen can be lost to the environment. Therefore, an integrated policy framework is needed to ensure that measures to reduce ammonia do not exacerbate other nitrogen-related issues. For example, while deep injection of manure on grassland can reduce ammonia emissions, it may increase the risk of leaching nitrate to groundwater (UNECE, 2021). Thus, multi-objective approaches of manure treatment such as anaerobic digestion of manure coupled with nutrient separation can be a viable solution. These systems can not only mitigate greenhouse gas and nutrient releases into the environment, but also provide economic opportunities to the local population through the sale of byproducts such as biogas, fibers and fertilizers.

Some additional caveats to consider when interpreting our results include the following. First, although we have identified the distributive issues associated with CAFOs in the state, we cannot assertively argue that these two occurrences are causally related. Environmental justice literature have identified two distinct factors: siting and sorting or their combination as root causes of environmental inequities related to pollution exposure (Mohai & Saha, 2015). The changing demographics that our study found could be caused by the in-migration or out-migration of various demographic groups, or even the differential birth rate of population groups. Since, we do not have information on the migratory and growth pattern of the population groups or the historical statistics of dairy farms, we are unable to determine why the differences across population groups are getting larger. It is important to note that while we chose to analyze data at the smallest available geographic region with the required data breakdown, this use of aggregated data presents a potential limitation. Specifically, the ecological fallacy may arise due to the mismatch between the spatial scale of analysis and the actual spatial distribution of the population or exposure. This can lead to incorrect or biased conclusions when interpreting the findings. Therefore, future research should aim to address this limitation by incorporating more fine-grained, individual-level data or utilizing alternative analytical techniques that can mitigate this potential source of error. Furthermore, a qualitative assessment of the local population's awareness, perception and experience might help us understand the power dynamics and other intricacies to critically examine the environmental justice landscape, which is otherwise impossible with quantitative assessment alone.

Chapter 3: Health Damages of Dairy Air Pollutant Emissions: An Assessment of New Mexico

3.1 Introduction

Air pollution is a significant environmental health issue and a leading cause of mortality worldwide. Both industrialized and developing nations grapple with this pervasive challenge. Air pollution is the second leading cause of non-communicable diseases such as heart disease, stroke, lung cancer, and birth defects (Prüss-Ustün et al., 2019), killing three times as many people as AIDS, TB, and malaria put together. It also causes 15 times more deaths than all conflicts and other forms of violence (Landrigan et al., 2018). According to the World Health Organization (WHO), almost everyone in the world, precisely 99%, resided in areas with higher levels of pollution than what is recommended (WHO, 2022). Air pollution can be broadly categorized as indoor or household air pollution and outdoor or ambient air pollution. Significant air pollution sources include incomplete combustion of fuels, chemical reactions involving various compounds, wildfires, waste decomposition, and transportation of dust particles. The health damages of air pollution can affect the economy in several ways, including higher medical bills, a lower quality of life, missed work hours, and even death.

Despite concerns regarding the pervasiveness of air pollution, and its impact on our health, there are some silver linings. Air pollution regulations, especially the ones aiming industrial and transportation sector emissions have reduced air pollution levels worldwide, including the US. Attention has therefore rightly shifted to other pollution sources such as agriculture, which remains highly unregulated despite contributing heavily to ambient air pollution. Among the largest agricultural emitters of airborne pollutants are animal farming activities, especially large-scale operations, which emit particulate matter with diameters less than 2.5 micrometers (PM2.5), both directly (primary) and indirectly (secondary) from precursors such as ammonia, nitrogen oxides, and nonmethane volatile organic compounds (Ma et al., 2021b). Ammonia is a significant emission from the livestock sector, capable of transforming into ammonium-containing aerosols, a major constituent of PM2.5 in densely populated regions worldwide (Moravek et al., 2019). Although hydrogen sulfide, ammonia, and some volatile organic matters can harm human health even in their original form, their highly reactive nature and short lifespan result in negligible ambient exposure. Studies estimate that 17,900 deaths in the US each year are due to agricultural production’s impact on air quality (Domingo et al., 2021). Of these deaths, 12,400, or 69% are driven by ammonia emissions, with 80% of these deaths attributable directly or indirectly to livestock production activities such as livestock waste management and production of animal feed.

Following the enactment of the Clean Air Act in 1963 (as amended), air quality has greatly improved in the United States due to lower emissions of criteria air pollutants from various emission sources (US EPA, 2018a). However, agriculture remains a sector with significant potential for emissions reduction. In fact, the release of ammonia from agriculture, primarily from manure storage and fertilizer use, is the largest contributor to total anthropogenic health damages caused by air pollution from all sectors, accounting for 12% of such damages (Goodkind et al., 2019). Thus, reducing emissions from agriculture could represent the final frontier for achieving meaningful improvements in air quality.

The US has over 1.1 million livestock facilities, 55,000 of which are dairy farms (USDA, 2019). The farm sizes corresponding to all major agricultural production have increased in the last few decades. However, the consolidation in the dairy sector has been the most remarkable. In 2017, a typical dairy farm had 1,300 cows, up from 80 cows in 1987 (MacDonald et al., 2018). In comparison to crop cultivation doubling in size, this represents a 16-fold increase in dairy farm size (MacDonald et al., 2020; USDA, 2019). While dairy farm sizes increased, their number decreased by three-quarters. However, total milk output in the United States has increased by 50% over the same period. Economies of scale are the key drivers of this trend, since bigger operations have lower costs and better gross returns owing to more intensive utilization of resources. This is mostly reflected in lower per-unit operating costs related to veterinary services, bedding and litter, energy, repair expenses and interest payment on operating capital. Furthermore, because large farms produce more milk per labor hour, they have lower labor costs per hundredweight of milk produced. Similarly, these farms are more likely to use computerized feed delivery and milking systems, which optimizes the volume and characteristics of milk produced while controlling feed costs.

The dairy farms are not only growing in size but are also concentrating in smaller geographic areas. This proximity enables dairy farms to share infrastructures and transportation networks for efficient milk production and processing, a necessity given the highly perishable nature of milk compared to other livestock products. While smaller farms primarily rely on family labor and integrated milk and feed production, larger farms tend to purchase feed, confine cows in barns and lots, and depend heavily on hired labor. Recently, milk production in the United States has shifted westward, with the western regions' share of total US milk output increasing from 31% in 1992 to 48% in 2017 (USDA, 2019). Several interconnected factors, such as differences in farm size, geographical advantages, and farming practices, are responsible for this shift (Sumner & Wolf, 2002). Although the economic rationale for the restructuring of the US dairy industry is strong, the environmental implications are less clear. High-density cattle herds in dairy producing regions may generate nutrient surpluses, posing challenges for manure management and increasing pollution risks, particularly when there is insufficient cropland nearby for nutrient assimilation. New Mexico exemplifies this trend, with approximately 337,000 dairy cows and a history of recent consolidation. Ranking 9th in the US for total dairy cows, the state's farms have the highest stocking density, averaging 2,357 cows per farm (USDA, 2019). These farms are concentrated in select southern and southeastern counties, where six counties host nearly 90% of the state's dairy cow inventory. This clustering exacerbates environmental challenges, particularly airborne pollution, making New Mexico an ideal study area for assessing the environmental and public health damages of dairy farm consolidation.

The objective of this study is to assess the health damages associated with air pollutant emissions from large dairy farms in New Mexico. We analyze the changes in atmospheric PM2.5 levels through two channels: primary PM2.5 and ammonia, emitted from large dairy farms. To achieve this, we utilize location and animal count data of dairy farms, emission factors, the InMAP Source-Receptor Matrix (ISRM) for each pollutant, population data, and the value of statistical life (VSL). By conducting a series of calculations, we estimate the total health damage, monetary value of these damages, their distribution across impact locations, and the marginal damages per livestock at the emission location.

This is the first study to rigorously quantify the dollar value of damages from CAFOs by combining unique datasets of location-specific farm information and an ISRM matrix accounting for the long-range transport and chemical transformation of the pollutants to provide location-specific estimates of marginal changes in pollution concentration and the resulting health damages. This establishes a case for future researchers to adopt a similar approach to quantify the emissions and damages from other types of CAFOs across other geographies. Through this comprehensive assessment, our study contributes to the understanding of the environmental, health, and socioeconomic impacts of large dairy farms and informs policy development for sustainable livestock production.

3.2 CAFOs and Health

Milk and milk products have high protein, calcium, vitamins, and fatty acids, which are essential parts of a balanced diet. However, questionable dairy farming practices, the sheer size of these operations and ineffective animal waste management may negatively impact the environment. Livestock waste is a complex mixture of chemicals and can generate harmful gases such as ammonia, hydrogen sulfide, and volatile organic compounds (VOCs), particulate matter; nutrients; pathogens; heavy metals and other contaminants (Hribar, 2010). Notably, the dust released by dairy farms is chemically distinct and biologically active compared to other forms of dust, posing a larger risk to human health. Another significant aspect of these wastes is that they may change into solid, liquid, and gaseous forms and negatively impact human health via air, water, soil, and food article contamination. Airborne pollutants can cause respiratory and cardiovascular disorders, while polluted water and food articles can lead to waterborne diseases including cholera, diarrhea, antimicrobial resistance, hormone abnormalities, and heavy metal poisoning, among others.

Few studies have assessed the environmental health impact of the livestock sector in the Southwest, leaving much uncertainty surrounding the possible hazards. Arnold (1999) found that the periphery of dairy farms had three times more flies than areas further away from the farms. Flies are known vectors of diseases such as typhoid, cholera, diarrhea, gastroenteritis, dysentery, anthrax, polio, trachoma, diphtheria, conjunctivitis, and tuberculosis. The study also found that there were higher cases of diarrhea and asthma in children who were exposed to dairy farms. The findings of this study should be interpreted carefully because of a small and non-representative sample. The study could not establish a firm association between dairy farms and air quality. However, the study pointed out the possibility of confounding factors interacting and influencing the results.

A study of North Carolina hog CAFOs identified a positive relationship between hog farms' spatial density in a zip code and many health consequences (Kravchenko et al., 2018). In a zip code with a hog density of over 215 hogs/km2, the incidence of emergency room visits due to kidney disease, tuberculosis, and low birth weights in infants increased by 8%, 30%, and 39%, respectively (Kravchenko et al., 2018). Another comparable study of North Carolinian hog and poultry operations shows that hog CAFOs' spatial density and proximity to poultry CAFOs had a statistically significant effect on birth outcomes (C. Wang, 2020). The study also suggested new directions for future research by bringing up the possibilities of alternate channels of exposure pathways to human beings.

A study by Williams et al., (2011) conducted in Yakima Valley, Washington found that cow allergen concentrations were four times higher in homes located closer to dairy operations (0.5 miles), compared to homes located more than 2.5 miles away. Ammonia concentrations were also higher in homes closer to dairy operations, with concentrations decreasing as distance from the dairy increased. PM concentrations did not show any significant differences between homes located at different distances from dairy operations. The results suggest that while allergens and ammonia are highly localized in terms of their concentration, PM2.5 can be transported over a relatively longer distance and affect the health of individuals.

Wing et al., (2008) examined the relationship between industrial swine operations and air pollution and odor in surrounding communities. The study focused on North Carolina, which has a high concentration of swine operations, and collected data on air pollution and odor from homes near the operations. The authors found that homes located closer to industrial swine operations had higher levels of hydrogen sulfide, ammonia, and particulate matter, which can have negative health impacts on nearby residents. Additionally, residents reported higher levels of odor annoyance and respiratory symptoms in areas closer to swine operations. The paper highlighted the need for more regulation of industrial animal operations to protect the health of nearby residents. The authors suggest implementing measures such as increased setback distances, better ventilation systems, and using alternative waste management methods to reduce the impact of animal operations on air quality and community health.

O'Connor et al., (2010) examined the association between proximity to animal feeding operations and the health of individuals living nearby. The systematic review assessed nine studies published until 2008. The study found inconclusive evidence of increased allergies among individuals with prior history. A cause-effect relationship could not be established between the health impacts and exposure variables in the review. Nachman et al., (2017) questioned the validity of this review owing to their use of a biased method of analysis, omission of key studies, and the inaccurate interpretation of the results. While systematic reviews and meta-analysis are considered gold standards of medical and epidemiological research, the serious allegations by prominent scholars regarding the misrepresentation of the facts diminish the value of this systematic review. This further demonstrates the contentious nature of this topic as well as the need for a rigorous scholarship to unravel the actual implications of consolidation in the livestock sector.

Thorne, (2007) in their review article examined the potential hazards associated with CAFOs and presented various strategies for reducing environmental and health impacts of the operations. Thorne also explored the regulatory framework for CAFOs in the US and noted the gaps in the existing regulations that allowed for the continued release of pollutants into the environment. The author also outlined various strategies to reduce the environmental and health impacts of CAFOs. Similarly, another monograph from the same series by Bunton et al. (2007) addressed several strategies for monitoring and modeling the emissions from CAFOs. The study's primary suggestion was to extend monitoring networks throughout the nation and to incorporate satellite data to supplement and interpolate observations from monitoring networks. The importance of identifying background levels of pollution to have a better understanding of how concentration fluctuates inside, and outdoors were also emphasized. The study also recommended further research to identify and evaluate the most suitable modeling of CAFO emissions that takes into consideration chemical transformation of pollutants such as ammonia and hydrogen sulfide.

CAFOs play an important role in modern society by creating jobs, stimulating rural economies, and promoting food security. They may, however, degrade environmental quality and public health. Livestock waste may pollute the air, water and soil and then enter the human body through those channels, impacting human health. Several studies have found an increase in diseases and health issues in communities near CAFOs. Existing research in the epidemiology and environmental fields provides some insights into the issue and its extent; however, specialty studies addressing distinct demographic and geographic settings are still needed. Furthermore, as previously stated, there is a need for studies that consider the chemical transformation of pollutants and how those pollutants harm human health using concentration-response functions. This study aims to bridge the knowledge gap and contribute to the existing literature by examining the human health effect of CAFOs in the context of an arid and semiarid region unique to the Southwest. By combining location-specific farm information and an InMAP Source-Receptor Matrix (ISRM) that accounts for long-range transport, dispersion, and chemical transformation of dairy emissions into potent pollutants capable of affecting human health, this study rigorously quantifies the economic value of damages attributable to CAFOs.

3.3 Data

Our study incorporates the following three major data sets: 1) data on dairy farms, 2) the InMAP Source-Receptor Matrix (ISRM), and 3) demographic data of receptor grids. Each of these data sets is explained in detail below. Data related to dairy farms is obtained from The New Mexico Environment Department, which includes the geographic coordinates and total discharge volume of all agricultural enterprises that are required to obtain a discharge permit. This list is then meticulously combed through to exclude non-dairy enterprises and cross-referenced with other data sources, such as Google map and online business directory. The total number of cattle per farm is then calculated by dividing the total discharge volume by 40, which is the total water used for consumption and cleaning purposes, per cow on a typical dairy farm. This information is then utilized to estimate the yearly ammonia output of each farm.

Our second dataset is generated using InMAP. InMAP (Interventional Model for Air Pollution) is a model that simulates the dispersion and impact of air pollutants on human health. The exposure to air pollution is estimated using a mix of data on emissions from different sources, meteorological data, and information on population density. The output from InMAP is generated as a source-receptor matrix (ISRM). This matrix illustrates the link between the sources of air pollution (e.g., power plants, industries, roadways, etc.) and the receptors (e.g., individuals, census blocks, etc.) impacted by that pollution. The matrix may be used to evaluate the health effects of pollution by calculating the exposure of receptors to pollutants from each source. In this study, the ISRM matrix developed by Goodkind et al. (2019) is used to estimate the marginal and total health damages across continental United States due to the emissions from large dairy farms in New Mexico. Among the several pollutants generated by dairy farms, our study focuses on ammonia, which interacts with other chemical species in the atmosphere to form secondary PM2.5 in the environment.

Goodkind et al. (2019) constructed the ISRM by running InMAP over 150,000 times, each time entering a one-tonne change in emission from a single grid cell. Each run of InMAP illutrates the effect of a 1-t change in emission at the source on PM2.5 concentrations at each receptor grid cell in the model. This procedure is performed on each of InMAP's 52,411 grid cells implying that there are 52,411 receptor grids in total. The grid cell sizes vary from 48 x 48 km in less populated areas to 24-, 12-, 4-, 2-, and 1-km sides in more populous regions. Likewise, the source grids corresponding to emission location (large dairy farms) are identified using the dairy farm's geographic coordinates. On the basis of this information, 132 dairy farms in New Mexico were assigned to 22 source grids. The total emission per source grid was calculated by aggregating the yearly ammonia emissions from each dairy farm inside that grid cell, where the number of cows was multiplied by the ammonia conversion factor.

Demographic data of the United States and correspondingly constructed grid cells are collected from US American Community Survey, using a five-year average of census block groups from 2008-2012. The Center for Disease Control National Center for Health Statistics county-level mortality data served as the baseline incidence while determining changes in the mortality due to exposure to PM2.5.

In addition to these three primary datasets, we also refer to parametric estimates from a variety of past studies to aid our estimation of health damages. The mean annual daily ammonia emissions at a dairy farm are assumed to be 82 g per day per animal (Grant et al., 2020). Similarly, the mean annual daily PM2.5 emissions at a dairy farm is assumed to be 0.34 grams per day per animal (Habib et al., 2022). These emission factors are reflective of the arid Southwest region of the United States, where an open-lot approach for livestock management is frequently used. We follow Krewski et al. (2009) to derive the concentration response function for the estimation of health damages. Similarly, the VSL is derived from the Environmental Protection Agency's (EPA) recommended value, which has been adjusted to 2022 USD.

Table 1: Summary statistics

	Total	*Mean*	*Median*	*Standard Deviation*	*Max*	*Min*
Dairy cows (heads)	202,415	1,533	1,200	1344	9,000	40
Ammonia emissions (tons/year)	6,058	46	36	40	269	1
Primary PM2.5 emissions (tons/year)	27.73	0.21	0.16	0.016	1.23	0.005

There are a total of 132 large dairy farms in New Mexico housing a total of 202,415 dairy cows in 2020. An average dairy farm in New Mexico has 1,533 cows, while the median number of dairy cows per farm is 1,200. These farms generate 6,058 tons of ammonia annually, of which a fraction is converted to PM2.5. The average ammonia emission per farm is 46 tons per year, with a range between 1.2 tons and 269 tons per year. Similarly, dairy farms in NM generate 27.73 tons of primary PM2.5 per year. An average farm emits 0.21 tons of primary PM2.5 per year and it ranges between 0.005 to 1.23 tons per year.

3.4 Methodology

To assess the total health damages of dairy air pollutants, their distribution and marginal health damages per animal at the source-grid level we use a combination of ISRM matrix, concentration response function and demographic data.

We look at a livestock sector with CAFOs holding the same animals that emit $k = 1,2, \dots, K$ types of pollutants. The emission factor of each pollutant is η^k tons/animal/year.

The ISRM matrix for each pollutant: an $n \times n$ square matrix

$$\boldsymbol{R}^k = \left(r_{i,j}^k\right)_{n\times n} \tag{3.1}$$

where the element $r_{i,j}^k$ in the matrix gives the value of the marginal change in the PM concentration at receptor grid j for a marginal emission of pollutant k in source grid i.

3.4.1 Assessment of Health Damages from Existing CAFOs

For an animal in any source grid i, the marginal change in the PM concentration at any receptor grid j is given by the element $c_{i,j}$ in the $n \times n$ square matrix.

$$\boldsymbol{C} = \sum_{k=1}^{K} \eta^k \boldsymbol{R}^k \tag{3.2}$$

Given existing CAFOs with animals $\boldsymbol{x} = (x_1, x_2, \dots, x_n)^T$ across the source grids, the changes in the PM concentration at the receptor grids is given by the $n \times 1$ vector.

$$\boldsymbol{F} = \boldsymbol{C}\boldsymbol{x} \tag{3.3}$$

where f_j is the changes in the PM concentration at receptor grid j.

To link the changes in PM concentration at a receptor grid with the changes in health damages, we utilize a concentration response function. Health damages can manifest in multiple forms such as physical and mental debilities and even death. Given the high value attributed to the VSL and the relatively lower value of cost of illnesses, an overwhelming majority of health damages from PM2.5 concentrates around premature mortality. Consequently, this aspect will be the exclusive focus of our investigation. In order to better comprehend the intricate interplay between particulate matter concentration and all-cause mortality, we embrace an exponential concentration response function, devised by Krewski et al., (2009). The relationship is defined as:

$$\mu = e^{\gamma f_j^k} \tag{3.4}$$

Where, γ = 0.00583 is the log-relative risk of mortality due to PM2.5 changes. This means with each 10 µgm^{-3} increase in PM2.5, the relative risk of mortality increases by approximately 0.6%, holding everything else constant.

Let a_j denote the population at receptor j and $\bar{\lambda}_j$ the baseline mortality rate at receptor j. The change in mortality at receptor grid j due to the existing CAFOs is:

$$d_j = a_j \bar{\lambda}_j (\mu - 1) \tag{3.5}$$

The change in total mortality across all receptor grids due to the existing CAFOs is:

$$d = \sum_{j=1}^{n} d_j \tag{3.6}$$

Assume v is the value of a statistical life. The monetary value of the damage (i.e., the change in mortality) due to the existing CAFOs is:

$$z = vd \tag{3.7}$$

Alternatively, we can estimate the damages from each pollutant and sum across pollutants to get the total damage. This way we can disaggregate the total damage by each pollutant (to compare damages from ammonia vs. those from PM):

$$\boldsymbol{C}^k = \eta^k \boldsymbol{R}^k$$

$$\boldsymbol{F}^k = \boldsymbol{C}^k \boldsymbol{x}$$

$$d_j^k = a_j \bar{\lambda}_j \left(e^{\gamma f_j^k} - 1 \right)$$

$$d^k = \sum_{j=1}^{n} d_j^k$$

$$z^k = vd^k$$

$$z = \sum_{k=1}^{K} z^k \tag{3.8}$$

3.4.2 Distribution of Health Damages via Downwind Concentration Mapping

To comprehend the spatial distribution of health damages, it is essential to examine the changes in PM2.5 concentration across the receptor grids. This metric provides an indication of the extent and intensity of exposure to PM2.5, and by extension, the potential health damages associated with such exposure. The distribution of health damage d_j across receptor grids is given by the individual $n \times 1$ vector f_j.

A three-panel figure is created to provide a macroscopic perspective of the distribution of PM2.5 concentration changes across the contiguous Unites States. Moreover, each panel in the figure also elucidates the relative contribution of each pollutant, as well as the pollutant-specific mechanisms underlying these distribution patterns.

3.4.3 Marginal Health Damage per Animal at the County Level

The marginal change in mortality across all receptor grids for an additional animal in source grid i is:

$$m_i = \sum_{j=1}^{n} a_j \bar{\lambda}_j (e^{\gamma c_{i,j}} - 1) \tag{3.9}$$

The monetary value of the damage (i.e., the marginal change in mortality) from an additional animal in any source grid i is:

$$w_i = vm_i \tag{3.10}$$

The locations of each farm are matched with counties to report the range of w for each county.

3.5 Results

We begin by delineating the ramifications of existing dairy farms on human health. We engage in a comprehensive assessment that links the increasing concentration of PM2.5 - a pollutant emanating from these CAFOs - with the associated health damages. This analysis is primarily facilitated by two illustrative tools, Figure 3.1 and Table 3.1, which expound on the geographical distribution of dairy farms, the ensuing changes in PM2.5 concentration, and the associated health implications.

Our investigation reveals that PM2.5 concentration, and consequently the severity of health damages, are markedly higher in regions proximate to dairy farms, suggesting a localized nature of this issue. More specifically, we observe that ammonia, a major by-product of these operations, contributes significantly to overall health damage. To further explore the spread of these pollutants, Figure 3.2 provides a detailed account of how the PM2.5 concentration changes across the receptor grids due to pollutants induced by dairy farms.

Subsequently, we present a granular analysis of the health damages on a per-animal basis at the county level. Table 3.3 enumerates the estimated monetary value of these marginal health damages for various counties, offering valuable insights that can inform policy decisions regarding dairy farm emissions and public health.

3.5.1 Assessment of Health Damages from Existing CAFOs

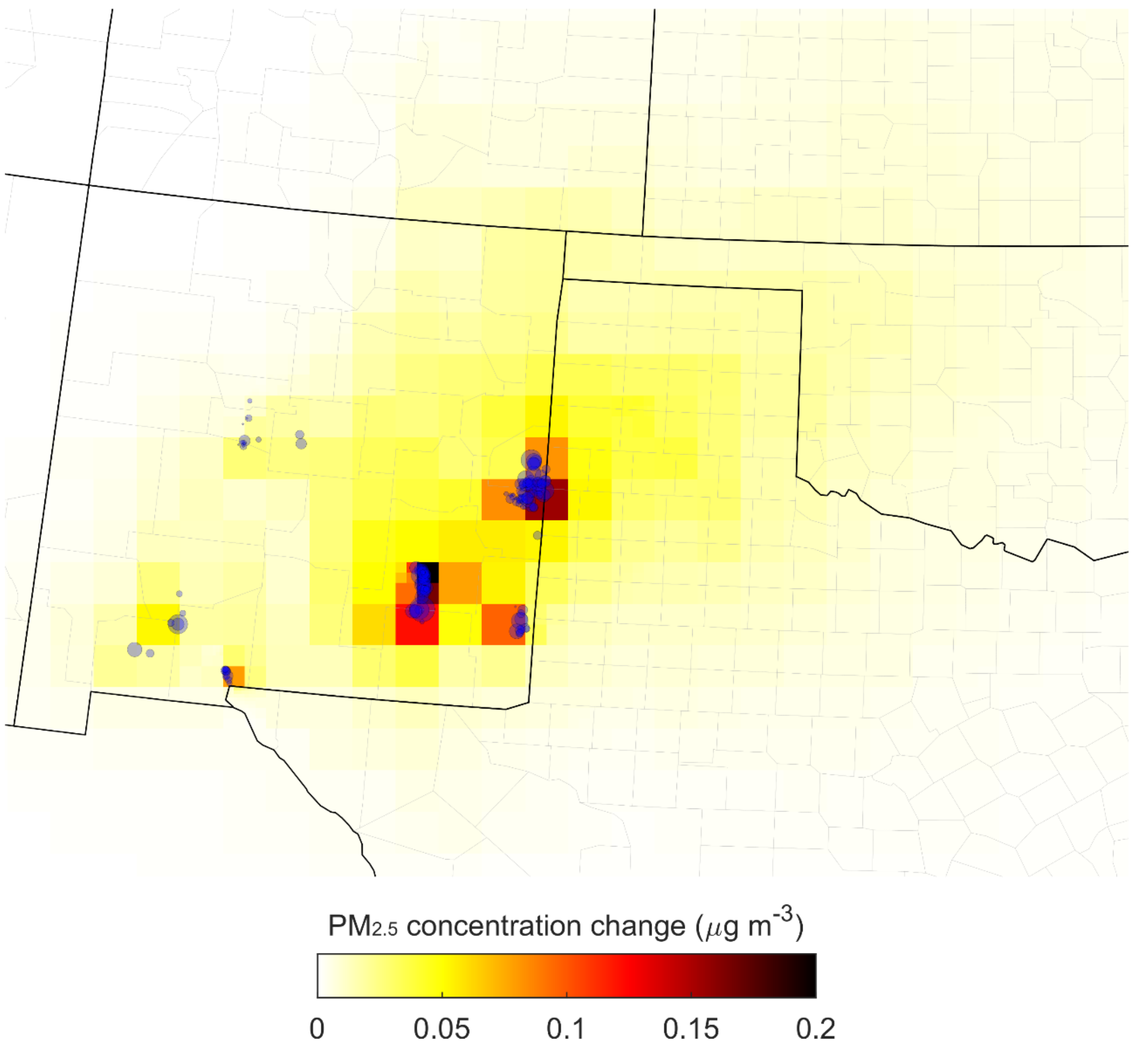


Figure 3.1: PM2.5 concentration changes across the receptor grids along with the dairy farms

Figure 3.1 illustrates the distribution of dairy farms across New Mexico, each represented by a blue circle, the size of which corresponds to the size of the respective dairy farm. The figure also projects changes in PM2.5 concentration, the result of emissions by these dairy farms, across New Mexico, using square grids. The gradation of color intensity aligns with the concentration changes, with darker hues signifying higher PM2.5 concentration and lighter ones representing lower concentration. The figure shows a robust correlation between PM2.5 concentration changes and the proximity of dairy farms. This figure also highlights the localized nature of pollution emanating from dairy farms, with a marked increase in pollution concentration commensurate with the number and size of the dairy farms. This suggests that dairy farm pollution is a localized issue. Additionally, the figure elucidates the wind patterns across the state, indicating a northeastward movement of pollution plumes from the dairy clusters.

Table 3.1: Assessment of health damages from existing CAFOs

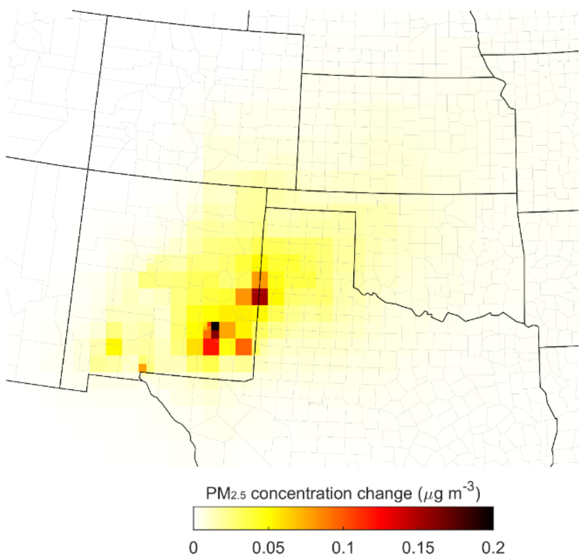
	Total change in mortality due to the pollutant	*Total annual health damages ($)*
Ammonia	12.336 (99.38%)	129,777,248
Primary PM2.5	0.076 (0.62%)	805,704
Total	12.41273	130,581,951

Table 3.1 presents a comprehensive assessment of health damages engendered by emissions from large-scale dairy farms in New Mexico. The table details the impact of two pollutants: Ammonia and Primary PM2.5. The first column elucidates the total mortality changes attributable to each pollutant, whilst the second column quantifies the ensuing health damages in monetary terms. It is observed that the pollutant-induced concentration changes from dairy farms in New Mexico result in approximately 12.41 deaths per year, translating monetarily to roughly $130.6 million. Notably, ammonia is found to have a substantially larger impact on mortality, causing 12.336 deaths, in comparison to primary PM2.5 which accounts for only 0.076 deaths. Consequently, 99.38% of the overall damage can be attributed to the secondary PM2.5 formed

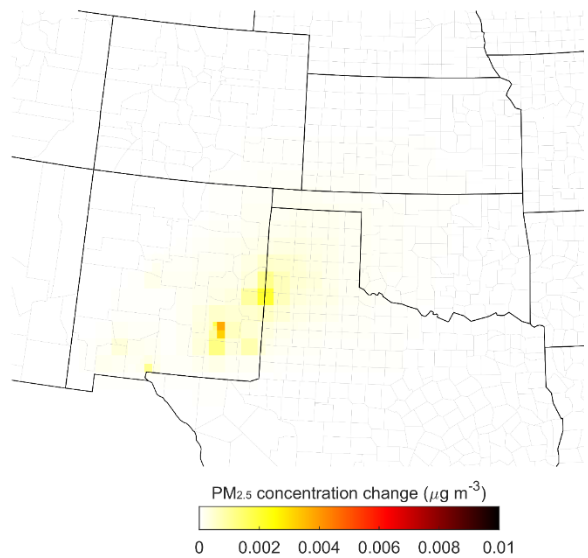
due to ammonia, while a mere 0.62% is ascribed to the primary PM2.5 emissions from dairy farms. These health damages, when evaluated in monetary terms, amount to approximately $129 million for ammonia and a significantly lower $0.8 million per annum for primary PM2.5.

3.5.2 Distribution of Health Damages via Downwind Concentration Mapping

(a): PM2.5 concentration changes across the receptor grids due to ammonia



(b): PM2.5 concentration changes across the receptor grids due to primary PM2.5



(c): Total PM2.5 concentration changes across the receptor grids

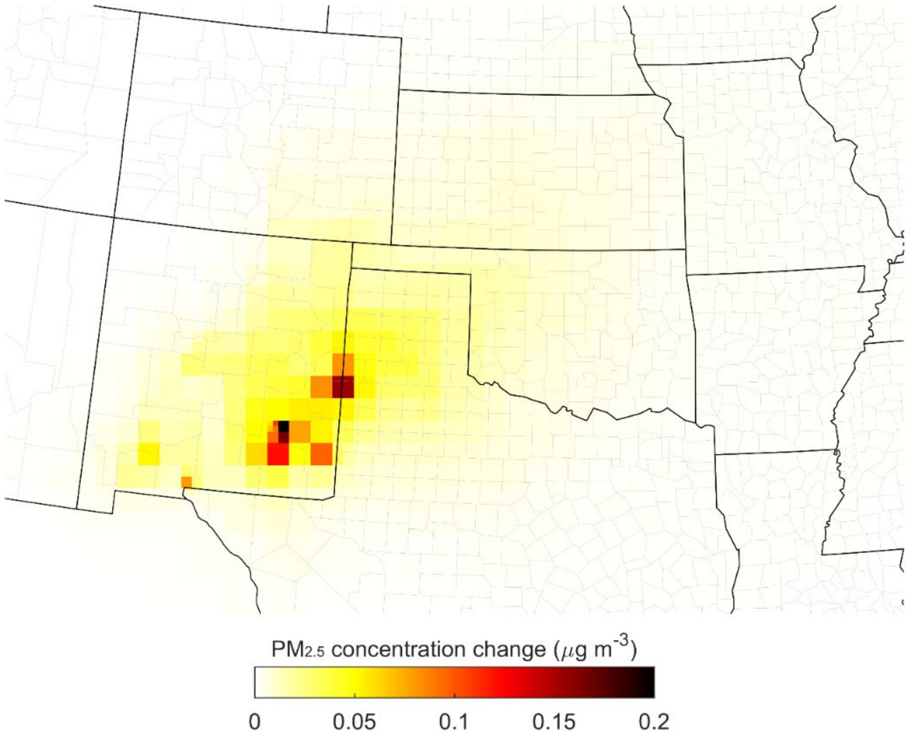


Figure 3.2: Distribution of PM2.5 concentration changes across the receptor grids due to dairy farm induced pollutants

Figure 3.2 further elucidates the distribution of PM2.5 concentration changes across the receptor grids due to dairy farm-induced pollutants. This figure substantiates the results for total concentration change as portrayed in Table 1, offering a broader perspective of the distribution of concentration changes across the contiguous United States.

The figure is divided into three panels, each serving a distinct purpose. Panels A and B of this figure depict the changes in PM2.5 concentration due to ammonia and primary PM2.5 emissions respectively, accentuating that the majority of the changes in PM2.5 concentration can be ascribed to ammonia emissions. It is worth noting that the scales utilized in panel A and B differ, as the impact of primary PM2.5 is imperceptible at the scale of panel A.

Panel C consolidates the information in panels A and B, providing a synthesized view of the total PM2.5 concentration changes across the receptor grids. This visual representation can guide us in understanding the distribution and potential health impact of PM2.5 emissions from dairy farms.

The concentration changes are observed to be highly localized, particularly around the areas proximate to dairy farms. This finding underscores the criticality of implementing effective emission control measures at the source, i.e., at the dairy farms, to mitigate the health damages inflicted by PM2.5 exposure.

3.5.3 Marginal Health Damage per Animal at the County Level

Table 3.3: County level estimates of marginal health damages

County	Monetary value of marginal damage in ($) – Based on the location of dairy
Bernalillo	1,634
Chaves	615-1158
Curry	627-649
Doña Ana	494-720
Eddy	615
Lea	668-815
Luna	494-505

Roosevelt	627-668
Sierra	468
Socorro	586
Torrance	536-631
Valencia	586-1033

Table 3.3 provides county-level estimates of the monetary value of marginal health damages resulting from changes in PM2.5 concentration due to dairy farm emissions. This table lists the counties and their estimated monetary values of marginal damage in dollars, with some counties exhibiting a single value while others have a range. The values reflect the estimated health damages emanating from PM2.5 emissions from dairy farms situated within each county. A discernible trend is the generally higher monetary value of marginal damage in counties with densely populated urban centers. For instance, Bernalillo County exhibits the highest estimated value of marginal damage ($1,634), while Sierra County records the lowest ($468). Counties such as Chaves and Valencia show a broad range of estimated values, implying that health damages may vary based on the specific locations of dairy farms within the counties. Interestingly, Curry and Roosevelt Counties, despite housing a substantial number of dairy farms, exhibit a moderate range of damage values, suggesting that population densities exert a greater influence on these estimates than the actual concentration changes.

Other counties, including Luna, Socorro, and Torrance, present lower to medium estimates of marginal health damages. Simultaneously, counties like Lea and Doña Ana demonstrate a medium lower value with a marginally higher upper value, reflective of their proximity to densely populated areas. The PM2.5 concentration changes are observed to decrease sharply with increasing distance from the dairy farms due to dispersion, thereby reducing the severity of health damages. In summation, this table offers invaluable insights for policymakers and stakeholders alike, encouraging them to contemplate the implications of dairy farm emissions and their impact on public health across these counties.

3.6 Discussion and Conclusion

Dairy farms play a pivotal role in the economy of New Mexico, with their impact also significantly recognized on the national stage. New Mexico is a prominent milk producer ranking ninth in the US in terms of volume of production. It ranks fourth in the country for cheese production producing 958 million pounds of cheese in 2021 which is 6.9% of the US total. Milk is also New Mexico's most important agricultural commodity (USDA, 2022). Dairy products including milk account for more than 52% of NM's livestock cash receipts. In 2021, the state produced 7.8 billion pounds or 907 million gallons of milk generating a total cash receipt of $1.26 billion (USDA, 2022). The annual milk production per cow in New Mexico was 24,541 pounds per cow, which is well above the national average of 23,948 pounds per cow (USDA, 2022).

Dairy farms in New Mexico have a profound economic impact, with each cow generating a cash receipt of $4,315 on average. However, juxtaposed with this economic yield is the associated health cost, which we estimate to range from $468 to $1,634 per cow. This health cost represents a substantial fraction of the cash receipt, varying between 10.85% and 37.87%. It is important to note that while the cash receipts per cow might be similar across dairy farms, the gross income can vary significantly due to differing cost structures. Farms situated closer to urban areas, although smaller in size, bear higher costs due to higher land prices and operational expenses. Interestingly, our study found that the marginal health damage is not intrinsically tied to the size of the farm but is instead influenced by its proximity to populated areas. This is particularly noticeable for farms located in counties such as Bernalillo and Valencia, which are in close proximity to population centers. Given these factors, there exists a compelling argument for the strategic relocation of farms near population centers to more rural areas, a move that could help mitigate marginal health damages while potentially enhancing gross revenue. Further deepening the economic perspective, if we juxtapose the marginal health damages of cows with the cash receipt per gallon of milk, we find that for each gallon of milk generating $1.39 for the farmers, it concurrently incurs a marginal health damage of $0.14.

Despite the apparent high social costs affiliated with milk production, one must consider the underlying rationale for the geographical placement and expansion of dairy farms in certain regions. Farms may have naturally migrated towards jurisdictions with diminished operating costs and potentially lower external costs, primarily driven by concerns surrounding regulatory repercussions. Alternatively, they could have been drawn to areas where the livestock sector is already significantly established, suggesting the existence of agglomeration economics (Isik, 2004; Krugman, 1992). Studies investigating the location choices of livestock farms have also proposed the pollution haven hypothesis, suggesting that decisions on the siting of livestock farms may be largely influenced by the objective to reduce environmental compliance costs (Herath et al., 2005; Isik, 2004). However, as these farms relocate to less-regulated jurisdictions, they inadvertently introduce similar externalities in their new locations, thereby inciting calls for regulations in these novel jurisdictions. This dynamic resembles a regulatory game of 'whack-amole', with dairy farms pursuing the path of least resistance, gravitating towards regions where regulations are most lenient. Consequently, while the monetary value of health damages in New Mexico may seem elevated, it is plausible that they are even higher in other states. Our study supports this notion, demonstrating that health damages resulting from dairy-derived emissions are amplified in regions with denser populations. New Mexico, characterized by a sparser population, particularly in rural areas where the majority of dairy farms reside, exhibits high productivity in its dairy farms, potentially attributable to factors such as favorable climate and feed availability. Therefore, policy formulation should not solely concentrate on the marginal costs, but also recognize the marginal benefits of dairy production.

However, it is paramount to acknowledge the limitations within our study. Our analysis primarily focuses on the transportation and transformation of emissions from dairy farms, computing the associated health damages. We have not incorporated other significant environmental and health detriments, such as water pollution, odors, ecosystem damage, greenhouse gas emissions, and the propagation of pathogens and parasites. Furthermore, our analysis only encompasses a subset of air pollutants emitted from dairy farms, excluding other potent emissions such as hydrogen sulfide, volatile organic compounds, allergens, and larger suspended particles. Due to a dearth of reliable emission parameters and relative risk functions pertinent to the study region, we were unable to model these pollutants. As a result, our findings likely provide a conservative estimate of the actual health damage attributable to air pollution from CAFOs.

Our study employs a deterministic approach in the calculation of emissions from dairy farms. However, research indicates that emissions of both ammonia and primary PM2.5 can hinge on an array of factors such as temperature, wind speed, and vapor pressure. Moreover, ammonia emissions can increase by as much as 6 to 13 times during the summer compared to winter months (Harper et al., 2009). As people tend to spend more time outdoors during the summer, this seasonal emission pattern could potentially lead to an underestimation of health damages in our study. The InMAP model partially compensates for seasonality in tracking annual-average impacts, but in locations with seasonal emission patterns, using an annual-average impact could introduce bias in the estimated impacts. The emission factors used in our study are derived from samples collected from representative dairy farms in Texas. Yet, each farm employs distinct manure management practices, and the emissions from our dairy farms may not directly correspond with those from the Texas studies. Depending on the manure management practices in place, the ammonia emission rate could be either underestimated or overestimated. For instance, research shows that the application of digested fibers produced by anaerobic digestion momentarily increases ammonia volatilization, while nutrient separation from manure decreases the ammonia content of the digested fiber and reduces emissions post-application to the field. Without farm-level data on manure management practices, we must rely on average emission factors for the entire region. Future research should investigate these facets to deepen our understanding of the health impacts of air pollution from dairy farms.

Our estimation of health damages in monetary terms constitutes another limitation. We rely on a single value of the VSL, as reported by the US EPA, a common yet contentious method. VSL is not universally accepted as the sole method to assess the value of health damages, and alternative valuation methods exist, such as valuing years of life lost or accounting for morbidity and mortality using disability adjustment factors. Though our chosen approach aligns with other literature reviews and the EPA VSL, future analyses should consider these alternative methods to render a more comprehensive understanding of the health damage associated with air pollution from dairy farms.

Prospective research can chart new paths to enhance our comprehension of the environmental, health, and socioeconomic impacts of CAFOs. The research scope could broaden to encompass the entire US and other types of CAFOs, affording a more holistic understanding of pollution distribution. This would not only elucidate the environmental health implications of CAFOs but also help pinpoint regions with the highest social damages. A lifecycle assessment of CAFOs, integrating livestock production with feed production and herd dynamics, alongside an evaluation of additional damages from water pollution and land use changes, will provide a more nuanced understanding of the issue. Given that the nutritional demands of our expanding population are primarily met by CAFOs, we must consider them an indispensable component of our lives. Thus, the development of spatial sorting models, incorporating factors such as land prices, water availability, demographic composition, and meteorological data, could assist in identifying optimal locations for dairy farms, mitigating their environmental, health, and distributional impacts. Equally, while studies often focus on the adverse impacts of large farms, few have compared these with traditional farming methods. Consequently, an examination of the economic trade-offs and environmental-health implications of transitioning from CAFOs to alternative livestock production systems, considering factors such as job creation, rural development, and food security, would contribute to informed decision-making towards sustainable livestock production systems. Another line of research could involve interdisciplinary collaboration to quantify the variability in emissions from individual farms using satellite data or measuring instruments. By incorporating information about various manure management techniques, we can assess how damages from each farm can differ based on an assortment of factors.

Three legislative enactments currently preside over CAFO air emissions—the Comprehensive Environmental Response, Compensation, and Liability Act (CERCLA, colloquially known as the Superfund Act), the Emergency Planning & Community Right to Know Act (EPCRA), and the Clean Air Act (CAA) (Hribar, 2010). However, certain CAFOs enjoy exemption from reporting their emissions, a privilege afforded by amendments to CERCLA. Only CAFOs that reach the size classification of 'large' are mandated to report any emission event that exceeds 100 pounds of ammonia or hydrogen sulfide within a 24-hour period, either locally or to the state under EPCRA. The EPA has also established a voluntary Air Quality Compliance Agreement, promising to refrain from litigation against offenders while levying a modest civil penalty. Environmental and community leaders have criticized these alterations, contending that the EPA has succumbed to pressures from the livestock industry. Furthermore, the changes introduce uncertainty regarding the monitoring of emission standards and air quality in the vicinity of CAFOs. Three distinct air quality standards under the Clean Air Act could potentially govern air emissions from CAFOs. National Emission Standards for Hazardous Air Pollutants (NESHAP) regulates hazardous air pollutants from various industrial sectors, including agricultural operations. CAFOs could fall under NESHAP if their emissions of hazardous air pollutants surpass specific thresholds. New Source Performance Standards (NSPS) require the EPA to establish NSPS for new, modified, or reconstructed sources of air pollution, including certain agricultural operations. While no specific NSPS for CAFOs currently exists, they could be subject to these standards if they emit regulated pollutants. National Ambient Air Quality Standards (NAAQS) set by EPA for certain air pollutants such as particulate matter, can also affect CAFOs. Ammonia itself is not a criteria air pollutant regulated under NAAQS. However, it can be indirectly controlled as it contributes to the formation of secondary particulate matter. States must develop plans to achieve and maintain these standards, which could indirectly affect CAFO operations.

Research has illustrated that reactive nitrogen in livestock manure exhibits a complex dynamic, its fate contingent on a host of factors, resulting in various end products including ammonia, nitrogen oxides, ammonium or nitrate compounds, and even molecular nitrogen. An integrated manure management framework and policy that controls emission from all sectors is necessary to prevent the leakage of reactive nitrogen through different media. Given that our study identifies ammonia as the main component of PM2.5 concentration, the development and utilization of abatement technologies specifically focused on mitigating ammonia emissions can play a pivotal role in improving the environmental health impacts of CAFOs. Promising ammonia abatement technologies include membrane filtration (Zarebska et al., 2015), photocatalysis (Altomare et al., 2012), air stripping (Yao & Zhang, 2019), ion exchange (Gurreri et al., 2020), wet scrubbing (Hadlocon et al., 2015), chemical precipitation (Cerrillo et al., 2015), and electrodialysis (L. Shi et al., 2018), which have demonstrated technical feasibility. In addition, biology-based techniques such as activated sludge (Montes et al., 2015), biochar adsorption (Kizito et al., 2015), and microalgae production (Joshi & Wang, 2018), have also shown potential.

Dairy farms already operate on razor-thin margins and, further government regulations in the form of pollution taxes and emission caps may not only stifle the expansion of this sector but also force many operations into insolvency. This harms not only the producers but may also affect the price and availability of milk products. As shown by the historical trends, small farm owners will be the first and most impacted. Therefore, the government should instead devise incentives and subsidies to encourage the adoption of pollution abatement measures. For instance, facilitating low-interest loans and grants to farmers to install anaerobic digesters and nutrient separation technologies could be one such measure. Despite their steep initial cost, these installations can generate positive cash flow over time, sustaining themselves while potentially serving as revenue generators for the farms. However, the question of who ultimately shoulders the cost of these governmental interventions remains. It can be achieved through increased taxes, the expense of which is shared throughout society, with consumers, producers and every taxpayer bearing the brunt. Or the cost can be absorbed into the price of milk and milk products considering the price elasticities to ensure net revenues do not fall. This may be the cost of achieving food security, rural development, and equitable transfer of wealth without compromising the environmental quality and public health.

While subsidies can achieve important policy objectives, they are not without controversy. Critics argue that they can distort markets, encourage overproduction and environmental degradation, and disproportionately benefit large agribusinesses at the expense of smaller family farms. Therefore, policymakers should consider these concerns while formulating necessary policies and regulations. This will ensure that the path toward environmentally friendly and economically sustainable farming practices navigates the potential pitfalls and trade-offs effectively.

Chapter 4: Economic Viability of Bioenergy Production on Large Dairy Farms: An Assessment for New Mexico

4.1 Introduction

Cattles have been domesticated for over 9000 years, primarily for their milk (Evershed et al., 2008). For much of this lengthy era, cattle rearing, and milk production practices remained relatively unchanged. However, the mid-twentieth century heralded a period of substantial technological advancement, catalyzing transformative changes within the industry. On larger farms, milking and feeding units started to mirror industrial manufacturing processes rather than traditional agricultural activities. Milk preservation techniques such as pasteurization and refrigeration significantly bolstered the dairy industry's growth, serving the nutritional needs of an expanding global population. However, this expansion led to an unprecedented increase in manure production. While traditional methods repurposed manure as soil amendment, firewood, flooring, plastering, and construction material, the sheer volume of manure generated daily by large farms rendered these traditional methods untenable. To address this challenge, a series of innovative and technologically advanced methods were developed over time. One notable approach involves the production of bioenergy from manure and animal waste—a solution that has proven to be both economically viable and environmentally sustainable. Such novel techniques offer encouraging solutions to manage the significant quantities of manure generated by modern dairy operations.

The large-scale farms also known as CAFOs produce huge amounts of animal wastes deteriorating the environmental quality, harming public health, and impacting the socioeconomic conditions of the residents. Pollution of the air, water and soil is the primary environmental damage of these farms. Surface runoffs or nutrients that seep into ground and surface water sources can pollute the water (Burkholder et al., 2007). Such contamination can cause nutrient overload, mainly phosphates and nitrogen, which can promote the growth of harmful algal blooms (Heisler et al., 2008). Consumption of cyanotoxin from algae and nutrient-contaminated water can lead to various respiratory diseases, gastrointestinal disorders, skin irritation, and blue-baby syndrome (Hribar, 2010). The algal blooms can also deplete oxygen levels in the water bodies affecting the diversity and abundance of aquatic life (Spellman & Whiting, 2007). Communities that rely on water and aquatic ecosystems in these bodies of water are among the worst hit. Similarly, the air born emissions from CAFOs can inflict various cardiovascular and respiratory illnesses. Additionally, residents living near CAFOs may experience adverse effects on their mental health and overall quality of life (Baliatsas et al., 2020; Schulze et al., 2011). Unregulated manure application can also disrupt the nutrient balance in soil, causing soil erosion and reducing soil fertility. Pathogens, pests, and parasites such as E. coli and Salmonella can infect humans or infest human dwellings through contaminated air, water, food, and other agricultural articles (Hribar, 2010). The secondary transformation of pollutants can trigger acid rain and ozone formation, harming plant life, corroding monuments, and man-made structures, and obstructing economic growth and human progress. Furthermore, disadvantaged demographic groups are more likely to experience the disproportionate harmful impacts from the mismanagement of manure and animal waste.

The livestock industry is also a significant contributor to GHG emissions, primarily methane and nitrous oxides, with higher radiative warming potentials than carbon dioxide (Bellarby et al., 2013). Radiative warming potential denotes the ability of a substance to accelerate climate change over a specific period. Methane and nitrous oxides possess radiative warming potentials 28 and 265 times higher than CO2 over a period of 100 years, respectively (Pachauri et al., 2014). In 2021, the livestock industry was responsible for nearly 36% of the total methane emission in the US (US EPA, 2023a). Among these, 26.8% emanated from enteric fermentation, and 9.1% from manure management. This study primarily concentrates on curbing emissions from manure storage and handling, as these processes are more amenable to engineering and control interventions. In 2021, methane emissions from manure management were gauged at 66.0 MMT CO2e, marking a 69% escalation from the 1990 level of 39.0 MMT CO2e (US EPA, 2023a). The average annual increment in emissions over this period was 0.8 MMT CO2e. This surge in emissions can be attributed to the heightened production and application of swine and dairy cow manure, with emissions from these sources inflating by 38% and 124%, respectively.

Stakeholders, including farmers and policymakers, are actively exploring innovative strategies for managing manure that can simultaneously promote environmental conservation and stimulate revenue generation. Composting, compaction and coverage, temperature control, anaerobic digestion, and periodic removal of slurries have been identified as primary methods to curtail GHG emissions from manure (Leip et al., 2010). Of these, anaerobic digestion alone can diminish methane emissions by 25-80%, given effective capture and combustion are in place, and field application of nutrient-stripped, digested slurry can yield a 30-50% reduction in nitrous oxide emissions (Clemens et al., 2006; Sommer et al., 2000). Anaerobic digestion constitutes a natural process wherein microorganisms decompose organic matter in the absence of oxygen, yielding biogas—a concoction of methane and carbon dioxide (O'Connor et al., 2020). A commercial AD system employs an engineered approach and a controlled design to process organic biodegradable matter within air-tight reactor tanks, thereby producing biogas (Vögeli et al., 2014).

Auxiliary technologies can bolster the economic and environmental benefits of AD systems. These include heat and electricity production, biogas upgrading, solid-liquid separation, digestate treatment, nutrient recovery, microalgae cultivation, and pre-treatment technologies. The integration of these technologies can facilitate direct revenue generation from the sales of gas, electricity, fiber, and nutrients. They can also engender secondary benefits such as job creation, reduced waste disposal costs, and diminished reliance on chemical fertilizers. Non-monetary benefits include decreased dependency on fossil fuels, improved soil nutrient balance, reduced odors, pathogens, and pests, and lessened ecosystem damages (Yiridoe et al., 2009). In developing nations, AD systems can further alleviate deforestation and exposure to indoor air pollutants (Al Seadi et al., 2008). The integration of household organic wastes into the AD system can also prolong the lifespan of landfills (Vögeli et al., 2014). Despite these benefits, high initial capital costs and the marketability of co-products still pose barriers to the widespread adoption of AD technology (Astill and Shumway, 2016).

New Mexico, a state prominent in dairy production, has witnessed remarkable growth in this sector over the past few decades. The industry ranks as the top revenue generator among all agricultural commodities. The state's annual milk production averages 7.8 billion pounds, generating $1.3 billion in total sales (USDA, 2019). The state also has the highest average number of cows per large dairy farm in the nation (USDA, 2019). These dairy farms, among the nation's most expansive and productive, are geographically clustered within a relatively compact region. Over 90% of the state's 326,946 cows are located in the five southern counties of Chaves, Curry, Roosevelt, Dona Ana, and Lea (USDA, 2019).

This study's objective is to evaluate the bioenergy potential of large dairy farms in New Mexico and assess the viability of various configurations of AD systems using comparative cost-benefit analysis. Our analysis embraces a continuous range of farm sizes numbering up to 25,000. To dissect the financial potential of the various technological combinations under consideration, we invoke the economic concept of Net Present Value (NPV). We also critically evaluate the profitability of AD systems, contrasting those that rely on the sale of co-products alone against those that also secure environmental credits. Furthermore, our study ventures into a stochastic evaluation of the impact of carbon credits on the viability of AD systems, reflecting the inherent uncertainty surrounding these environmental instruments. A sensitivity analysis is also undertaken to gauge the resilience of revenue streams against parameter fluctuations. Ultimately, we incorporate the non-market benefits of AD systems into our analysis, illustrating how acknowledging and internalizing these benefits can further justify the feasibility of AD systems.

Our exploration contributes to the expanding corpus of literature on economic and environmental evaluations of manure management, inextricably intertwined with bioenergy production, specifically within arid land regions and the broader context of the US Southwest. We expand the analytical scope to encompass alternative technology components and novel revenue streams, thereby furnishing fresh empirical evidence on the economic viability of AD systems within these regions. We also update earlier cost and revenue functions, rendering them more pertinent for future investigations of analogous systems in other parts of the country. This study is the first to monetize the health benefits of AD systems, providing a comprehensive assessment of the non-market benefits of this technology. Our findings present invaluable insights for policymakers and potential investors who harbor interest in installing AD systems in arid regions and elsewhere, thereby significantly advancing the discourse in this field.

4.2 Background

The process of anaerobic digestion, a natural phenomenon manifesting in environments such as swamps and the gastro-intestinal tracts of ruminants, has been understood and harnessed since ancient times (Vögeli et al., 2014). The Assyrians were the pioneers in leveraging biogas as early as the 10th century, with the Persians following suit in the 16th century (Müller, 2007). Italian physicist Volta documented the process of methane generation from organic matter in 1776, instigating further exploration into the connection between organic matter decomposition and methane production through the 17th to 19th centuries (US EPA, 2020a). The first commercial AD/biogas plant was established in Bombay, India in 1859, followed by its use in England in 1895 to illuminate streetlamps (Wilkinson, 2011). The advent of this process began in open-air anaerobic ponds but was later refined with the introduction of enclosed tanks and heating/mixing apparatus. Despite the ongoing research and development of AD systems in the Western world, the prevalent low prices of coal and petroleum acted as deterrents to its widespread adoption. However, fuel shortages during WWII and the 1970s prompted countries with limited fossil fuel reserves to invest in micro-level AD systems, utilizing human, animal, and kitchen waste. Anecdotal evidence suggests an excess of 5 million operational AD/biogas systems globally, mostly on a single-family home scale. The global biogas electricity production capacity, which was less than 2.5 GW in 2000, had grown to over 21.5 GW by 2021 (IRENA, 2022).

Europe is the global leader in biogas electricity production, contributing over 14 GW to the total of 21.5 GW generated globally (IRENA, 2022). This significant surge in European biogas production can be attributed to the favorable support schemes enacted by several European Union (EU) member states. As of 2015, the European continent boasted over 17,400 biogas plants, with Germany housing an estimated 8,000 commercial digesters (Scarlat et al., 2018; US EPA, 2020a). Among EU countries, Denmark and the Czech Republic lead in per capital biogas production, while Sweden, Norway and France lag (*Database - Eurostat*, 2023). The majority of EU-produced biogas is harnessed for heat and electricity generation, with countries such as Germany, Italy, Denmark, the Czech Republic, and France leveraging agricultural waste for bioenergy, while Sweden, Norway, Switzerland, and Finland utilize municipal wastes (Gustafsson & Anderberg, 2022; Scarlat et al., 2018). In Sweden, Norway, and Finland, biogas is predominantly utilized as a transportation fuel (Gustafsson & Anderberg, 2022). The prime motivator for biogas uses in Europe is energy security, closely followed by environmental and sustainability concerns.

Contrarily, low to middle-income nations in Asia and Africa have gravitated towards small-scale biogas systems that capitalize on locally sourced, affordable materials. These systems typically fulfill the basic energy requirements of single households or small neighborhoods, though with lower yields and a higher percentage of impurities. China leads Asia in electricity generation from biogas plants, with an installed capacity of 1.7 gigawatts out of a total 2.9 gigawatts capacity of the whole continent (IRENA, 2022). A total of 43 million biogas users were counted in China in 2013 (Giwa et al., 2020). As a result of government subsidies, India had around five million household biodigesters in 2014 (Mittal et al., 2018; Sikora, 2021). Meanwhile, Africa exhibits a relatively nascent stage of AD system adoption with a total capacity of 0.05 gigawatts in 2021 (IRENA, 2022). However, the continent has seen a fivefold increase in total capacity over the past decade, led predominantly by South Africa and Egypt. In Latin America, numerous agricultural waste projects have been implemented, and urban areas extract landfill gas, resulting in a total bioelectricity production capacity of 0.6 gigawatts in 2021 (IRENA, 2022). Particularly in energy-scarce, remote regions, small-scale biogas systems offer an invaluable alternative to traditional energy sources like firewood, which carry significant health risks. Thus, the utility of AD systems extends beyond their immediate energy generation capabilities, providing a sustainable and health-conscious energy solution for communities worldwide.

In the United States, the predominant sources of biogas production are landfills and wastewater treatment plants that use anaerobic digesters. Recently, there has been a surge in interest towards the utilization of dairy and swine manure for energy production. According to the American Biogas Council (2023), there are 1,269 water resource recovery facilities and an additional 68 independent systems within the US that utilize anaerobic digesters for processing food waste. The EPA further documents the operation of 331 farm-based digesters (US EPA, 2022) along with 532 landfill gas projects (US EPA, 2023b). Biogas is mainly harnessed in engine-generators or boilers to generate electricity and heat, though there is an emergent trend towards refining biogas into biomethane (IEA, 2020).

However, the expansion of AD systems in the United States has been somewhat hampered by the relatively high labor and capital costs associated with these systems, coupled with their lower energy efficiency in comparison to conventional energy sources such as grid-connected electricity and fossil fuels. Nevertheless, the increasing impetus from governmental incentives and a growing pro-environmental ethos presage a brighter future for the adoption of AD systems.

According to AgSTAR's calculations, over 8,000 large dairy and hog operations in the US could potentially generate nearly 16 million megawatt-hours (MWh) of energy annually and displace approximately 2,010 megawatts (MWs) of fossil fuel-fired generation through biogas recovery from AD systems (US EPA, 2022). From this theoretical potential, 2,704 candidate farms alone could contribute nearly 60% or 9.24 million MWhs of energy equivalent to 1,172 MWs of fossil-fuel-fired generation. California leads the nation in terms of the number of candidate farms for bioelectricity production from dairy manure, followed by Idaho, Wisconsin, Texas, and New Mexico. In New Mexico specifically, there are 88 candidate farms that possess a methane emission reduction potential of 8.3 million tons and a methane production potential of 6.26 billion cubic feet per year (US EPA, 2018b). If all 144 potential biogas systems (including wastewater, landfills, and manure management) were built in New Mexico, it could generate estimated $432 million in capital investments, create 3,599 construction jobs and 239 permanent positions, and reduce GHG emissions equivalent to growing 606 million coniferous tree saplings for 10 years (American Biogas Council, 2023). Currently, there are only 16 biogas systems in New Mexico, comprising 12 wastewater treatment systems, three landfill systems, and one system for manure management.

Anaerobic digesters are considered as one of the 10 building blocks to reduce GHG emissions and generate clean and renewable energy. Their role aligns with 12 of the 17 Sustainable Development Goals, including the augmentation of renewable energy, mitigation of climate change, amelioration of waste management, and employment creation, all of which are buttressed by biogas generation (Obaideen et al., 2022). However, the financial viability of these systems is often challenged by steep initial costs (Bishop & Shumway, 2009; DeVuyst et al., 2011; Kruger et al., 2008; Q. Wang et al., 2011). Various government grants such as Conservation Innovation Grants, and the Environmental Quality Improvement Program, can help to defray the initial capital outlay of these projects (Cowley & Brorsen, 2018).

Renewable energy policies can also positively influence the adoption of AD systems. State mandates such as renewable portfolio standards (RPS), interconnection standards, net metering, feed-in tariffs, and financial incentives can all serve to stimulate renewable energy generation. A suite of financial tools, including grants, loans, rebates, and tax credits, further support farmers in this endeavor (US EPA, 2014). Federal tax incentives, including Renewable Electricity Production Tax Credit, the Investment Tax Credit, the Residential Energy Credit, and the Modified Accelerated Cost-Recovery System, have a particularly profound impact. Research indicates that these financial incentives can determine the success or failure of an AD system, and favorable policies have catalyzed a proliferation of AD systems in regions with supportive regulatory frameworks and renewable energy incentives (Cowley & Brorsen, 2018).

The advent of carbon credit markets presents a unique opportunity for biogas producers, and dairy farmers who invest in methane capture technologies such as anaerobic digesters. Carbon credits are tradable instruments that allow entities to offset emissions that are difficult to mitigate by investing in initiatives that prevent or eliminate emissions elsewhere. These markets can have two forms: compliance and voluntary. Compliance markets are utilized by legal jurisdictions to satisfy their legal obligations, while voluntary carbon credit markets are used by private parties to meet their emission reduction goals (Blaufelder et al., 2020).

Regulatory measures like Renewable Portfolio Standards (RPS) incentivize the use of renewable sources for electricity generation. These policies mandate or encourage utility providers to supply a predetermined share of electricity from eligible renewable resources. Most states have instituted their own RPS programs, which incorporate a renewable electricity certificate (REC) trading system to curtail the cost of compliance (US EPA, 2015). Net metering is another policy that allows electric utility customers to install qualifying renewable energy systems on their properties and connect them to an electric utility's distribution system. Feed-in tariffs provide special rates for purchasing electricity from certain types of renewable energy systems, while interconnection standards establish uniform processes and technical requirements for connecting renewable energy sources to the electric grid.

Biogas can also be processed and sold as biofuels or alternatives vehicle fuels which are regulated and incentivized by federal and state level policies. The Low Carbon Fuel Standard (LCFS), for instance, aims to reduce the carbon intensity of transportation fuels by setting a target carbon intensity value for fuel suppliers (US EPA, 2020b). To reduce compliance costs with this standard, the LCFS uses a REC trading system, similar to cap and trade for the transportation sector Akin to the cap-and-trade system for the transportation sector, the LCFS utilizes a REC trading system to mitigate compliance costs. The renewable identification numbers (RINs) system is another incentive mechanism that monitors the production, use, and trading of biodiesel and other renewable fuels. Before 2014, biogas derived from AD could only qualify for D3 RINs when used as a transportation fuel in the form of liquefied natural gas or compressed natural gas (US EPA, 2020b). In 2014, the EPA expanded this pathway to specify Compressed Natural Gas (CNG) or Liquefied Natural Gas (LNG) as the fuel and biogas as the feedstock, enabling fuels derived from landfill biogas to qualify for cellulosic biofuel (D3) (US EPA, 2020c). These policies ensure that renewable energy producers are duly compensated for their efforts, and any surplus electricity generated can be credited for future use. These interconnections between dairy farming, bioenergy production, and carbon credit markets open unique avenues for exploring manure management strategies that bolster economic development while mitigating GHG emissions.

The state of New Mexico exemplifies a robust environmental stance and proactive renewable energy assistance programs. The state aims to reduce GHG emissions by 45% below 2005 levels by 2030 and achieve net-zero emissions by 2050. New Mexico Energy Transition Act mandates renewable energy standards for investor-owned utilities and rural electric cooperatives. Recognizing anaerobic digesters as a zero-carbon resource, the Act supports New Mexico in reaching its clean energy targets. Anaerobic biodigesters that meet the state's renewable energy requirements are eligible to claim RECs.

This study aims to evaluate the viability of AD systems for large dairy farms by comprehensively assessing the cost and revenue parameters of various technology combinations and environmental incentive regimes. It considers dairy farms with herd sizes up to 25,000 cows and compares the

NPVs of two technological alternatives. We also perform a stochastic assessment to observe the impact of uncertainties in carbon credit prices on the viability of AD systems. A sensitivity analysis is also undertaken to gauge the resilience of revenue streams against parameter fluctuations. Ultimately, we incorporate the non-market benefits of AD systems into our analysis, illustrating how acknowledging and internalizing these benefits can amplify project profitability. By providing valuable insights for policymakers and investors keen on promoting the widespread adoption of AD systems in arid regions and beyond, this study fills a gap in the literature on economic and environmental assessments of manure management coupled with bioenergy production.

4.3 Methodology

This study assesses the economic feasibility of integrated AD systems, focusing on their capacity to generate revenue for farmers and their potential to mitigate environmental externalities. To evaluate the impact of herd size on the net present value (NPV) of an AD system, we considered dairy farms with herd sizes up to 25,000 cows. The cost and revenue equations are the linear functions of herd sizes therefore the NPV changes almost linearly with the increase in the farm size.

4.3.1 Components of an AD System

Anaerobic digesters are available in various configurations and types. They may be stand-alone systems that solely produce electricity or biogas as the primary product, or they may be integrated systems using modular technology components to yield auxiliary co-products such as high-value fibers and nutrients, in addition to the primary product. Each technology component varies in terms of input and output and carries associated costs. Figure 1 provides a schematic representation of an integrated system that encompasses all five technological components, their associated co-products, potential environmental credits, and attainable external social benefits.

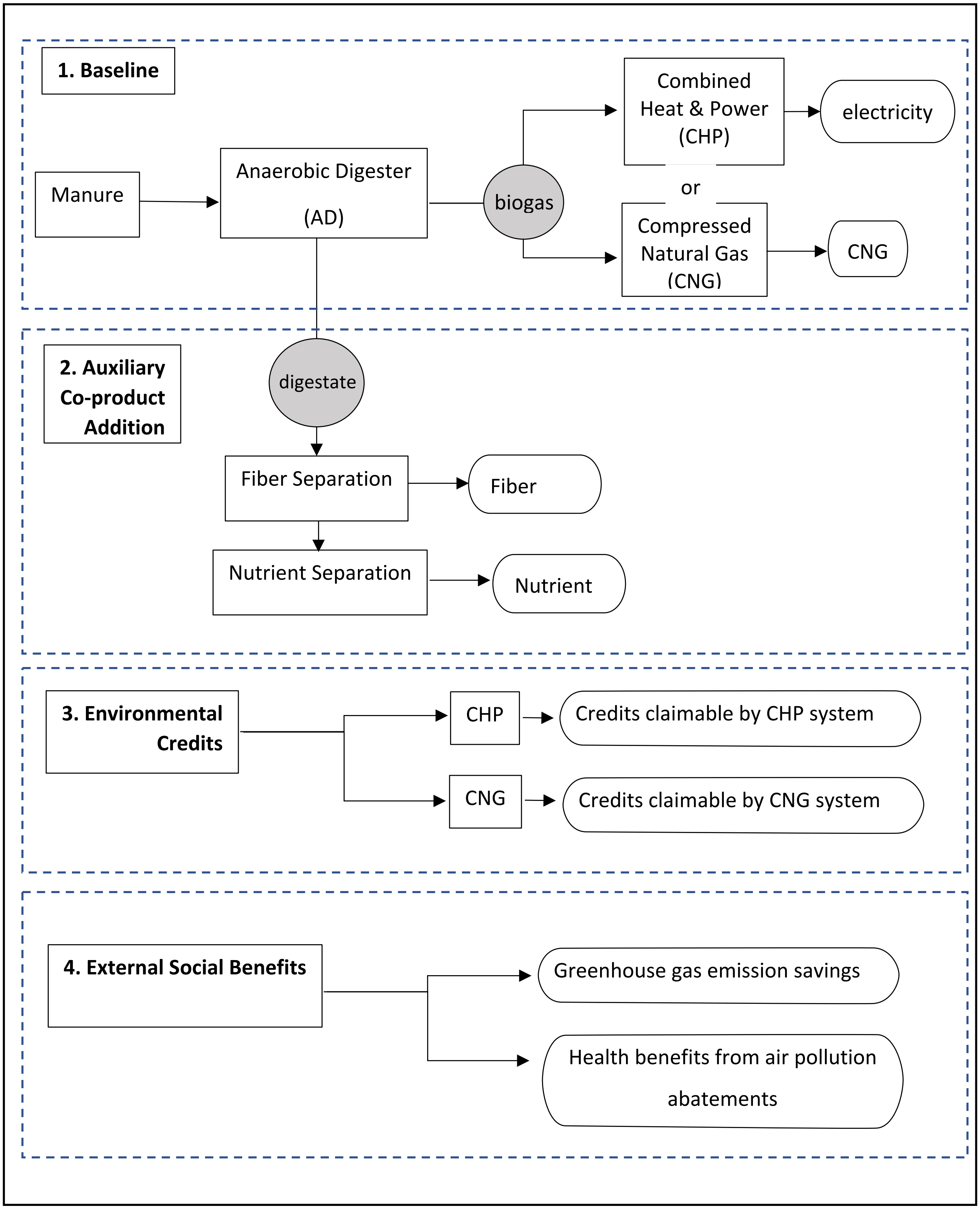


Figure 4.1: Schematic representation of an integrated AD system with technological components, environmental credits and external social benefits

i. Anaerobic digester (AD)

The AD unit serves as the base component of an AD system, converting organic solids into biogas and fiber through the agency of anaerobic bacteria. The resultant biogas and fiber, however, necessitate further processing through CHP or CNG units to make them marketable. In our study, we assume the use of a complete mix AD, with the biogas subsequently processed by either CHP or CNG units. As such, while the AD system incurs costs, it does not have an associated revenue function.

ii. Combined heat and power (CHP)

The CHP unit is a technology component which when combined with the AD unit, forms the basic functional AD system or base system. The CHP unit produces two co-products: heat and electricity. While the primary products of the CHP unit are electricity and heat, we only include the revenue generated from the electricity sales, and do not monetize the value of the heat produced. We also assume 100% of the generated electricity to be connected to the electric grid.

iii. Compressed natural gas (CNG)

CNG is another technology component that can be combined with the AD unit to form the basic functional AD system. The main product of this unit is natural gas, which is derived from the biogas being scrubbed of water and contaminants before its compression for delivery or utilization. CNG can serve as biofuel for transportation or as an energy source for heating and cooking in residential settings. While it is possible for AD system owners to connect their system to the national CNG pipeline, we do not take this into consideration due to the high cost of pipeline integration.

iv. Fiber separation (FS)

FS serves as an auxiliary component within the AD system, producing high-value fibers that can be sold under two different labels depending on the market preference and demand. Selling the fiber as a peat moss replacement enables charging higher prices, whereas selling it as a soil amendment results in lower price points. Although the system solely produces high-value fibers, we consider two alternative revenue functions, one for high-value fiber (peat moss replacement) and another for low-value fiber (soil amendment).

v. Nutrient Separation (NS)

The NS unit is another auxiliary component of an integrated AD system, producing high-value fertilizer products by separating phosphate and ammonia from the effluent. The NS unit requires a preceding fiber separation process to function effectively, as it relies on the separation of solid fiber from the effluent to ensure a smoother process. The NS unit generates revenue through the sales of high-value fertilizers, targeting specifically the agricultural industry where these nutrients can be applied directly into the field.

4.3.2 Cost, Revenue and Net Present Value

The capital cost and operation and maintenance (O&M) costs of the AD systems are calculated using equations (4.1) and (4.2). Similarly, the revenues and transactional costs of environmental acquisition are calculated using equations (4.3) and (4.4).

Capital cost:

$$C(x) = \begin{cases} v_1 x + f_1, & if\ x < \alpha \\ v_2 x + f_2, & if\ x \geq \alpha \end{cases} \quad (4.1)$$

Where, the capital cost function is a piecewise function dependent on the threshold size of the farm α. The farm size or the number of cows per farm is represented by x. The capital cost comprises both variable and fixed costs associated with a specific technology component. The variable costs tied to a particular technological component reflect expenses that change based on the farm size. Whereas the fixed costs encompass costs that stay constant regardless of the farm size within that cost structure.

For farm with a size less than α, the capital cost is calculated using the first cost function where v_1 is the variable cost and f_1 is the fixed cost. Similarly, for farms with size equal to or greater than α, the capital cost is determined by the second cost function where v_2 is the variable cost and f_2 is the fixed cost. This piecewise function allows for different cost structures depending on the size of the farm.

Operation and maintenance cost:

$$\Omega(x) = \begin{cases} w_1 x + g_1, & if\ x < \beta \\ w_2 x + g_2, & if\ x \geq \beta \end{cases} \quad (4.2)$$

The O&M cost function also exhibits a piecewise structure where, w_1 and g_1 represent the variable and fixed O&M costs of the first cost structure. Similarly, w_2 and g_2 represent the variable and fixed O&M costs of the second cost structure. β is the threshold size of the farm for O&M function.

Revenue:

$$R(x) = z_1 x\, p_1 + z_2 x\, p_2 \quad (4.3)$$

z_1 represents the marginal output of a product per cow tied to a particular technological component and p_1 represents the prevailing market price of this product. Some components of the AD system yield multiple products or yield products that command multiple prices in the market. Therefore, z_2 and p_2 represent the marginal output per cow and the price of the second product or alternative specifications for the same product depending on the situation.

The following equation show the revenues and transaction costs associated with the environmental credits:

Revenue:

$$R(x) = a_1 x \, p_3 \tag{4.4}$$

Transaction cost:

$$\xi(x) = a_2 x \, p_3 + b \tag{4.5}$$

Where,

a_1 and a_2 represent the variable component of the cost and revenue. p_3 represents the marginal price of the credit and b represents the fixed component of the cost where applicable.

Net present value (NPV), a yardstick of profitability, carefully weighs the time value of money. To assess the economic viability of the anaerobic digestion system, a generalized NPV function was used. The function calculates the NPV of the project for a given farm size by considering the present value of the revenue stream and the present value of the operation and maintenance costs. The discount rate and project life form are integral components of the calculation. The NPV function was constructed using the following equation:

$$\lambda(x) = \sum_{t=0}^{T}\left(\frac{R(x)}{(1+r)^t}\right) - \sum_{t=0}^{T}\left(\frac{\Omega(x)}{(1+r)^t}\right) - C(x) \tag{4.6}$$

Where, r is the discount factor T is the capital lifetime. We assume that the salvage value of the project is zero. In general, the rule of thumbs for investment decision is to greenlight a project when the NPV exceeds zero. The NPV also serves as a reliable metric to compare the profitability of diverse technological alternatives. The greater the NPV, the more viable the project.

The assessment of costs, revenue, and NPV is contingent on the values ascribed to a gamut of parameters and variables. Table A1 in the appendix lists all the parameters and variables utilized in the appraisal of cost, revenue, and NPV.

4.3.3 Deterministic Scenario Analysis

We use a combination of four scenarios to assess and compare the viability of various AD system configurations using a fixed price for co-products and environmental credits. The primary goal of this assessment is to optimize the private benefits, as measured by NPV, of AD operators.

Scenario 1 (Baseline):

The first scenario evaluates the NPVs of the base AD system, constituted of either AD+CHP or AD+CNG. These system's primary products are electricity (generated by CHP) and compressed natural gas (generated by CNG). This scenario does not consider the production of any co-products or the attribution of environmental credits. For subsequent analysis, the AD+CHP and AD+CNG configurations are referred to as CHP system or CNG system, respectively, and serve as the basis of comparison for alternative technology components.

Scenario 2 (Auxiliary Co-product Addition):

In the second scenario, we evaluate the investment decision of integrating the FS and NS units with the base system. The FS and NS units bring their own associated costs and revenues, which contribute to the total costs and revenues of the base system. We initially introduce the FS unit to the base system and calculate the NPV, considering the possibility of selling the auxiliary co-product as either a peat moss replacement (high-value fiber) or a soil amendment (low-value fiber). Subsequently, we add the NS unit to the previous configuration and calculate the NPV of the fully integrated system.

Scenario 3 (Environmental Credits):

The third scenario explores the potential impact of securing environmental credits on the economic viability of the base AD system. Our analysis considers the existing environmental credits available in New Mexico and explores the theoretical possibility of introducing additional credits currently unavailable in the state. The types of credits available for the CNG and CHP systems are different, with their own revenue parameters affecting the viability of a system.

Unlike Scenario 2, obtaining environmental credits does not require the installation of additional technological components and therefore does not incur additional capital and O&M costs. However, some environmental credits may have associated transaction costs, such as a percentage of the credit claim or a fixed price. The parametric values of environmental credits are available in Table 4.4 and Table 4.5.

Scenario 4 (Co-product Addition plus Environmental Credits):

Finally, in the fourth scenario, we evaluate the viability of an integrated AD system by considering both auxiliary co-product sale and environmental credit acquisition possibilities. This scenario represents the combination of the most realistic and conservative aspects of Scenario 2 and Scenario 3. For instance, we assume that all the fiber produced by the FS unit is sold as low-value fiber and only those credits that are currently available in New Mexico are considered for environmental credit acquisition. This comprehensive assessment enables a deeper understanding of the factors influencing the profitability of AD systems with either CHP or CNG technologies.

4.3.4 Calculation of External Social Benefits

Quantifying GHG Emission Savings

The potential savings in GHG emissions, contingent on methane combustion from the AD systems (CHP or CNG), is outlined in this section. A comprehensive GHG budget, inclusive of lifecycle assessment of dairy farms and the associated supply chain such as feed production and various phases of dairy cow development, lies beyond the scope of this study. Consequently, emissions linked to the transportation of manure or feedstock and additional emissions within production processes are not incorporated in our calculations. We estimate the GHG emission savings by contrasting methane emissions from dairy cows with the amount of methane theoretically capturable and convertible to carbon dioxide via anaerobic digestion. The calculation is carried out as follows:

$$G = \left(\frac{\kappa * x * e * S}{1000}\right) \tag{4.7}$$

where,

$\kappa = 76.65 \frac{kg}{cow} / year$ represents the annual per cow methane emission from manure (Todd et al., 2011), $e = 28\ tons\ CO2e$ denotes the GHG savings achieved by combusting a ton of methane to carbon dioxide, as specified by the Intergovernmental Panel on Climate Change (2014). The monetary value assigned to each ton of carbon dioxide equivalent saved is denoted by S, which is an estimate of the social cost of carbon, encapsulating the economic damage from GHG emissions. Current EPA guidelines and recent research suggest this value to fall between \$51 and \$190 (IWG, 2021; Rennert et al., 2022).

Quantifying Health Benefits from Air Pollution Abatement

AD systems can also yield health benefits, given their role in curtailing primary and secondary pollutants. Studies have suggested that AD systems integrating nutrient separation generate most of these benefits. In fact, the application of digested manure into the field without nutrient separation may even increase the ammonia emissions over a short duration. Therefore, the inclusion of a nutrient separation module in the AD system contributes to a higher external health benefit, while a system devoid of nutrient separation could potentially yield negative external health benefits.

Chapter 3 of this dissertation determined that the monetary value of reduced mortality due to reduction in ammonia emissions can range from \$468 to \$1634 per cow, dependent on the location of the dairy farm in New Mexico. Certain studies have shown nutrient recovery of ammonia from the fiber to range from 57% to 86% (Shi et al., 2022). We have adopted the lower value of this recovery factor (57%), estimating our health benefits from reduced ammonia emissions to range from \$267 to \$931.

4.3.5 Risk Assessment

Sensitivity Analysis

Sensitivity analysis is a critical aspect of any quantitative study, serving as a litmus test for the robustness of the results against the volatility of the input parameters. In this study, we assess the impact of variations in both prices and functional parameters on the NPV of two AD systems—CHP and CNG—in the context of a typical farm in New Mexico with 3,187 cows.

Our sensitivity analysis considers all potential and existing revenue streams, even those currently unattainable, to provide a comprehensive evaluation of each parameter's impact on the NPV. The sensitivity analysis was performed using two different sets of input parameters. In the first set, the parameters were directly related to the revenue streams, including the prices of electricity, carbon credits, RECs, tax credits, fiber, phosphate, and sulfate. In the second set, the parameters were related to the capital investment and the calculation of NPV, including the discount rate, capital lifetime, and capital cost.

The price parameters were changed between zero to two times their original values to illustrate the effect of a missing revenue stream and the potential impact on NPV if the price was doubled. On the other hand, functional parameters were adjusted between 0.5 to 1.5 times their original values to explore the impact of halving or a 50% increase in parameters on the NPV.

For each variation of parameters, we computed the NPV and stored the results in a data frame. The data frame was then used to create a plot, showing the variation in NPV as a function of the parameter variation. Each parameter is represented by a different color, allowing for an easy comparison of their relative impacts on the NPV.

The sensitivity analysis identifies the parameters that most significantly affect the NPV. It should be noted that, while our NPV is conjectural due to its hypothetical assumptions, it serves as a valuable indicator when assessing the differences in NPVs arising from parameter changes.

Monte Carlo Analysis

A triad of Monte Carlo simulations were performed to examine how stochasticity in price parameters affects the NPV of an AD system. This assessment explicitly explored three scenarios associated with the uncertainty in carbon credit pricing, focusing on its impact on the NPV of a typical New Mexican dairy farm with 3,187 cows. The Monte Carlo simulation was applied to the optimal configuration of the AD system (AD+CHP+FS+NS), as established by deterministic evaluations. The three distinct calculations are as follows:

i) Stochasticity in prices of all co-products and existing environmental credits, including the attainment of RECs and carbon credits.

ii) Stochasticity in the prices of co-products and carbon credits, excluding the attainment of RECs.

iii) Stochasticity restricted to the carbon credit prices, while the coproduct prices remain constant, excluding the attainment of RECs.

Each price parameter adhered to a triangular distribution, informed by both prevailing and assumed price data. A triangular distribution is a continuous probability distribution with a probability density function shaped like a triangle. It is defined by three values: the minimum value, the maximum value, and the mode. In this case, these values represent the range and most likely values of each price parameter.

This Monte Carlo Analysis facilitates an in-depth exploration of the potential variability in the NPV due to the stochastic nature of price parameters, thereby providing a more robust and realistic understanding of the economic viability of the AD system.

4.4 Data

This study draws on multiple data sources to assess the viability of different configurations of AD systems. An AD system can have different technological components, each with their own costs and revenues. The cost and revenue functions used in this study were obtained from Astill and Shumway (2016) and were based on the Anaerobic Digester System Enterprise Budget Calculator. These parameters originally developed by AD engineers, were collected from previous studies and industry partners. To adjust for inflation, the dollar value associated with the capital infrastructures was updated to 2021 dollars using Chemical Engineering Price of Construction Indices (CEPCI) (Access Intelligence, 2023). The operation and maintenance costs were also updated to 2021 prices using the Consumer Price Index (CPI). When official sources were available, the price of co-products and environmental credits were updated to 2021 levels. In their absence, they were adjusted using the CPI. All values reported in the study were annual unless otherwise stated.

4.4.1 Costs and Revenues

Both capital and operating costs are important while assessing the viability of an AD system. Capital costs, a one-time expenditure, are incurred at the project's inception, encapsulating the cost of infrastructure, machinery, installation labor, and other startup expenses. Conversely, operating and maintenance (O&M) costs are recurring costs over time which is assumed to be steady in our analysis. The parametric values of capital costs and O&M costs are listed in Table 4.1 and 4.2 as follows.

Table 4.1: Cost parameter for capital cost (adjusted to 2021 dollars using CEPCI and CPI)

	v_1	f_1	v_2	f_2	α
AD	158	2,263,545	786	694,556	2500
CHP	322	828,790	-	-	-
CNG	593	1,530,182	-	-	-
Fiber Separation	50	-	-	-	-
Nutrient Separation	508	24,112	-	-	-

For the AD unit, its capital cost function varies depending on the threshold size of the system represented by α. For systems that have fewer than 2500 cows, v_1 and f_1 are used for the calculation of capital cost whereas for systems than have 2500 or more cows, the cost function with v_2 and f_2 are used. This variation reflects the different cost dynamics associated with different sizes of AD systems.

Table 4.2: Cost parameter for O&M cost (adjusted to 2021 dollars using CEPCI and CPI)

	w_1	g_1	w_2	g_2	β
AD	36	-	-	-	-
CHP	81	2,521	67	62,679	4500
CNG	32	43,812	-	-	-
Fiber Separation	7	-	-	-	-
Nutrient Separation	115	-	-	-	-

For the CHP unit, the threshold size of the farm related to O&M costs as represented by β is 4500. For CHP systems that have lower than 4500 cows, w_1 and g_1 are used as variable and fixed costs respectively. However, when the size of farm increases to 4500 or more cows, w_2 and g_2 are used for the calculation of O&M costs.

The revenue generated by an AD system hinges on several determinants. Our assessment only considers the cash flows related to the investment, defining the system boundary by excluding all costs and revenues that would have transpired irrespective of the AD system's adoption. Thus, activities such as milk production and on-farm crop production, although inextricably linked with the AD system, are excluded from our assessment. Our focus remains affixed on benefits that farmers can materialize as revenue streams. For instance, cost savings resulting from heat generation do not enter our calculation, as we only consider co-products with a potential market. Revenues can be generated through two channels: firstly, by selling co-products, and secondly, by availing various environmental credits. The revenue parameters for all technology components associated with the sales of coproducts are outlined in Table 4.3.

Table 4.3: Revenue parameters (adjusted to 2021 dollars using CEPCI and CPI)

	z_1	p_1	z_2	p_2
CHP	1,703	0.06	-	-
CNG	21	6.03	-	-
Fiber Separation	1	165.34	1	25.6
Nutrient Separation	0.92	103.24	0.4	372

The complexity of our system necessitates a more nuanced representation for certain technological components. For instance, nutrient separation unit concurrently yields multiple auxiliary co-products (sulfates and phosphates). The fiber separation unit on the other hand yields a single auxiliary co-product that can be marketed under different labels and price points depending on the market conditions. To accommodate this intricacy, we introduce z_2 and p_2 into our calculation. Here, z_2 denotes the marginal output of the second co-product or alternatively it represents the marginal output of the same product when sold at a different price point. In the same vein, p_2 represents the price of the second co-product or the price of the same product sold under a different label.

The acquisition of environmental credits generates revenue for the farmers. which can be claimed after the sales or at the end of year in the form of tax rebate. This revenue, which can be realized immediately upon the sale of credits or at the end of the year as a tax rebate, plays a significant role in our analysis. We assume that the revenue is acquired directly after the sale, similar to the transaction process for any coproduct sales.

The process of acquiring environmental credits does not necessitate the installation of new machinery nor does it impose additional operations and maintenance costs. However, certain transactional costs may be incurred. These costs can be a fixed percentage of the revenue or a combination of lumpsum amount and a percentage cut from the revenue. Table 4.4 and Table 4.5 list the parameters associated with revenue generation and transactional costs of environmental credits.

Table 4.4: Revenue parameter for environmental credits (adjusted to 2021 dollars using CEPCI and CPI)

	a_1	p_2
Carbon credit	3	22.04
REC	1,703	0.20
Tax credit	1,703	0.02
RIN	247	1.58
LCFS	6	187.11

Table 4.5: Transaction costs of environmental credits (adjusted to 2021 dollars using CEPCI and CPI)

	a_2	p_2	b
Carbon credit	0.35	22.04	5,250
REC	17	0.20	-
RIN	25	1.58	-
LCFS	0.6	187.11	-

4.4.2 Variables and Parameters

Table A1 in the appendix lists all the variables and parameters used in this study. NPV is calculated employing a 4% real discount rate and a 20-year capital lifetime, consistent with Astill and Shumway (2016) and other pertinent literature. The value of x represents the total number of milk cows in a dairy farm and thus reflects the farm's size. We assume that 42.75 cubic meters of manure is produced per WCE per year, of which 90% is collected and deployed in the AD system.

The prices of electricity and CNG used in our study are based on the average 2021 prices of the Southwest region. The CNG scrubbing rate, which signifies the percentage of biogas transmuted to CNG is derived from Astill and Shumway (2016). The fiber separation system produces high-value fiber, which can potentially be traded as a peat moss replacement for $165.34 per ton or as a soil amendment for $25.6 per ton, adjusted to 2021 dollars. The price of ammonium sulfate hinges on the June 2021 market price, which has experienced a significant increase in recent years. The price of phosphate is predicated on Astill and Shumway (2016), adjusted to 2021 dollars.

The price of environmental credits is obtained from official sources. Carbon credit prices are based on the 2021 average auction settlement price in the California cap and trade market. Renewable energy certificate (REC) prices are predicated on industry data for Xcel Energy, which delivers electricity and natural gas to parts of Eastern New Mexico overlapping with dairy-producing regions. Renewable Identification Number (RIN) prices are based on the average price of qualified RIN in 2021 as published by the US EPA.

New Mexico has a renewable energy production tax credit in place. However, its tax structure is complicated and subject to statewide limits, introducing uncertainties regarding eligibility and claimable amounts. Therefore, we use a simplified tax incentive structure, as per Astill and Shumway (2016), to discern how it might invigorate the growth of AD systems in the state. Concurrently, despite the non-existence of a Low Carbon Fuel Standard (LCFS) in New Mexico at present, ongoing legislative discourse suggests its imminent implementation. Therefore, we incorporated it as a prospective credit scheme for New Mexico, based on the 2021 average LCFS prices in California.

4.5 Results

4.5.1 Deterministic Scenario Analysis

Scenario 1 (Baseline):

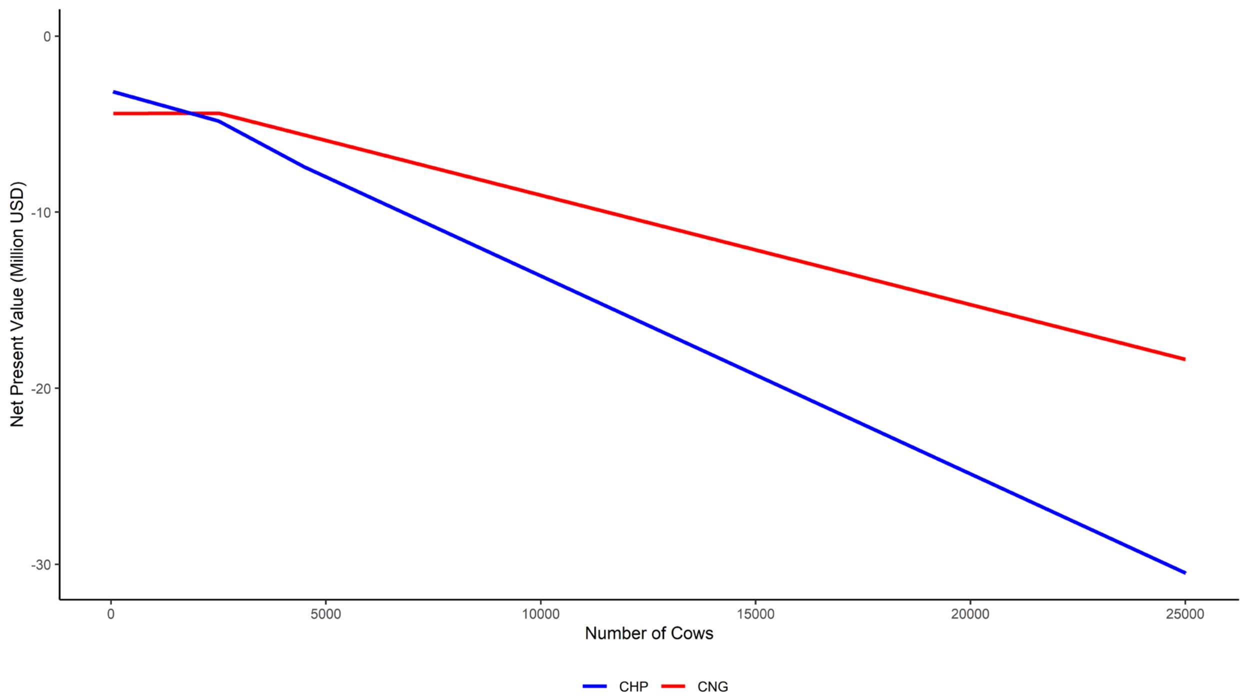


Figure 4.2: NPV of CHP or CNG systems, by herd size

Figure 4.2 delineates the NPVs of a continuous range of herd sizes up to 25,000 cows, employing either CHP or CNG technologies, while solely selling the primary products of electricity or CNG, respectively. The results demonstrate a persistent negative NPV across all dairy farm sizes, indicating that in the absence of auxiliary co-product sales or environmental credits, the base AD system does not generate positive revenue. Moreover, an inverse relationship between farm size and NPV is observed, with larger farms registering greater negative NPV values. This pattern persists for both CHP and CNG systems.

Scenario 2 (Auxiliary Co-product Addition):

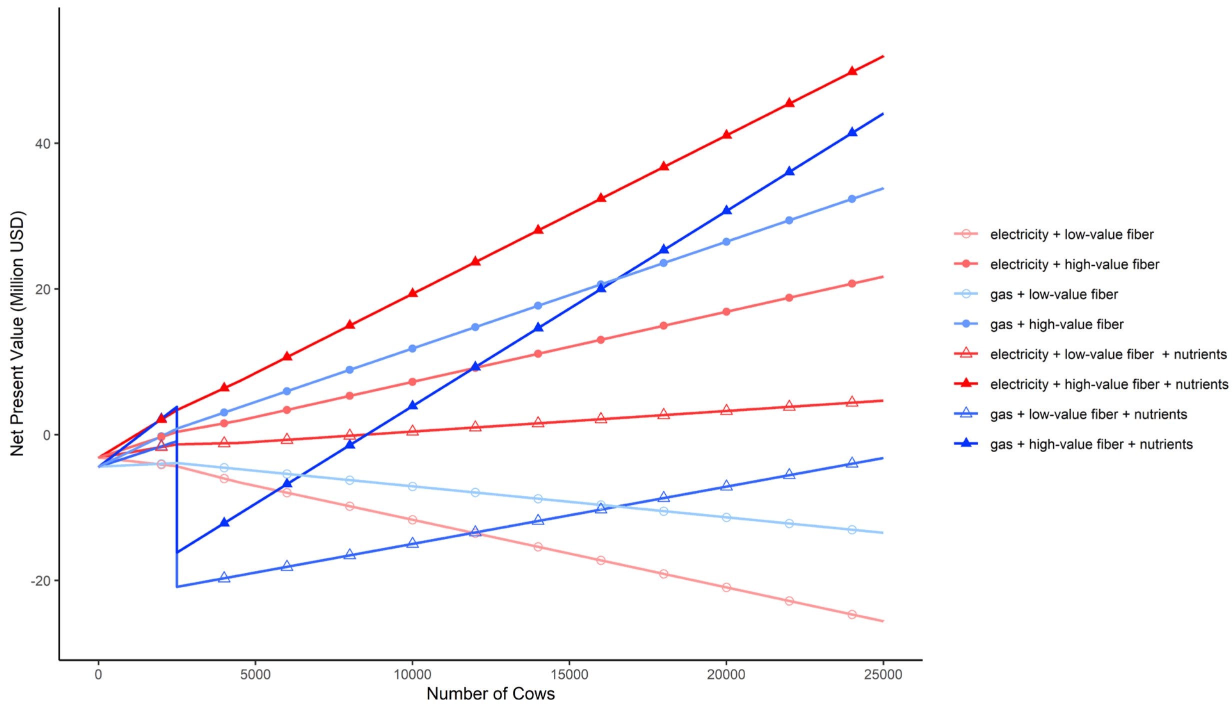


Figure 4.3: NPV of CHP or CNG systems with auxiliary co-products, by herd size

Figure 4.3 presents the NPVs of a continuous range of herd sizes up to 25,000 cows, utilizing either CHP or CNG technologies, while also incorporating auxiliary co-products derived from auxiliary components. Specifically, our assessment focuses on the integration of a fiber separation unit and a nutrient separation unit, with the co-products of interest being fiber and nutrients. As mentioned earlier, the fiber can be sold as a peat moss replacement or soil amendment, contingent upon prevailing market conditions.

For the configuration where fiber is sold as a low-value soil amendment, both CHP and CNG systems exhibit negative NPVs across all farm sizes. Conversely, when fiber is sold as a high-value peat moss replacement, both technologies generate positive NPVs beyond a certain farm size. The breakeven size for farms adopting CHP+FS and selling the fiber as peat moss replacement is 2,220, while the breakeven size for farms adopting CNG+FS and selling the fiber as peat moss replacement is 2,097.

Additionally, the integration of a nutrient separation unit into the systems comprising fiber separation results in elevated NPVs. For a system deploying CHP+FS+NS and selling the fiber as a low-value soil amendment, the breakeven size is 8,479. In contrast, while the NPV of a system deploying CNG+FS+NS increases with herd size, it does not reach a positive value within the range of our study. Therefore, no breakeven size can be identified for this specific technology configuration.

Finally, when the systems—both CHP+FS+NS and CNG+FS+NS—are capable of selling the fiber as a high-value peat moss replacement, their NPVs markedly increase, achieving breakeven sizes at 1,203 and 1,336, respectively.

Scenario 3 (Environmental Credits):

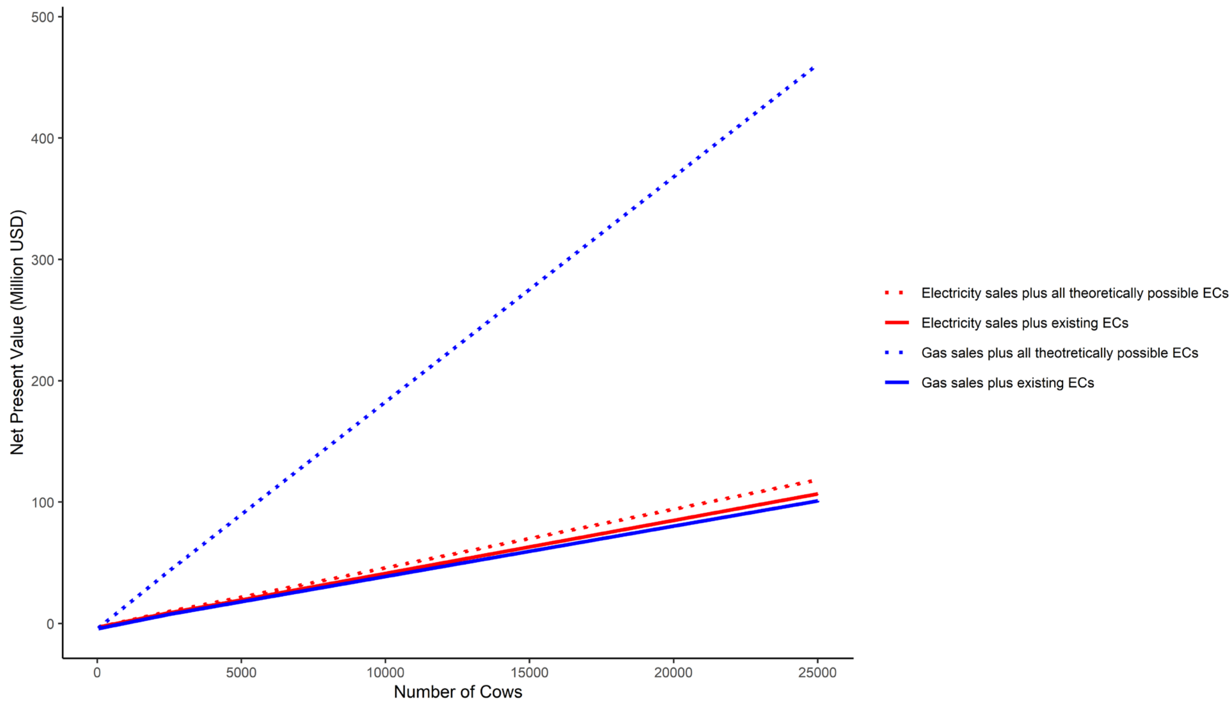


Figure 4.4: NPV of CHP or CNG systems with environmental credit acquisition, by herd size

Figure 4.4 depicts the NPVs of a continuous range of herd sizes up to 25,000 cows, utilizing either CHP or CNG technologies, while also capitalizing on environmental credits. We evaluated two scenarios: one with existing environmental credits and another with all potential credits. CHP and CNG systems can claim distinct environmental credits. Currently, CHP systems can claim carbon credits and RECs, while CNG systems can claim RINs. By claiming these credits, the NPV of the system swiftly escalates, resulting in a breakeven size of 665 for CHP systems and 918 for CNG systems. Although not currently available, CHP systems can also theoretically claim tax credits, which curtails the breakeven size to 606. Similarly, CNG systems can theoretically claim LCFS credits, which notably improves the system's profitability and lowers the breakeven size to 229. When only existing environmental credits are considered, the CHP system yields a higher NPV compared to the CNG system, whereas the CNG system exhibits a significantly higher NPV when all theoretically possible credits are taken into account.

Scenario 4 (Co-product Addition plus Environmental Credits):

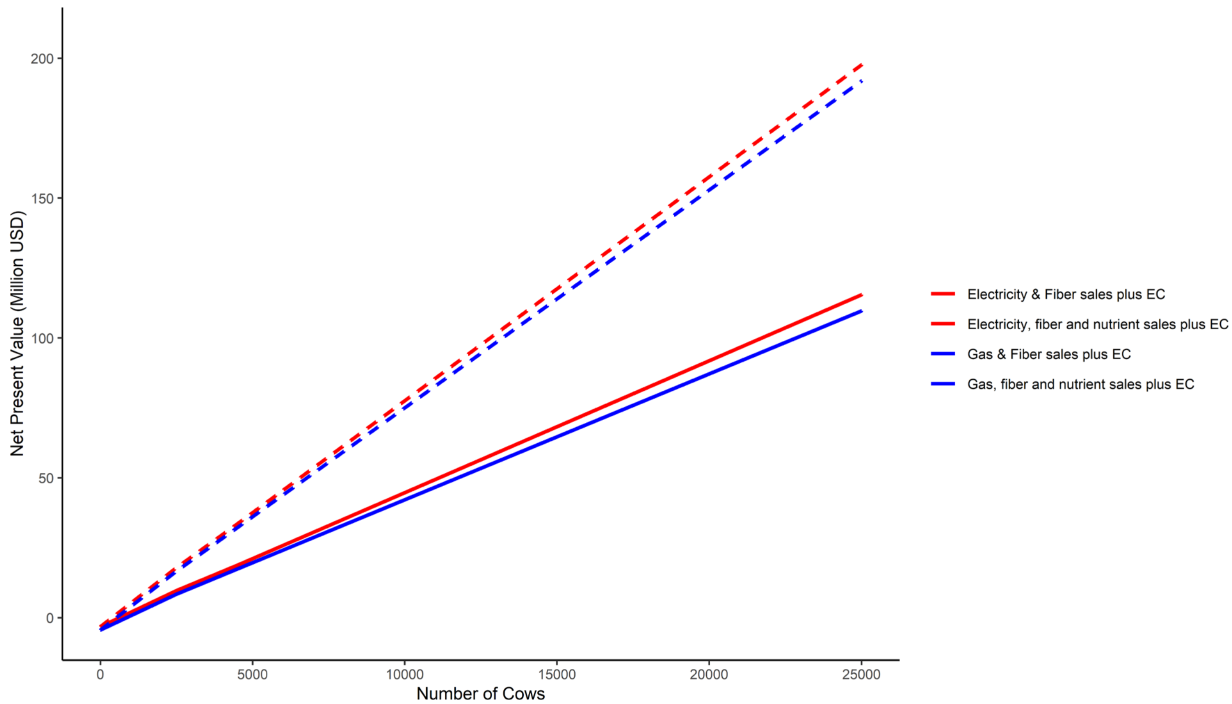


Figure 4.5: NPV of CHP or CNG systems with Co-product sales and environmental credits obtention, by herd size.

Figure 5 presents the NPVs of a continuous range of herd sizes up to 25,000 cows, deploying either CHP or CNG technologies, and incorporating co-product sales along with existing environmental credit realization. In this assessment, we operate under the conservative assumption of selling fiber as a low-value soil amendment. Initially, we examine the integration of fiber separation components and existing environmental credits into the AD systems, followed by the addition of nutrient separation components to the previous configuration, and compute the corresponding NPVs. For systems incorporating fiber sales and existing environmental credits, the breakeven size for CHP and CNG systems are 620 and 856, respectively. With the incorporation of both fiber and nutrient sales along with the attainment of existing environmental credits, the breakeven size for CHP and CNG systems decreases to 379 and 522, respectively. Our results indicate that the CHP system exhibits a higher NPV in both configurations.

Table 4.6: Breakeven size for each scenario and configurations

Scenario 1

Products sold	Breakeven size
Electricity	None
Gas	None

Scenario 2

Products sold	Break even size
Electricity + low value fiber	None

Scenario 3

Products sold	Breakeven size
Electricity + existing credits	665
Gas + existing credits	918
Electricity + all possible credits	606
Gas + all possible credits	229

Scenario 4

Gas + low value fiber	None
Electricity + high value fiber	2220
Gas + high value fiber	2097
Electricity + low value fiber + nutrients	8479
Gas + low value fiber + nutrients	None
Electricity + high value fiber + nutrients	1203
Gas + high value fiber + nutrients	1336

Products sold	Breakeven size
Electricity + low value fiber + existing credits	620
Gas + low value fiber + existing credits	856
Electricity + low value fiber + nutrients + existing credits	379
Gas + low value fiber + nutrients + existing credits	522

Table 4.6 provides the breakeven sizes of AD systems across an array of scenarios and configurations. AD systems that rely solely on the sale of gas or electricity do not yield a positive NPV for any farm size, thereby precluding the possibility of a breakeven size, as evidenced in Scenario 1.

A similar pattern emerges in Scenario 2, where AD systems centered on selling electricity combined with low-value fiber or gas, or gas coupled with low-value fiber, likewise fail to generate a positive NPV, thus ruling out breakeven sizes. However, the table changes with the addition of high-value fiber to the equation. The breakeven size for systems leveraging electricity and high-value fiber is noted to be 2,220, while those utilizing gas and high-value fiber exhibit a slightly lower breakeven size of 2,097.

When nutrients are incorporated into the mix, we observe that the breakeven size for configuration producing electricity paired with low-value fiber and nutrients is 8,479. In contrast, gas systems featuring low-value fiber and nutrients do not reach a breakeven size due to their inability to generate a positive NPV at any farm size. The breakeven sizes for electricity and gas systems that integrate high-value fiber and nutrients drop to 1,203 and 1,336, respectively.

In Scenario 3, where environmental credits are claimed, AD systems experience a boost in profitability, which in turn diminishes the breakeven size. Systems that combine electricity and existing environmental credits reach a breakeven size of 665, while the configuration with gas attain a breakeven size of 918. If all theoretically possible credits are incorporated, the breakeven sizes further contract to 606 for electricity and 229 for gas.

Scenario 4, which amalgamates the more realistic aspects of Scenarios 2 and 3, witnesses further enhancements in profitability. For instance, the breakeven size for electricity combined with low-value fiber and existing credits is 620, compared to 856 for gas paired with low-value fiber, nutrients and existing credits is 379, while the same configuration for CNG systems registers a slightly higher breakeven size of 522.

4.5.2 Calculation of External Social Benefits

Quantifying GHG Emission Savings

Based on the range of social cost of carbon values of $51 to $190, the monetary value of annual GHG savings per cow would range from $109 to $408. If we consider a hypothetical scenario where all the farms in New Mexico with a total of 292,000 cows adopt AD systems, then the total GHG savings would amount to be $32 million to $119 million per year. For an average dairy farm in New Mexico with 3,187 cows, the GHG savings would range from $0.35 million to $1.3 million per year.

Quantifying Health Benefits from Air Pollution Abatement

Using a range of marginal benefits of ammonia reduction from $267 to $931 for an AD system equipped with nutrient separation, we calculated the associated health benefits. If the entire state of New Mexico adopted AD systems with nutrient separation, the total health benefits would be between $78 million and $272 million. For an average dairy farm in New Mexico with 3,187 cows, the annual health benefits resulting from ammonia abatement would range from $0.86 million to $2.97 million per year depending on the location of the farm.

4.5.1 Risk Assessment

Sensitivity Analysis

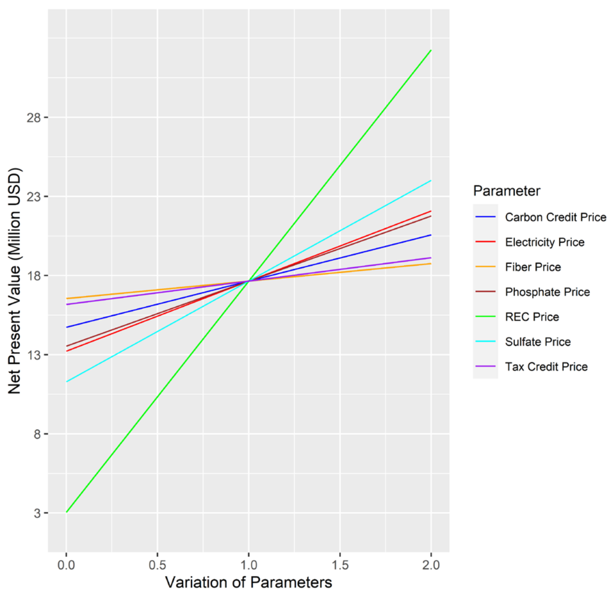
A sensitivity analysis was conducted to delve into the fluctuating influences of different price parameters on the economic feasibility of two systems—CHP and CNG—within an AD framework. Figure 4.9 presents the results of this analysis, depicting the sensitivity of the NPV to varying prices and functional parameters.

In the CHP system, the REC price was found to be the most sensitive parameter. This sensitivity can be observed starkly when the REC price is reduced to zero, simulating a scenario where REC is no longer available. This results in a substantial drop in the Net Present Value (NPV) of the system from approximately $18 million to a mere $3 million. Other sensitive parameters in descending order of influence include the prices of sulfate fertilizer, electricity, and phosphate fertilizer. The least sensitive parameters were found to be fiber price, tax credit and carbon credit prices, implying the relative insensitivity of NPV to changes in these variables.

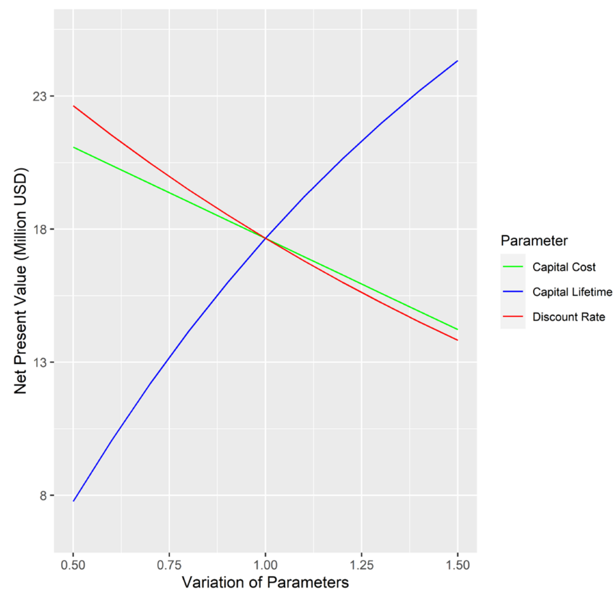
For the CNG system, the LCFS price is the most sensitive parameter. This is evident when the LCFS is removed, causing the NPV of the system to plummet into negative territory, from around $42 million to negative $3 million. The RIN price, gas price, and sulfate fertilizer price follow suit in terms of sensitivity. The least sensitive parameters for this system are the fiber price and the price of phosphate fertilizer, suggesting that changes in these parameters will have a lesser impact on the system's NPV.

The sensitivity analysis also extended to functional parameters, revealing a high level of sensitivity to all three parameters - discount rate, capital cost, and capital lifetime - for both the CHP and CNG systems. The NPV exhibits an inverse relationship with the discount rate and capital cost, while it shows a positive relationship with the capital lifetime. A reduction in capital lifetime by half to 10 years precipitates a decline in the NPV of the CHP system to around $8 million from $18 million, and for the CNG system, it drops to $14 million from $42 million. As the opportunity cost of the investment increases, as denoted by the rise in the discount rate, the NPV of the system diminishes sharply for both systems. Furthermore, the NPV of both the CHP and CNG systems is highly susceptible to shifts in the capital cost. A halving of the capital cost significantly bolsters the profitability of both systems, as is clearly illustrated in the accompanying graphs.

A) Varying prices (CHP system)

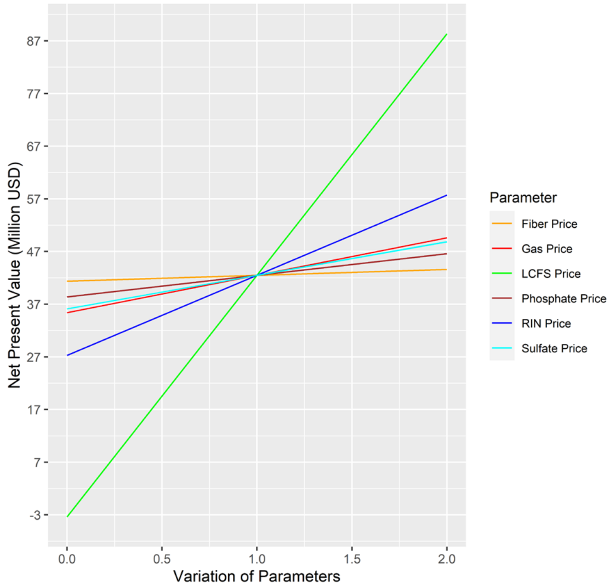


B) Varying functional parameters (CHP system)



D) Varying functional parameters (CNG system)

C) Varying prices (CNG system)



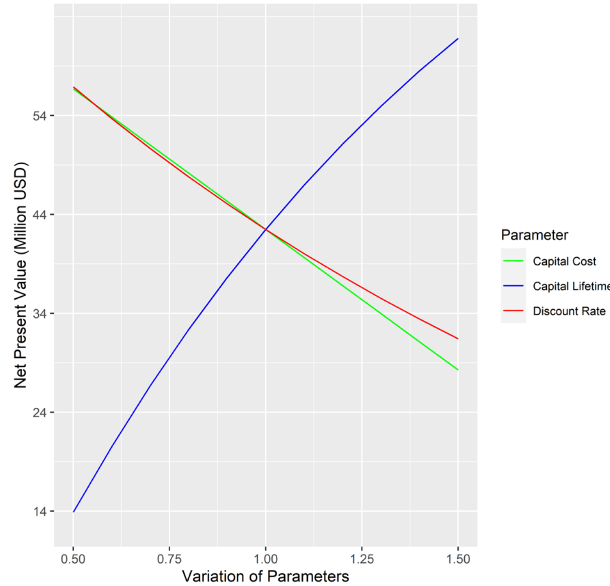


Figure 4.9: Sensitivity analysis of the CNG and CHP system for a farm size of 10,000 cows varying price levels and functional parameters.

Monte Carlo Analysis

A triad of Monte Carlo Analyses were performed to examine the influence of volatility in price parameters on the NPV of the most optimal configuration of the AD system. The deterministic assessment identified CHP+FS+NS with environmental credit acquisition as the most optimal configuration. In this context, we explored three scenarios focusing on the uncertainty in carbon credit prices to determine their impact on the NPV of a typical dairy farm in New Mexico that has adopted the optimal AD configuration with a herd of 3,187 cows.

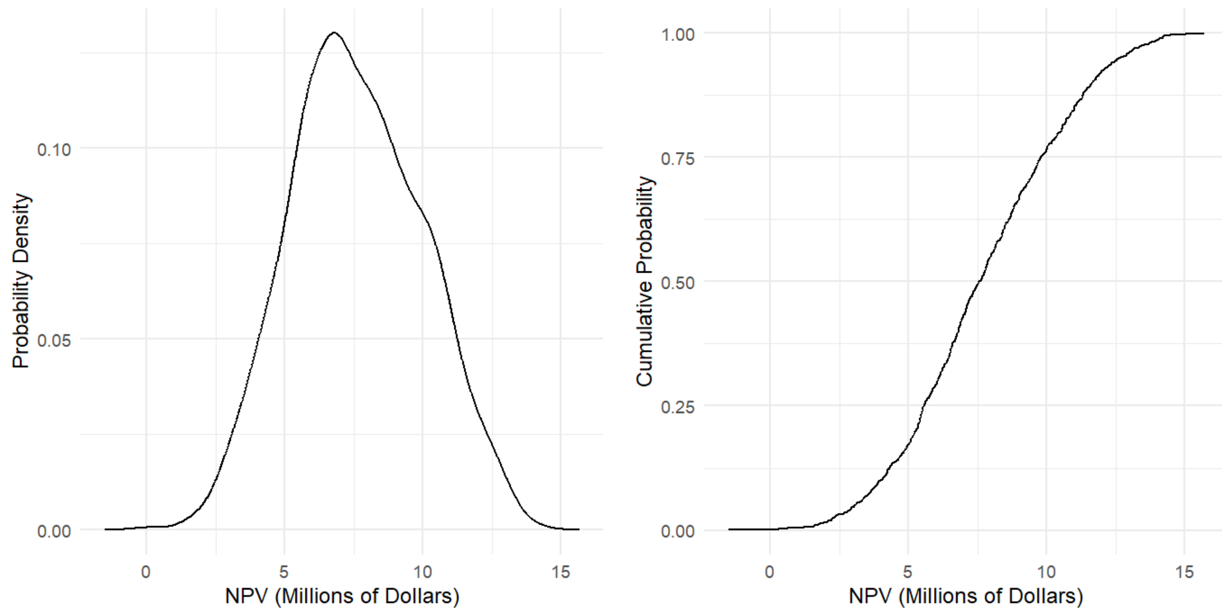


Figure 4.6: Probability distribution function (PDF) graph and cumulative distribution function (CDF) graph of a typical dairy farm adopting CHP+FS+NS with stochastic prices of all co-products and existing environmental credits (carbon credits + RECs)

First, we introduced uncertainties across all price parameters. The PDF graph shows that most NPV values are densely concentrated between \$5 and \$10 million. The CDF graph demonstrates that the likelihood of zero NPV is virtually negligible. Therefore, for an average dairy farm generating revenues from electricity, fiber and nutrient sales, in addition to carbon credits and RECs, the economic rationale supports investing in the AD system. This is due to the practically non-existent probability of incurring a loss within the acceptable risk boundaries of price fluctuations.

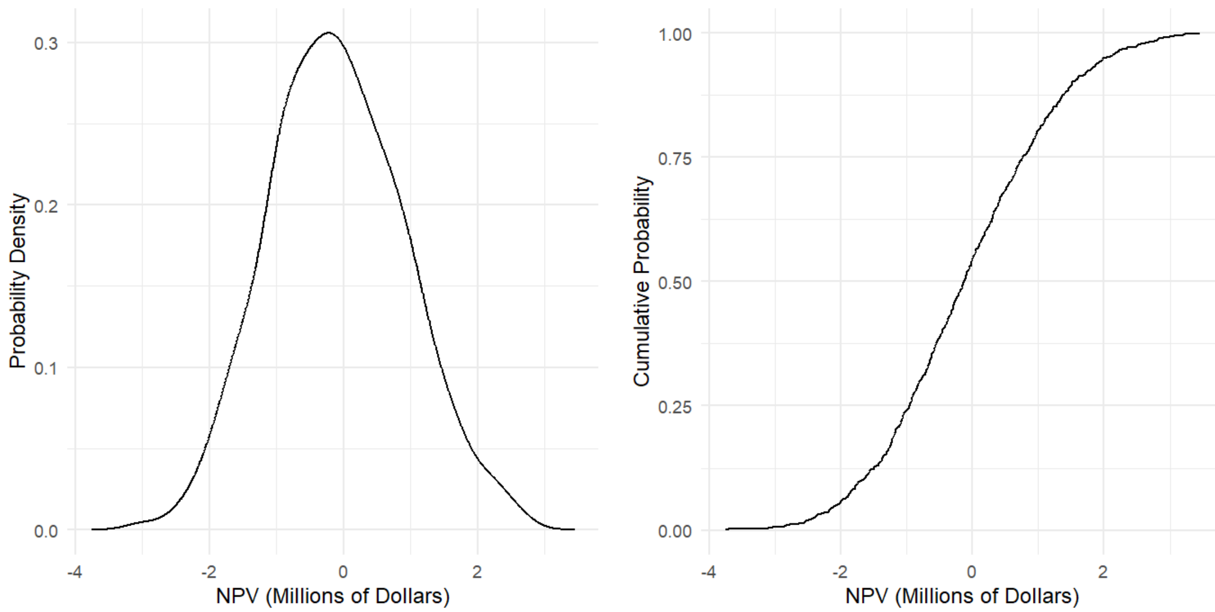


Figure 4.7: The PDF graph and the CDF graph of a typical dairy farm adopting CHP+FS+NS with stochastic prices of co-products and carbon credits

Next, we considered a scenario where a typical New Mexican dairy farm can procure carbon credits but not the RECs. All price parameters maintain the same level of uncertainty as before. The PDF graph indicates that most of the NPV values are concentrated between -$2 and $2 million. Given the absence of REC and the uncertainties pertaining to the prices of co-products and carbon credits, the viability of an AD project becomes questionable. This conclusion is further validated by the CDF graph, which indicates that the viability of the AD project resembles a coin-flip decision, balanced precariously with a 50% chance of failure and a 50% chance of success.

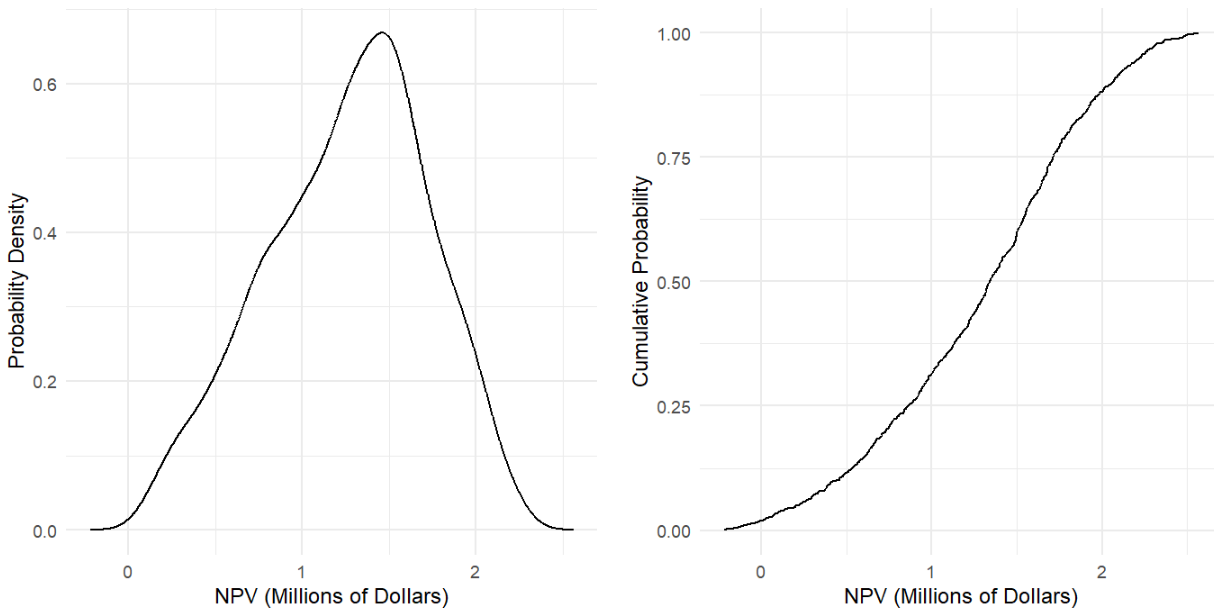


Figure 4.8: The PDF graph and the CDF graph of a typical dairy farm adopting CHP+FS+NS with stochastic carbon credit prices and stable co-product prices

For the last scenario we consider stochasticity in carbon credit prices and stable prices of co-products sold. We exclude the possibility of attaining RECs in this scenario as well. The PDF graph illustrates that although the NPV of the AD system remains predominantly positive, it is not as significant as in the first scenario. The CDF graph corroborates this observation. The outcome indicates that carbon credits can still serve as an enticing incentive for AD operators to remain viable, particularly in the absence of other more lucrative incentives, assuming that the prices of other co-products remain stable and relatively high within the market range. The tail on the left of the graph representing the worst possible outcomes suggests that there is a non-zero chance of negative NPV, and the AD operators should be aware of and be prepared for this low probability but potentially high impact event.

4.6 Conclusion and Discussion

We conducted a comprehensive assessment to evaluate the potential and viability of AD system installation in dairy farms across New Mexico. The analysis involved four distinct scenarios and utilized NPV as a measure of investment viability. The scenario analysis was conducted under deterministic conditions to provide an overview of viability for all revenue streams and farm sizes. Additionally, we performed a stochastic assessment of NPV to offer a more realistic account of the outcomes for a typical dairy farm in New Mexico. Furthermore, we calculated the social benefits associated with AD systems, specifically focusing on methane destruction, greenhouse gas emission savings, and nutrient separation to mitigate health risks and particulate matter formation, resulting in human health benefits. Lastly, we conducted a sensitivity analysis to demonstrate the impact of changing various parameters on the results.

Our analysis identified the CHP system with fiber and nutrient separation as the most optimal configuration in terms of both financial and environmental benefits. A marginal analysis of costs and revenues for this ideal configuration is necessary to gain a deeper understanding of the financial aspects. For an average New Mexican dairy farm with 3,187 cows, the marginal NPV of the optimal configuration is $5,077 per cow. The configuration has a marginal capital cost of $2,150 per cow and a marginal O&M cost of $3,267 per cow. With a marginal revenue of $10,495 per cows, we can observe that the system's gross margin is about 48%. The revenue and costs calculated here are based on the present value of cashflows generated in the project's lifespan of 20 years. When we break down the revenue to highlight the contribution from different components of the system, we can see that revenue from RECs contributes the most (43.68%), followed by nutrient separation (31.31%). Electricity sales, the main product of the CHP system, accounts for only 13.23% of the overall revenue. Carbon credit and fiber sales contribute the least with 8.48% and 3.30% respectively. While this analysis reveals that certain revenue sources contribute less than others, sustaining all revenue streams is critical to ensuring the portfolio diversification and dispersal of the risk associated with the discontinuance of a revenue source.

If we consider the external benefits of AD systems, the question of whether to install such a system becomes less relevant, the question rather turns into when and where to install it. The marginal external benefits of AD systems are substantial: the benefits from GHG emission savings over 20 years range from $1,789 to $6,697 per cow, depending on the social cost of carbon used. We assume a 4% discount rate and 2% annual appreciation in the value of social cost of carbon in this calculation. Additionally, the marginal health benefits from reduced pollution range from $4,382 to $15,281 per cow, depending on the location of the AD system. The marginal external benefits range from $6,171 to $21,978 per cow, whereas the marginal private benefits amount to $10,495. This indicates that the positive externality of AD systems may not be fully captured by the realization of private benefits alone. In some cases, government intervention and incentives may be necessary to internalize this externality and achieve an optimal level of AD installation.

The livestock sector has faced criticism for its contribution to climate change, leading to a negative perception among consumers. To meet changing consumer demands and improve their environmental image, livestock operations can adopt AD systems, actively reducing their carbon and pollution footprints. This aligns with the growing trend seen in other industries, such as the airline sector where companies actively emphasize and publicize their emissions reduction initiatives. By embracing AD systems, the livestock sector can address environmental concerns, rebrand themselves as climate-friendly, and potentially command higher prices. This strategic shift in perception sets them apart from competitors not prioritizing environmental stewardship, enhancing their reputation and profitability. Embracing sustainable practices allows the livestock sector to thrive in a consumer landscape valuing climate-conscious product.

The sensitivity analysis highlights the reliance of AD systems on environmental credits for their viability. However, it is important to acknowledge that these credits can be conditional, subject to quotas or terms, and may even be discontinued due to regime changes or other factors. Additionally, some farmers hold principles that oppose receiving government handouts, including these credits (Cowley & Brorsen, 2018). Capital cost has also been consistently identified as a critical factor affecting NPV installation. Our sensitivity analysis supports the argument that reducing the cost of capital may generate positive NPVs for otherwise unprofitable operations. To address this challenge, providing grants to offset the initial costs of AD implementation could be instrumental in persuading hesitant farmers to embrace the technology. Likewise, offering low-interest loans presents another avenue for individuals who hold principles opposing government assistance. These initiatives can support the implementation of AD systems and help overcome financial barriers, contributing to their long-term viability.

There are some caveats to our study that warrant discussion. When calculating NPVs, we assumed an idealistic world where every legal and administrative hurdle is overcome, and every component functions smoothly. However, the real world is rarely so perfect. Although our stochastic assessment incorporated uncertainties across prices, the real world could present even greater challenges, such as a lack of market for the products produced by the AD system. Production does not always equal sales; however, we assumed them to be equivalent. We might not be able to connect electricity to the grids, or there might be too many technical and administrative hurdles. The fiber produced might not find a market due to the lack of agricultural land nearby, the high cost of hauling farther distances, or the unwillingness of farmers to accept manure-based amendments. Similarly, the environmental credits that we claimed as certain might be difficult to access and subject to limitations, served on a first-come basis, or removed over time. Furthermore, the 20-year project duration is a long time to ensure everything goes as planned. Machine components can break before the 20 years elapse, and it might be too expensive to replace them. The GHG emission savings in our calculations only consider the destruction of methane. However, AD systems with nutrient separation units can also reduce the emissions of nitrous oxide, another potent GHG which has not been accounted for in this study. Therefore, the net external benefits calculated might be a lower-bound of actual benefits.

Policymakers must address these uncertainties if they wish to tackle the externalities associated with livestock production. One potential solution as discussed before is the utilization of high-value fiber produced by AD systems with fiber separation as a substitute for peat moss. Peat moss, although beneficial for its water-holding properties, poses environmental challenges due to the extraction and usage processes, which destroys carbon sequestering bogs and wetlands. By replacing peat moss with high-value fiber, we not only generate revenue but also mitigate secondary carbon emissions. However, it is important to note that consumers may not readily associate manure with peat moss substitutes. Even though the fiber obtained from AD is heat-treated and largely free of odor and pathogens, there is a perception among general consumers that manure products are unpleasant and contaminated. To bridge this perception gap, government intervention can play a role in raising consumer awareness and collaborating with industry leaders to certify AD fiber as a legitimate peat moss substitute. Additionally, in cases where there is limited market acceptance or absence of a market, the fiber produced can be utilized as a soil amendment in rangelands. The low moisture content of this fiber reduces transportation costs, enabling it to be transported over longer distances. By creating demand for the product in rangeland applications, farmers can be assured of a market for their product. To ensure the viability of AD systems, it is essential to establish markets for as many of their co-products as possible and enforce environmental credits. Policymakers can play a key role in facilitating this process and promoting sustainable practices within the livestock industry.

The implementation of the LCFS has been under consideration by the New Mexico legislature. This standard is already established in California, Oregon and British Columbia, Canada. The LCFS for CNG generated in New Mexico can theoretically be claimed in Oregon or California if used as transportation fuel in those jurisdictions. However, the significant cost associated with transporting such fuel and the irony of carbon emissions resulting from the process pose challenges. LCFS lowers the average carbon intensity of transportation fuels, making the transition to net-zero carbon emissions more feasible. As a result, enacting the appropriate regulations will not only help farmers produce additional cash and enhance public health, but will also aid the state in meeting its climate goals, eventually benefiting society as a whole.

This study assessed various alternatives and opportunities within the AD system from the perspective of revenue maximization for dairy farmers. In the US, when discussing AD systems, farmers often perceive them as a burden and a regulatory requirement. However, this pereption should be challenged. In certain cases, AD systems have the potential to generate higher revenues compared to the dairy system itself, especially considering the narrow profit margins in the industry. While this study has utilized available information on prices and uncertainties to provide a realistic assessment of the AD system's viability, future researchers can delve deeper by incorporating comprehensive farm-level data. This would allow for the determination of optimal locations, sizes, and the number of AD systems to be installed in clusters, targeting areas with the highest social cost of environmental and health damages. Additionally, a lifecycle assessment of the entire supply chain would be beneficial in understanding the overall impact of greenhouse gas emissions and other environmental costs and benefits associated with AD operations. This assessment would not only identify areas for further improvement but also enable the branding of livestock as reduced carbon emitters, facilitating the marketing of products accordingly.

Chapter 5: Conclusion

5.1 Dissertation Summary

This dissertation focuses on the environmental and health implications of CAFOs in New Mexico and proposes a potential solution. The study seeks to answer three primary research questions: (1) Do environmental justice indicators correlate with proximity to dairy farms and exposure to farm emissions? (2) What is the overall health damage caused by dairy air pollutants, and are all farms equally harmful? (3) How can we address the pollution concerns while ensuring that dairy farms remain financially viable?

To answer the first research question, we analyzed demographic data, dairy information, and satellite data to assess the distribution of environmental justice indicators and exposure indicators across dairy and non-dairy regions in New Mexico. Our findings reveal that foreign-born populations and Hispanics are disproportionately affected by emissions from CAFOs, and living near dairy farms or in areas with elevated ammonia levels is linked to lower family income, fewer high school graduates, and higher poverty rates. This study's insights can inform policy decisions aimed at reducing environmental injustice, benefiting not only policymakers in New Mexico but also stakeholders and activists facing similar challenges.

To answer the second research question, we utilized an ISRM matrix, emission parameters, and dairy-level data to estimate the concentration change of particulate matter and determine the total health damages caused by dairy farms. Our results indicate that dairy farming contributes significantly to health damages in New Mexico, with increased PM2.5 concentrations from dairy farm emissions causing 12.41 annual deaths, equivalent to $129 million in monetary terms.

Ammonia is the primary pollutant responsible for these health damages, contributing 99.38% of the damages through its transformation as secondary PM2.5. This study is one of the first to quantify and monetize the health costs related to dairy farms, and future research should expand to include other livestock types and geographical regions to provide a more comprehensive understanding of health damages from CAFOs.

To answer the third research question, we evaluated the viability of a proven solution in the context of New Mexico by assessing the cost and revenue parameters of various technology combinations and environmental incentive regimes for two alternative technologies. Our findings reveal that the configuration with fiber and nutrient separation has the largest private and social benefits due to a reduction in harmful ammonia emissions. We identify potential challenges that farmers may face, such as high initial capital costs and a lack of market for co-products and provide recommendations for policymakers on how to address these challenges to optimize net benefits for both private and public parties.

5.2 Key Takeaways

In conclusion, the three studies presented in this dissertation have drawn attention to two dimensions of issues emanating from CAFOs: i) localized concerns ii) global repercussions. On a local scale, CAFOs significantly amplify concentrations of pollutants such as ammonia and particulate matter, imposing substantial human health costs and disproportionately affecting marginalized communities. Globally, CAFOs contribute to radiative forcing from GHG emissions. Despite the dichotomy of these issues, they are not mutually exclusive, and integrated solutions like AD systems can address both local pollution and global climate change if deployed appropriately.

Mitigating localized environmental pollution necessitates a careful balancing act between efficiency and equity. Policy tools should be chosen in such a way that they do not inadvertently lead to disproportionate exposure for certain demographics. The control of ammonia emissions, a primary pollutant, particularly from regions with high livestock density, can decrease overall pollution and mitigate existing inequities. We can draw lessons from the European Union and Canada's successes in air pollution regulation as inspirations for future policy development. Given the volatility of ammonia and its potential transformation into other harmful forms, strategies to reduce gaseous ammonia emissions should be cognizant of potential reactive nitrogen leakage that could exacerbate nitrogen-related issues. Therefore, an integrated policy framework addressing air, water, and soil emissions of ammonia and its derivatives from livestock and crop operations should be considered.

Our exploration of the net external costs of dairy farms, as gauged by health damages and GHG emissions, reveals that dairy farms in New Mexico impose a substantial societal and global cost. However, in relative terms, these costs might be lower than in other regions. Therefore, a balanced approach that aligns environmental conservation with economic practicality and food security might involve strategically relocating dairy farms from densely populated areas like California and the Midwest to less populated regions. However, this would require a more comprehensive assessment of CAFOs across the entire US and the distribution of their potential costs and benefits.

Given the thin operational margins of dairy farms, it's imprudent to burden them with overly restrictive policies. A more effective approach might involve government incentives and subsidies to encourage the adoption of pollution abatement measures. This could include facilitating low-interest loans and grants for the installation of AD systems and nutrient separation technologies, which offer substantial societal benefits. However, the financial implications of these interventions need to be carefully evaluated to ensure fair burden-sharing among consumers, producers, and taxpayers.

The adoption of AD systems offers a promising avenue for the livestock sector to mitigate their carbon and pollution footprints through methane destruction and nutrient separation. However, the viability of these systems is heavily contingent on the availability of environmental credits and the capital cost. Policymakers can foster AD implementation by offsetting initial costs through grants, offering low-interest loans, and helping establish markets for AD co-products.

Finally, the potential of high-value fiber produced by AD systems as a substitute for peat moss presents an exciting opportunity for carbon emission mitigation. Government intervention can play a crucial role in transforming consumer perceptions, certifying AD fiber as a legitimate substitute, and establishing demand in applications such as rangeland soil amendment. Ultimately, the quest for environmental justice and the reduction of pollution from livestock operations necessitate a multifaceted approach, one that combines policy reforms, technological advancements, and market incentives in a harmonious and sustainable way.

There are several avenues for future research in the field of environmental justice, air pollution, and livestock operations:

Geographical Expansion of Studies: Expand the scope of research to include the entire US and other types of CAFOs. This will help provide a comprehensive understanding of the distribution of pollution and identify regions with the highest social damages.

Lifecycle Assessment of CAFOs: Conduct detailed lifecycle assessments of CAFOs, integrating livestock production with feed production, herd dynamics, and water pollution and land use changes. This could help provide a more nuanced understanding of the environmental impact of CAFOs.

Optimal Location Identification: Develop spatial sorting models that incorporate factors like land prices, water availability, demographic composition, and meteorological data to identify optimal locations for dairy farms that minimize their environmental, health, and distributional impacts.

Comparative Studies: Carry out studies comparing the impacts of large farms with traditional farming methods. This could inform the discussion on the economic trade-offs and environmental-health implications of transitioning from CAFOs to alternative livestock production systems.

Policy Impact on Dairy Farm Operations: Investigate how further government regulations in the form of pollution taxes and emission caps might affect dairy farm operations, especially those operating on thin margins.

Research must expand to include comprehensive assessment of the environmental, health, and socioeconomic impacts of CAFOs. This includes identifying optimal locations for such operations, considering their environmental, health, and distributional impacts. Current regulations governing CAFO air emissions need reevaluation, given that exemptions and voluntary agreements leave ambiguities in standards and monitoring. By exploring these research avenues, we can deepen our understanding of the complex interplay between livestock operations, air pollution, and environmental justice, informing more sustainable and equitable policy decisions.

Appendix

Table A1: Parameters and variables in the Model

Parameter/Variable	Units	Values	Data source	Notes
Wet cow equivalent (x)	Milk cows	1 to 25,000	Assumed	
Discount Rate	percent	4	Assumed	
Capital lifetime	Years	20	Assumed	
Manure utilization rate	percent	90	Astill and Shumway, 2016	
Electricity price	$/kWh	0.06	https://www.eia.gov/electricity/wholesale/xls/archive/ice_electric-2021final.xlsx	Average price in 2021

CNG scrubbing rate	percent	97	Astill and Shumway, 2016	
CNG price	$/MMBTU	6.03	https://www.eia.gov/dnav/ng/hist/n3035nm3A.htm	NM avg for 2021
High value fiber price	$/Tons	165.34	Astill and Shumway, 2016	Price of peat moss replacement product, adjusted to 2021
Low value fiber price	$/Tons	25.6	https://rex.libraries.wsu.edu/view/pdfCoverPage?instCode=01ALLIANCE_WSU&filePid=133329 9966000184	

			2&download=true	
Phosphates price	$/tons	103.24	Astill and Shumway, 2016	CPI adjusted to 2021
Ammonium sulfate price	S/tons	372	https://www.chemanalyst.com/Pricing-data/ammonium-sulphate-64	June 2021 price
Carbon credits price	$/MT CO2e	$22.04	https://ww2.arb.ca.gov/our-work/programs/cap-and-trade-program/program-data/cap-and-trade-program-	Average 2021 price in California cap and trade program

			data-dashboard	
Renewable Energy Certificate (REC) price	$/ kWh	$0.20	https://www.srectrade.com/blog/srec/srec-markets/new-mexico	
Tax credit	$/ kWh	$0.02	Astill and Shumway, 2016	
Renewable Identification Number (RIN) price	$	$1.58	https://www.epa.gov/fuels-registration-reporting-and-compliance-help/rin-trades-and-price-information	Average price of qualified RIN in 2021

Low Carbon Fuel Standard (LCFS) price	$	$187.11	https://ww2.arb.ca.gov/resources/documents/weekly-lcfs-credit-transfer-activity-reports	Average for 2021

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