Small Dairy Climate Change Research: An economic evaluation of strategies for methane emission reduction effectiveness and appropriateness in small and large California dairies

Final Report: Contract No. 17-0750-000-SG

Prepared for the California Department of Food & Agriculture

Submitted by:

California Dairy Research Foundation
2020 Research Park Drive, Suite 110
Davis, CA 95618
Prepared by:

Denise Mullinax, Executive Director, California Dairy Research Foundation, mullinax@cdrf.org

Dr. Deanne Meyer, Livestock Waste Management Specialist, University of California, Davis/UC ANR, dmeyer@ucdavis.edu

Dr. Daniel Sumner, Director UC ANR Agricultural Issues Center and Frank H. Buck, Jr. Distinguished Professor, dasumner@ucdavis.edu

June 30, 2018 through March 31, 2020

Research conducted did not use human or animal subjects

Disclaimer

The statements and conclusions in this Report are those of the contractor and not necessarily those of the California Department of Food and Agriculture. The mention of commercial products, their source, or their use in connection with material reported herein is not to be construed as actual or implied endorsement of such products.

Acknowledgments

The research team thanks those dairy producers who provided information from their specific Alternative Manure Management Program (AMMP) applications. We appreciate assistance from staff at Regional Water Quality Control Boards (Central Valley, San Francisco Bay, North Coast, Santa Ana, and Lahontan), State Water Resources Control Board, San Joaquin Air Pollution Control District and California Department of Food and Agriculture for their assistance. We appreciate California Department of Food and Agriculture staff who provided redacted files from AMMP and Dairy Digester applications for use. Gratitude is extended to Dr. Christine Miller who did the initial data management in the data harmonization process and Zaira Yasmin Joaquin-Morales for her fastidious attention to record harmonization and data management. Thanks are extended to Patricia Price for her involvement in the project and assistance with record harmonization and management.

We appreciate contributions of several additional collaborators. Pablo Valdes-Donoso contributed to the framing of the project and early efforts to assemble and manage relevant data. Elizabeth Fraysse contributed to economic data preparation and analysis. Dr. Kevin Comerford provided useful contribution throughout the project and offered comments and corrections to the draft report.

Finally, Scott Somerville is a co-author of all the economic analysis and especially contributed to the assessment of practices and their costs. Antoine Champetier is a primary co-author to the economic analysis and especially contributed substantial parts of the economic modeling, simulation methodology and the simulation of economic impacts.

CONTENTS

TABLE OF FIGURES

TABLE OF TABLES

EXECUTIVE SUMMARY

The California dairy industry is complex, diverse and dynamic. It grew rapidly for decades before reaching its current size about a dozen years ago, producing about 40 billion pounds of milk and more than $6 billion per year in farm revenue. It has long faced and continues to face complex economic and environmental issues that demand informed, research-based and data-driven public and private responses. The trend for increased herd size and decreased number of herds translates to increased fixed costs per cow in smaller herds when capital improvements are developed.

California's efforts to reduce greenhouse gas emissions have identified methane emissions reductions targets of 40 percent from dairy manure handling from 2013 levels, by 2030. The state initiated two major programs, the Dairy Digester Development and Research Program and the Alternative Manure Management Program, that seek to facilitate voluntary reductions in methane emissions from dairy manure handling in California.

Study Objectives

This research study was sponsored by the California Department of Food and Agriculture to examine relationships between manure handling practices, dairy farm size and methane emissions reductions options. The study begins by describing detailed technical relationships in California dairies. It goes on to quantify manure methane emissions by manure handling practices and dairy farm size and reviews technical applicability of strategies for methane emissions reductions used on farms of different sizes and housing design.

The study turns next to the economic relationships and implications of the highlighted practices. The approach developed a detailed mathematical simulation model calibrated to data on costs associated with manure handling practices, dairy farm size and housing categories. Impacts were projected for different potential configurations of manure handling practices on milk production and methane emissions for each herd size category. Specifically, analyses evaluated how manure handling patterns link to dairy farm size and methane emissions patterns when alternative time horizons were considered.

Manure Management Practices

Detailed description of housing and herd sizes show that 91 percent of mature dairy cows (lactating and dry) in California were in the Central Valley. About 20 percent of mature cows in this region were in herds of 1,035 mature cows or fewer and about 20 percent were in herds with 4,120 mature cows or more. These represent the lower and upper two deciles of Central Valley mature dairy cattle. Since herd housing affects manure handling and emissions, it is important to recognize that about three-fourths of mature cows were in dairies with freestall housing systems (where cows are fed and may lie down in stalls within open sided, roofed permanent structures) about one-fourth were in non-freestall housing (where cows are mainly in corrals, often with shaded areas and an adjacent feeding apron). A large majority of herds (about 74 percent) had some form of gravity or mechanical separation of solids from liquid manure components, which contributed to reduced methane emissions.

About 6 percent of California's mature cows were in Southern California, mostly in San Bernardino and Riverside Counties. These were non-freestall facilities and manure was handled predominantly in a dry form (scraped from corrals and removed regularly). Northern California coastal dairies represent 3 percent of mature cows. These are smaller dairies when compared with dairies from other parts of California. When cattle were pastured, no manure was collected. When cattle were not pastured, solid, liquid or slurry manure was collected. The amount of manure collected varied by location, weather and grazing opportunities.

Analyses of Alternative Manure Management Program practices for freestall and non-freestall facilities by different herd sizes were conducted. At any given herd size, freestall dairies were assumed to collect 2.4 times more manure and had greater emissions when compared with non-freestall dairies. This provided the greatest opportunity for emissions reductions. Across manure treatment technologies, weeping walls had the greatest emissions reductions (about 43 percent) followed by screw press separators (about 24 percent) and stationary inclined screens (about 16 percent). Partial flush to scrape conversion at 30 percent of manure scraped was similar to emissions reductions from screw press separators.

The Alternative Manure Management Program has been used by many producers to install methane emissions reduction technologies. As a percent of herds within a herd size category, less than 10 percent of herds sought funding in herds less than 751 cows and about 15 percent or more of freestall herds sought funding for herd sizes 751 to 2,000. Non-freestall dairies had about 15 percent application rate for herds between 1,751 and 2,500 cows. In the Central Valley far more projects were funded on freestall dairies than non-freestall dairies. More freestall and non-freestall dairies received funding with fewer than 1,250 cows. In the Central Valley 70 percent of funded projects included solid separation. Dairies in the North Coast were funded for compost bedded pack barns (34 percent of projects funded) and solid separation (39 percent). The difference in preferences was a function of how animals were housed and manure was managed.

To achieve useful and interpretable economic simulations, California dairy farms were characterized in one of seven groups of producers, based on herd-size and housing. Different herd distributions of mature cattle were used for economic analysis to incorporate the greatest amount of existing data. Herd sizes of fewer than 500 cows per herd, between 500 and 2,000 cows per herd and greater than 2,000 cows per herd were used to allow greatest inclusion of existing economic data. One group, with fewer than 500 cows per herd, represented organic milk production. The organic farms used more pasture, had much higher costs and sold into a separate high-priced local market. The six groups of conventional dairies included two housing types—freestall and non-freestall, for each of three herd size categories. For these analyses, the seven groups with estimated share of statewide total cows were:

- Organic (less than 2% of cows)
- Freestall, less than 500 cows (about 3.6% of cows)
- Non-freestall, less than 500 cows (about 1.3% of cows)
- Freestall, between 500 cows and 2,000 cows (about 32.9% of cows)
- Non-freestall, between 500 cows and 2,000 cows (about 8.2% of cows)

- Freestall, more than 2,000 cows (43.9% of cows), and
- Non-freestall, more than 2,000 cows (8.8% of cows)

These shares are approximate and were used only as base for the economic simulations that are reported as percentage changes from the baseline. For the smaller herds especially, the precise share has negligible impact on any results. We used data on size distributions in the U.S. Census of Agriculture as discussed in Chapter 7, and information summarized in Section 4.2 related to housing.

In this report herd size and housing groups are used to categorize herds based on manure handling, emissions and projected economic outcomes. The terms upper or lower two deciles or larger and smaller herd sizes (more than 2,000 cows or less than 500 cows) are used in separate sections of the report. These three herd size categories are used to organize the data, analyses and simulation outcomes. However, these are not definitions of large or small dairy farms because the physical and economic relationships in dairy farming are not so simple. Whether a dairy farm is considered larger or smaller depends on many complex considerations. Farms with the same number of cows may be considered larger or smaller depending on the economic and physical context and the purposes of the categorization or analyses. For example, milk production, an alternative measure of farm size, accommodates difference in animal productivity. Other considerations include vertical integration—the degree to which the farm produces its own feed and replacement heifers, and the degree to which it further processes milk into consumer products. For some purposes milk revenue is a useful measure of the size of dairy farms, but that measure can vary from period to period by 50 percent or more depending on the price of milk. Financial value added, the economic returns to own-supplied inputs, can also be a useful measure of dairy farm size that subsumes cow productivity, vertical integration and revenue. Therefore, it is often misleading to refer to a farm with more or fewer cows as simply large or small.

For each group methane emissions reductions and cost change were evaluated compared to a 2013 baseline when some share of dairies in that group shift to an alternative manure handling practice.

The baseline manure collection was a flush system for the conventional dairies and a scrape system for the organic dairies. The five alternative practices evaluated included:

- Compost bedded pack barn (dairies with less than 500 cows)
- Solid separation, with open solar drying
- Solid separation, with composting
- Scrape conversion, and
- Lagoon digesters (not for dairies with less than 500 cows or non-freestall dairies with less than 2000 cows).

Main Results for Economic Impacts of Methane Emissions Reductions

Adopting the manure handling practices listed above would reduce manure methane emissions per cow. These practices were also more costly than the baseline practice. The economic logic underlying the detailed model derived in Chapter 4 is straightforward. Manure handling practices that are costly relative to the baseline reduce potential profitability and economic viability of adopting dairy farms. Groups with larger cost increases per unit of milk production lose out in competition with groups that experience smaller cost increases. In our simulations, as these economic pressures play out over time, they have impacts on aggregate emissions, costs and herd size distributions.

Both manure emissions reductions per cow and cost per cow differed by group. For example, for freestall dairies with less than 500 cows that adopted a compost bedded pack barn, the estimated methane emissions reductions was almost 87 percent compared to the baseline technology. The reduction in emissions was about 65 percent for the non-freestall herds, which had lower emissions in the baseline. The compost bedded pack barn practice raised the cost of milk production by 9 percent per cow—a very large increase in costs, equivalent to half of labor costs.

Adopting a digester reduced methane emissions by almost 83 percent on freestall dairies and by almost 58 percent for the non-freestall dairies. In the scenarios examined, adoption of digesters added very little cost per cow to the dairy farm due to current public (California Climate Investment funds) and private (digester developer company) investments. To date, different business models have been used for digester development with State funds contributing up to 50 percent of the development cost. The remainder of the financing has ranged from 100 to zero percent dairy producer equity owned. Under current practices and policies, non-farm companies have partially financed the construction and operation of some digesters in exchange for use of biogas generated. The biogas produced qualifies for credits under the federal Renewable Fuel Standard and the California Low Carbon Fuel Standard programs.

Alternative manure handling practices affected emissions differently and provided opportunities for dairies with smaller herds to contribute to methane emissions reductions. Installation of digesters on smaller facilities in particular is location specific and requires connection to a cluster biogas line with an end use identified. Not all dairies are located well for digester installation and these dairies are likely to rely on alternative manure management practices to accomplish emissions reductions. Additionally, business longevity risks must also be considered prior to anaerobic digester development. The fixed costs per cow is increasingly greater for smaller dairies to install methane mitigation practices. This is due to both the smaller number of cows over which fixed costs are distributed as well as the increase in project costs due to rising costs of resources needed (concrete, steel, labor).

A series of adoption scenarios were examined across six groups and the manure handling practices were compared to the baseline. Each scenario evaluated the effect of a specific rate of adoption of one of the alternative practices by each herd size group.

Adoption rates for the 2021 base line or zero scenario were identified for what was anticipated in summer of 2019. Scenarios evaluated 30 percent (Scenarios 1 and 3), 40 percent (Scenario 2), variable between 5 and 60 percent (Scenarios 4 and 5) rate of adoption within groups. Implications were calculated within each group for farm costs, price of milk, quantity of milk production and methane emissions reductions. Aggregating across the groups identified impacts—in percentage terms—of a scenario of practice adoption rate on statewide milk production and methane emissions reductions.

For example, Scenario zero considered a set of practices that approximated what will likely to be in place by 2021 after the adoption of new manure handling practices by California dairies since 2013. These assumptions were made pre-COVID-19. As a result of this adoption pattern, and with a 5-year adoption horizon, milk production decreased by about one percent for the smaller dairies and rises slightly for the larger dairies, while the California milk price remains unaffected. Overall methane emissions decline by about 23 percent for all the groups. In this scenario, about 82 percent of the overall decline in methane is contributed by the digester adoption among the freestall dairies with more than 2,000 cows.

Scenario 5 used different adoption rates of the same practices as Scenario zero. With the adoption pattern of Scenario 5, use of only the less costly manure handling practices by the dairies with less than 2,000 cows just about eliminates the reduction in milk production on these dairies observed in scenarios that assume adoption of higher cost practices. In Scenario 5, milk production is essentially unchanged from the baseline for any group and neither total milk production nor the farm price of milk change for California. Because of the low-cost manure handling practices used in Scenario 5, dairies with less than 500 cows contribute very little to aggregate reduction in methane emissions. Under Scenario 5, digester adoption among herds with more than 500 cows contributes 99 percent of the total emission reduction. Aggregate methane reduction reached almost 35 percent over a five-year horizon.

It is useful to put the impacts of adoption of manure management practices that reduce methane emissions in the context of the changes underway in the California dairy industry, especially in the evolution in patterns of dairy farm size. For many years, in California and throughout the United States, consolidation within the industry resulted in fewer and larger dairy herds while aggregate milk production has risen.

In California, for several decades until 2007, the number of dairy herds was decreasing while aggregate milk production and mature cow numbers were increasing. Since 2007, California's total milk production has been relatively stable. This report has considered the economic situation of the California dairy industry in the context of national and global milk markets. The California dairy industry also competes for land and water, especially in the San Joaquin Valley, with industries that produce tree nuts, other tree and vine crops as well as vegetables. The median projection (recognizing inherent uncertainty) used similar aggregate number of milk cows (pre-COVID-19) to be roughly constant looking into the future.

Against this backdrop of a stable number of cows overall, detailed Census of Agriculture data were used for the past three decades to estimate underlying trends in number of cows in each of the three size categories among our groups. Over this period, the number of cows in herds of fewer than 500 cows has declined by an average of about 5 percent per year. This estimated rate was used as part of the baseline to consider the impact of the Scenarios of manure handing practices listed above.

The impacts of the underlying trend toward dairy herd consolidation is more strongly noticeable the longer the time horizon. The empirical logic is clear. As time passes, some of the dairies with fewer than 500 cows exit, while other dairies within this category move into larger herd size categories. The net result is fewer cows in herds with less than

500 mature cows, and more cows in herds with more than 500 cows. A potential exception to the gradual reduction in the number of smaller herds is related to the organic segment found mostly in north coast counties of California. This is a small share of the industry and follows a somewhat different set of supply and demand patterns. In our long-term Scenarios, the number of cows in the organic segment remained unchanged. This specific assumption about organic farms has no measurable impact on the aggregate results.

The next analysis evaluated impacts of changes in manure management practices coinciding with the herd size trends operating over time. For example, Scenario zero, represented the approximate pattern of manure handling practices already adopted and implemented. Data from the 10-year forward projection identified milk production declines among dairies with fewer than 500 cows by about 42 percent. In that scenario, emissions decline only slightly faster, by about 44 percent. Milk production on dairies with between 500 and 2,000 cows decreased by about 14 percent and methane emissions from those herds decreased by about 20 percent. But for the dairies with more than 2,000 cows, underlying trends cause milk production to rise by about 14 percent, while methane emissions decreased by 25 percent. Thus, under Scenario zero the larger herds produce much more milk, but because emissions per cow declines, they produce much less methane in aggregate.

In Scenario zero, overall milk production remains roughly unchanged while California methane emissions are reduced by 25 percent. The reduction in emissions is caused by a combination of two factors. The first is the reduction in manure methane emissions per cow due to adoption of manure handling practices. The second is the shift in the number of cows from practices with higher manure emissions per cow to practices with lower manure emissions per cow. This pattern is stronger over the 20-year horizon with 66 percent decrease in milk production on dairies with fewer than 500 cows and 26 percent increase in milk production on dairies with more than 2,000 cows. Over 20 years, aggregate methane emissions decline by about 27 percent for Scenario zero.

It is useful to consider effects of the underlying herd size trends on results of Scenario 5. Scenario 5 assumed adoption of relatively low-cost manure handling practices on about 10 percent of the dairies with fewer than 500 cows and adoption of digesters on a significant share of the dairies with more than 500 cows, especially the largest freestall herds. When the Scenario 5 pattern of manure handling practices is applied to the baseline with underlying trends toward larger herd sizes, the two forces that each reduce methane emissions reinforce each other.

Over the 10-year horizon milk production on the dairies with less than 500 cows decreased by about 40 percent and methane emissions decreased similarly. However, the freestall dairies with between 500 and 2,000 cows now also reduce manure methane emissions per cow as they adopt digesters. Emissions decreased by 29 percent as milk production decreased by 14 percent on these dairies. On the freestall dairies with more than 2,000 cows, which operate with most of the cows in the state, milk production increased by 15 percent and methane emissions was reduced by 48 percent. Overall methane emissions decreased by about 37 percent.

These impacts are even larger for the 20-year horizon. After 20 years, because of underlying trends in the economics of dairy farm size, milk production and methane emissions among farms with fewer than 500 cows decreased by about 65 percent. Meanwhile production decreased by about 26 percent on the farms with between 500 and 2,000 cows. Milk production increased by 26 percent on the farms with more than 2,000 cows. Despite producing more milk, methane emissions decreased by 43 percent on the freestall dairies with more than 2,000 cows. These farms have a 66 percent digester adoption rate under Scenario 5. The result is that overall, methane emissions from manure management for the state decreased by about 40 percent.

Conclusion

Economic impact of methane emissions reductions varies by herd size and manure management practices employed. Methane emissions from California dairy manure management are declining with adoption of alternative manure management practices and installation of dairy digester projects with biogas capture and use. Continued funding of Alternative Manure Management Program practices provides assistance to dairy producers regardless of herd size to participate in and contribute to manure methane emissions reductions. It is likely that without public funds smaller dairies will be disproportionately impacted by higher fixed costs per cow associated with mitigation measure practice installation resulting in faster migration to either larger herds or cessation of business.

PROJECT INTRODUCTION

Assembly Bill 32 (AB 32, 2006) began California's greenhouse gas (GHG) reductions path. The first step was to determine a statewide GHG emissions limit equivalent to 1990 and return to 1990 emissions 2020. It further established a goal to reduce emissions 80 percent below the 1990 amounts by 2050. Senate Bill 32 (SB 32, 2016) provided an interim target of a reduction of GHG to 40 percent below the 1990 inventory by 2030. As a result of Senate Bill 1383 (SB 1383, 2016) the California Air Resources Board was directed to approve and implement a comprehensive strategy to reduce emissions of short-lived climate pollutants to achieve a reduction in methane and hydrofluorocarbon gasses by 40% and anthropogenic black carbon by 50 percent below 2013 levels by 2030. The California Air Resources Board (CARB) (CARB, 2014) identified that methane was nine percent of California's total GHG emissions. Methane is an important component of the GHG family and is far more potent in global warming potential than carbon dioxide, especially in a shorter term, 20-year horizon. Fifty-eight percent of the state's methane emissions have been attributed to agricultural sources, primarily dairy manure (25 percent), dairy enteric (20 percent), non-dairy enteric (10 percent) and rice (3 percent) (CARB, 2017).

California is home to about 1.7 million dairy cows and nearly as many replacement heifers (USDA, 2020). Cattle consume, digest and convert feed to human edible food (milk and meat). Cattle consume forages (non-human edible food) that, along with other feed (predominantly co-products and by-products of other commodities), are digested by microorganisms in the rumen, which acts as a large fermentation vat. Feces and urine are excreted and comprise manure. Manure managed under anaerobic conditions produces methane.

Dairy operations provide critical economic contributions to local rural communities in the form of steady, year-round on-farm employment, allied industry careers beyond the farm gate, and local community civic support. Understanding the whole-farm environmental and economic impacts of implementing methane emission reduction strategies for both small and large operations is needed to foster wise investment of time, management and capital resources.

Similar sized dairy operations have similar housing and manure handling practices. Yet large variations exist in how individual facilities are operated. Local climate (precipitation, fog and solar radiation) play a role in manure handling. Dairies of similar size also differ in current equipment, manure system handling capacity, and resource management. Labor available for manure handling and management is variable and increasingly becoming less available.

Dairy managers, industry leaders and policy makers need credible and relevant information regarding multiple methane emissions reduction options and strategies, including associated analyses of costs and revenues. Although several research projects have recently begun to better understand the methane emission reduction potential of various manure management strategies, none include a thorough assessment for the applicability of those strategies to operations based on size, scale and existing production facility configuration. Both short- and long-term economic impact assessment of methane reduction potential for small and large dairies is needed to allow for optimal investment and greatest environmental benefit.

Investment of public and private funds is necessary to reduce manure methane emissions. Baseline information regarding manure management and treatment are unknown statewide. Previous work (Meyer et al., 1997; Meyer et al., 2011) surveyed manure management in Glenn and Tulare Counties and Tulare, Fresno and Madera Counties. These studies focused on management practices irrespective of herd size.

It is unknown if the best methane reduction strategies are similar regardless of dairy size. Understanding baseline manure management conditions and cost-effective and appropriate methane emission reductions strategies for both smaller and larger dairy facilities is paramount to achieving the 40% reduction goal and ensuring efficient and effective investment of resources. Each of seven tasks were completed to provide the required analyses.

This project specifically addressed the question of how smaller dairies may differ from larger dairies in manure management practices and potential methane emissions reduction strategies. Each of seven tasks was analyzed and is presented in subsequent chapters. For the purpose of these analyses two teams of researchers were used. Tasks 1 through 3 were conducted by investigators familiar with dairy housing and manure management. Tasks 4 through 7 were conducted by investigators familiar with dairy economic analyses.

Project tasks:

1. Categorize California dairies by herd size, animal housing, manure treatment and storage practices in order to evaluate best metrics for small and large dairies.
2. Quantify estimated methane emissions as low, high and average based on herd size (small and large), housing design and manure handling categories.
3. Review strategies and technologies currently or potentially used to reduce manure methane emissions for applicability to small and large dairies.
4. Compare economic impact of methane emission reduction strategies identified on small dairies versus large dairies.
5. Compare whole-farm economic and environmental impacts of methane emission reduction strategies identified on small and large dairies.
6. Compare methane reduction potential at small and large dairies, presented as a cost-benefit analysis of environmental and economic impacts on an estimated 1, 5 and 10-year scale.
7. Model and project sustainability (especially economic feasibility) of small dairies in California over an estimated 5, 10 and 20-year time scale in consideration of new environmental regulations including reductions for methane emissions, inflation, interest rates, feed prices, dairy product prices, labor costs and location of the dairies.

CHAPTER 1 CATEGORIZE CALIFORNIA DAIRIES BY HERD SIZE, ANIMAL HOUSING, MANURE TREATMENT AND STORAGE PRACTICES IN ORDER TO EVALUATE BEST METRICS FOR SMALL AND LARGE DAIRIES.

Introduction

Dairy farmers are dedicated and innovative individuals. Herd size (number of mature and replacement animals) and productivity changed as new advances occurred. Mechanization during the industrialization of agriculture first reduced the labor needed to grow crops. Later, electrification of rural areas led to mechanical milking machines and then refrigeration of milk (bulk tanks). Research breakthroughs in sperm collection and preservation led to artificial insemination. Nutritional research led to greater understanding of animal needs and the ability to formulate rations for specific energy, protein, and fiber requirements of cattle. As herd sizes increased, utilization of allied industry services also increased. What was once done by farm labor became a fee for service contract.

The face of today's dairy industry began during the time of farm specialization in the 1950s and 1960s (Blayney, 2002). Defining smaller or larger herd sizes is relative to herd size distribution at a specific point in time. Information about changing herd size by geographic area is available since the United States Department of Agriculture (USDA) conducts a census every five years. The USDA National Agricultural Statistics Service (NASS) identifies facilities by size. In 1978, the USDA NASS data for milk cow herd size included a category for 100 or more dairy cattle. Additional categories were added as herd sizes grew and the number of herds declined. In 1992 and 1997, the 500 to 999 and 1,000 or more categories were added. The 2007 census included a 2,500 and greater category, and in 2017 the analysis included a category for herds with 5,000 or greater head. In each of these census years discussed, the smallest category was 1 to 9 milk cows.

In addition to the USDA NASS, there are regulatory Acts with herd size definition. The Reauthorization of the Coastal Zone Management Act (1990) identified specific categories of nonpoint source pollution for each coastal state to incorporate into their programs. Small dairies were defined as 20 to 69 head (28 to 97 animal units). Small dairies were to design and implement manure management systems that included collection and control of waters contacting feed and manure nutrients up to and including a 25-year, 24-hour storm event. Large dairies (70 or greater head; greater than 98 animal units) were required to incorporate specific storage structure design criteria for facility wastewater and the runoff from the 25-year, 24-hour storm event. Both sized facilities needed appropriate existence and management of waste utilization facilities. Separate Federal Regulations, the Clean Water Act, as amended (1972), defined the term animal feeding operation as a lot or facility where animals have been, are, or will be stabled or confined and fed or maintained for a total of 45 days or more in any 12-month period and crops, vegetation, forage growth, or post-harvest residues are not sustained in the normal growing season over any portion of the lot or facility. Herd size categories were defined as: small (less than 200), medium (between 200 and 699) and large (700 and more) mature dairy cow herds, whether milked or dry. Although many modifications to the Clean Water Act have occurred since 1972, these categories and their numeric definitions have remained in place (US EPA, 2012).

All California dairies generate liquid manure from the milking parlor. This includes water used for udder hygiene, to clean milk contact surfaces and to wash down the milking barn area. Federal and State regulations prescribe mandatory equipment and barn cleaning required to maintain Grade A status. Manure and milk residue collected is transferred to liquid manure storage. Milk barn water generation was evaluated and highly variable in the Central Valley (Meyer et al., 2006). Once milk is harvested it goes through plate coolers for heat exchange to transfer heat from milk (chill) to water or propylene glycol before milk enters the bulk tank. Inclusion of ice chillers on dairies during the last 15 years has reduced the fresh water needed to cool milk and ultimately reduced the total volume of the liquid waste stream.

Animal housing and facility infrastructure are designed and built with specific manure collection and handling practices. Two predominant housing types exist in California (Meyer et al., 2011). Freestall housing consists of an open barn structure typically joined with a corral. The barn roof covers a drive through feeding lane as well as animal housing. Freestalls are open cubicles that provide sufficient space for animals to rest comfortably on a clean, dry environment and minimize injuries to animals. These are aligned in a row perpendicular to the feeding lane. Cubicles are aligned so animals on one side of a pen are parallel to one another and are nose to nose with animals on the opposite side of their cubicle. The number of rows of freestalls within a pen may vary (two rows head to head is most common). A center drive lane is present with animal pens on either side. This lane is utilized to deliver feed to cattle. Feedline misters or soakers are used to modify ambient temperature and cool cattle when temperatures are elevated. Freestalls are bedded with dried manure usually. Almond shells or rice hulls may be used to extend dried manure use. Sand is an alternative which is not available or cost effective in most locations. Sand requires additional management to minimize damage to pumps in the manure system. Manure deposited on concrete surfaces associated with freestalls is collected and transported to liquid manure storage structures.

Non-freestall housing consists of earthen lots or corrals. Drive lanes are present for feed delivery. Similar to freestall facilities, cattle stand on concrete feed aprons to access feed. Manure deposited on earthen lots dries and is managed in its solid form. Manure deposited on the concrete feed apron may be scraped into earthen lots and distributed to maximize solar drying or may be flushed or scraped for liquid/slurry storage.

Manure collected in the liquid form will gravity flow to the liquid storage structure. Liquid structures may be designed for storage or treatment depending on initial retention time and volatile solids loading rate design criteria. In some instances, pumping is required to get manure to its final destination. Solid liquid separation is accomplished by mechanical (stationary inclined, vibrating or inclined screen with drag conveyor paddles) or gravity systems (concrete basins with small dewatering area, small or large earthen basins, or large concrete lined basin with large side dewatering surfaces made of tri-bar flooring or other durable material). When solid liquid separation is used it prevents entry of solids into the storage/treatment structure.

Modifications to manure collection, transfer, treatment and storage must be done with a complete analysis of the ramifications to the entire manure stream management and potential impacts to animal husbandry.

Key to understanding potential use of methane emission reduction strategies is understanding how manure is managed and if differences in manure management exist based on herd size. The approach for this Task was to obtain and harmonize existing public data to describe animal housing and manure management systems present on California dairies.

Materials and Methods

Task 1.1: Obtain records of dairies from Regional Water Quality Control Boards and San Joaquin Valley Air Pollution Control District to identify herd sizes, animal housing and manure management system design.

Data of mature cows (milking and dry) from Regional Water Quality Control Boards (Region) 1 (North Coast), 2 (San Francisco Bay), 5 (Central Valley), 6 (Lahontan) and 8 (Santa Ana), San Joaquin Air Pollution Control District (SJVAPCD), and the State Water Resources Control Board (SWRCB) Fee Unit were obtained and harmonized (Figure 1.1). Direct dairy information was not obtained from other regions as they have less than 5 commercial dairies each. These herds were identified from the SWRCB Fee Unit or personal communication. The term mature cows is used to represent lactating and dry (not lactating) cows at dairies. This term is used by Water Regulatory Agencies in California. Lists for Grade A and Grade B dairies were obtained from the California Department of Food and Agriculture (2018). List contents were current as of November, 2018. Lists have no animal information inserted and were revised based on November, 2019 SWRCB Fee Unit information when dairies not on the list could be identified and cross referenced to the previous list from the California Department of Food and Agriculture. No one list contained all information needed to fully describe herd size, animal housing and manure management systems. San Joaquin Valley Air Pollution Control District permit information (2016) provided information on housing and some information on manure management. The animal numbers represented facility capacity numbers and not necessarily actual animals at the facility. The SWRCB Fee Unit list was used to identify mature cow herd size, the basis for fee calculations. All lists were used to verify location and when possible herd housing and manure management characteristics. An aerial analysis of each dairy was conducted to verify select information in SJVAPCD permits, animal housing and manure collection/handling systems. Inconsistencies were resolved by roadside verification of facilities or by contacting an individual familiar with the facility. Figure 1.1 depicts data harmonization processes.

Facilities were binned by 250 mature cattle intervals. Intervals were identified to capture roughly the lower and upper two deciles, and the remainder of mature cow numbers for dairies in Region 5. Figure bin values differ in Region 5 for herd sizes over 3,000 mature cows due to fewer herd numbers.

Task 1.2: Determine the use of mechanical or gravity separation systems, liquid manure storage impoundments or anaerobic digesters on farm related to facility size and type.
Analysis evaluated aerial images of dairies in the Central Valley to identify presence of gravity separation systems (small or large) and manure storage/treatment ponds. Presence or absence and actual number of separation and storage or treatment ponds were documented. Analysis of each dairy and its manure treatment process was completed for each dairy in the Central Valley to determine the use of mechanical or gravity separation systems, liquid manure storage impoundments or on-farm anaerobic digesters. The analysis of Google Earth images was coded to identify if liquid manure storage structures were likely to be handled as gravity separation (solids removed on some regular interval) or as liquid storage. Gravity separation systems (GSS) were further refined by looking at facilities chronologically to see if solids were removed on any regular interval or if structural surface area size was narrow enough and sized appropriately to be managed as a separation system. Small gravity separation systems were identified based on professional judgment and assumed to have solids cleaned out less than every six months. Large gravity separation systems were assumed to have solids cleaned out more than every six months. Presence of mechanical separators was identified by data in SJVAPCD permits and verified with aerial analysis. However, functionality of separators was not determined. Presence of anaerobic digesters or use of vacuum manure collection systems was identified by SJVAPCD permit information.

Detailed information regarding manure management is not part of the Annual Reports dairy operators submit to their Regional Water Quality Control Board (dairies in Regions 1, 2, 6, and 8). Professional experience from farm visits made prior to this project was used to describe manure management practices in these Regions.

Task 1.3: Evaluate and analyze herd size by manure collection, treatment and storage categories.
Integrate information from Task 1.1 and 1.2 to represent manure collection, treatment and storage categories by herd size.

Task 1.4: Evaluate a subset of Waste Management Plan volatile solids loading rate and liquid storage retention time, volume and surface area by herd size and/or pounds milk produced.
A random subset of Waste Management Plans was obtained from Region 5. These Plans were developed by Professional Engineers as a requirement of the Dairy General Order to identify storage needs and submitted in 2012 per the General Order requirements. Plans were reviewed and preliminary analyses were conducted to determine relationships between volatile solids loading rate and liquid retention time, or volume and surface area of storage area by herd size.

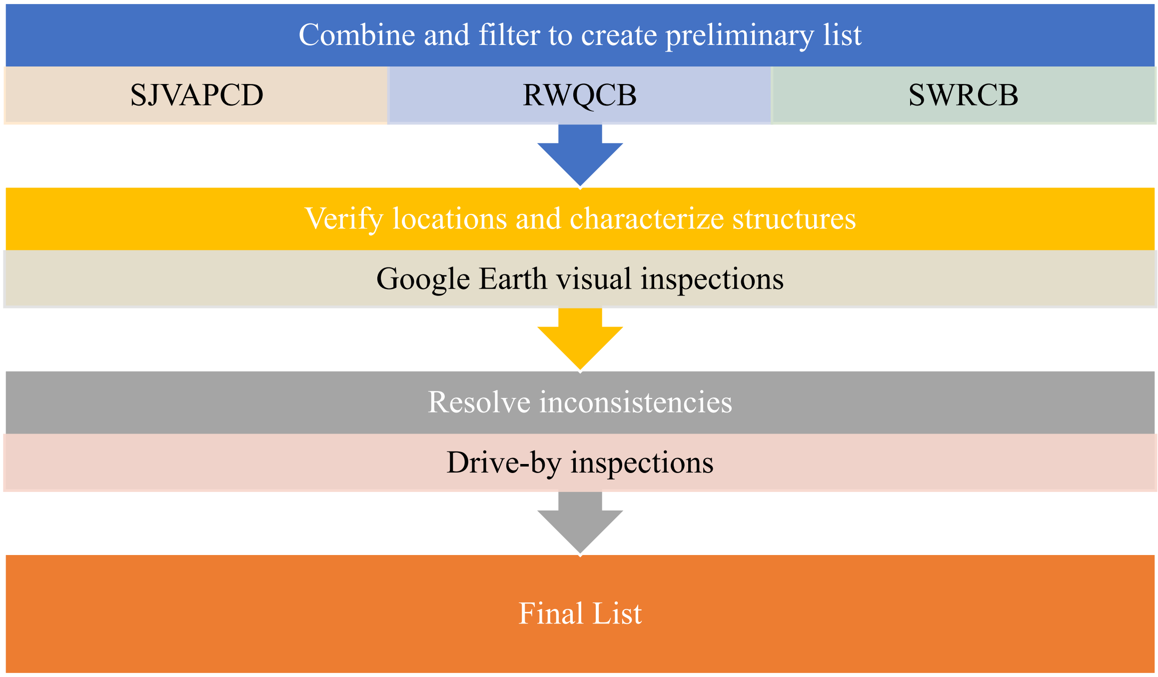


Figure 1.1 California dairies list construction process. Records were obtained from San Joaquin Valley Air Pollution Control District (SJVAPCD), Regional Water Quality Control Board records (RWQCB), and State Water Resources Control Board (SWRCB) fees division.

Results

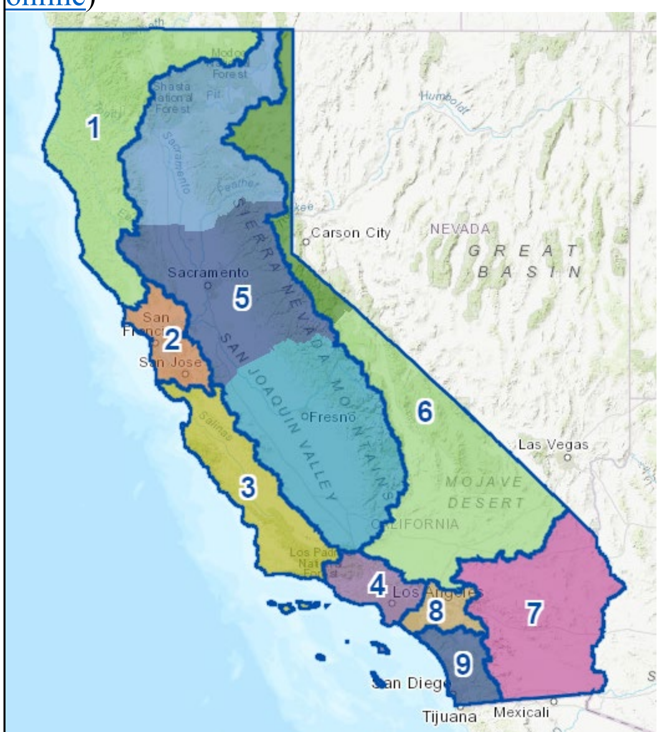
Task 1.1 Herd size, animal housing and manure management system design.
Tremendous regional differences exist in California dairy herd numbers and animals (Table 1.1). Herd size distributions are not normally distributed. Distribution curves have positive skew and are leptokurtic. Herd size distribution is shown in Figures 1.2 (Region 1), 1.3 (Region 2), 1.4 (Region 8) and 1.5 (Region 5).

Region 5 has 90.99 percent of milking and dry cows in California. Region 8 has 4.33 percent of milking and dry cows in California. Together, mature cows (milking and dry) in Regions 1, 2, 6, 7 and 9 make up the remainder (4.68 percent). Average herd size ranged from 333 (Region 1) to 2,802 (Region 6).

Table 1.1 Dairy herd number, size and cumulative animal count by geographic region.

Regional Water Quality Control Board [1]	Herd number	Animals[2]	Animals as percent of CA dairy herd	Herd size range	Average (Standard Deviation)
1	114	38,016	2.14	30-1,700	333 (270)
2	38	14,342	0.81	40-950	377 (204)
5[3]	1,116	1,615,013	90.99	36-10,776	1,447 (1,384)
6	8	22,126	1.25	1,540-4,600	2,802 (1,599)
7	2	3,600	0.20	800-3,998	2,599 (1,326)
8	66	76,922	4.33	215-5,000	1,165 (787)
9	4	4,987	0.28	319-1,955	1,247 (686)
Total	1,348	1,775,006			

[1]Regional Water Quality Control Board jurisdiction: 1, North Coast; 2, San Francisco Bay; 5, Central Valley; 6, Lahontan; 7, Imperial; 8, Santa Ana; 9, San Diego (available online)



[2]Mature (lactating and dry) cows.
[3]Includes 8 pasture dairies containing 3,874 cows.

Coastal dairies (Regions 1 and 2) have smaller herd sizes when compared to dairies in other regions of California. Coastal dairy herd size is based on land available for pasture or cropping, access to water, labor availability, and ability to sell milk. As a group, dairies in these regions are older with some barns more than 100 years old. Many dairies produce organic milk, thereby restricting their feed purchase and milk market options. Some herds have processor-imposed limits on milk production.

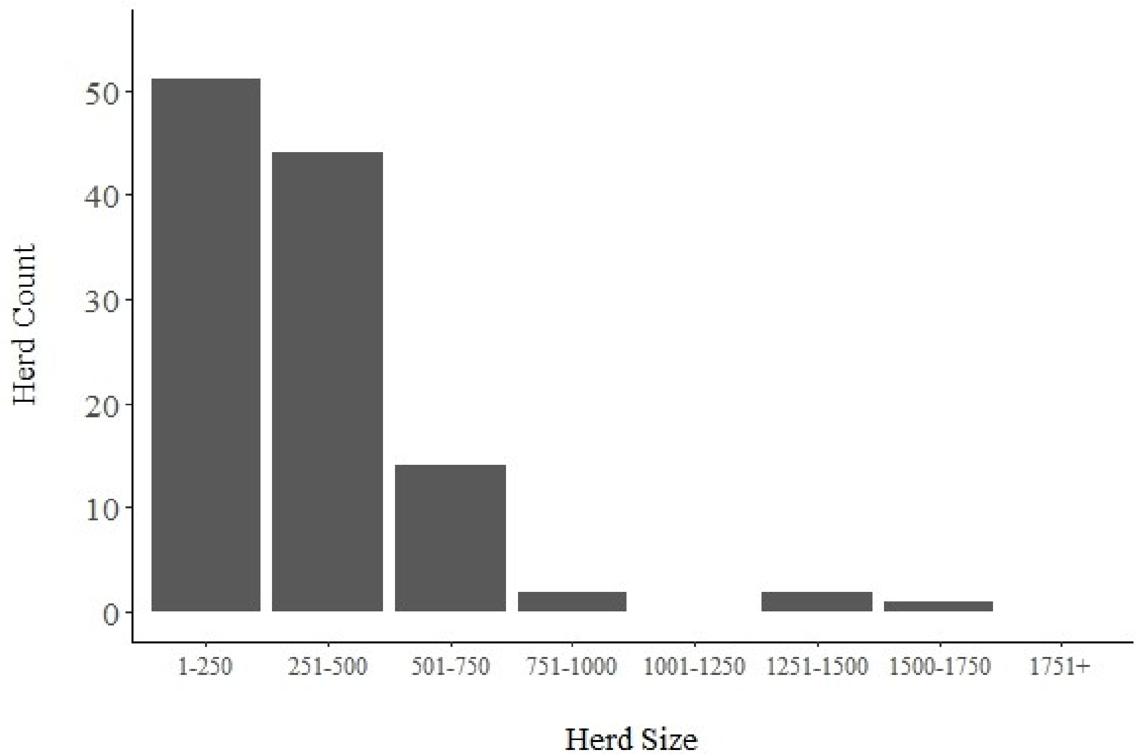


Figure 1.2 Distribution of dairy herd count by size in Region 1, North Coast.

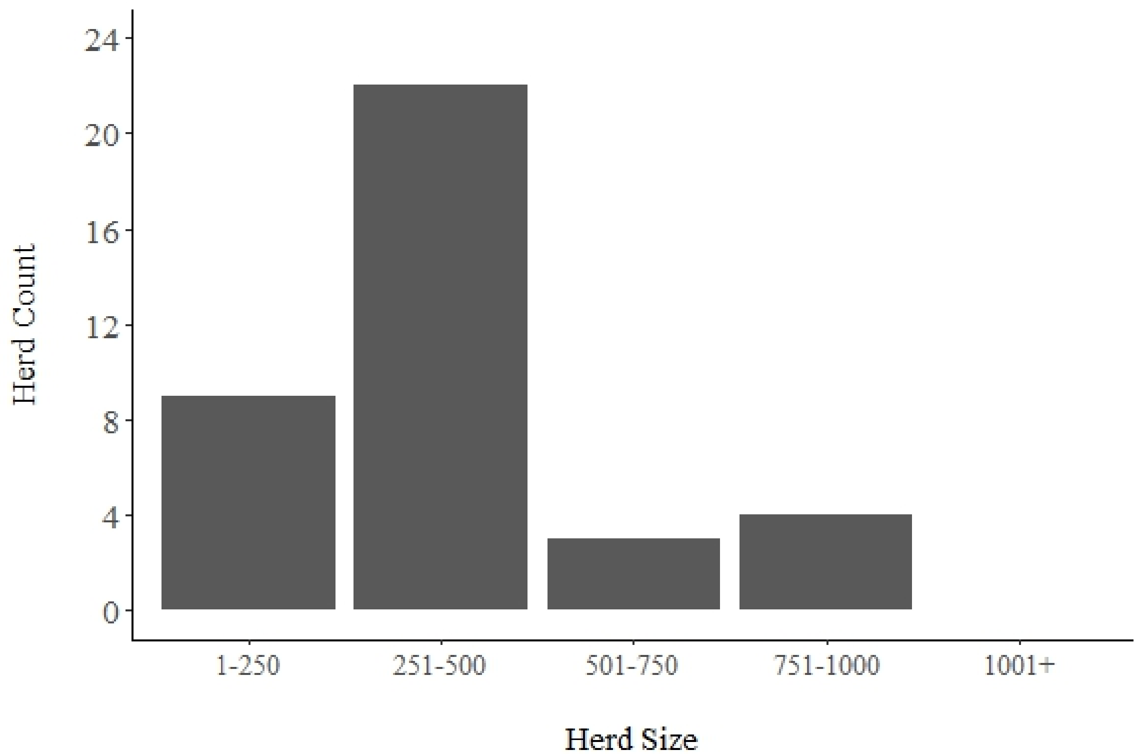


Figure 1.3 Distribution of dairy herd count by size in Region 2, San Francisco Bay.

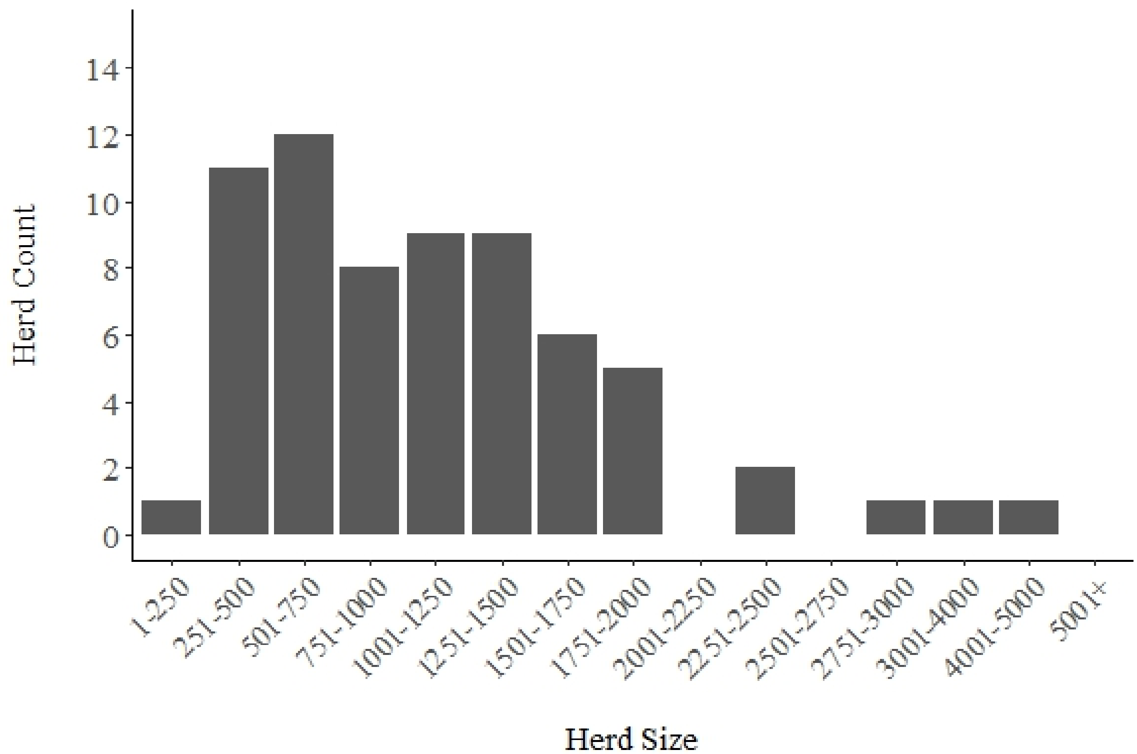


Figure 1.4 Distribution of dairy herd count by size in Region 8, Santa Ana.

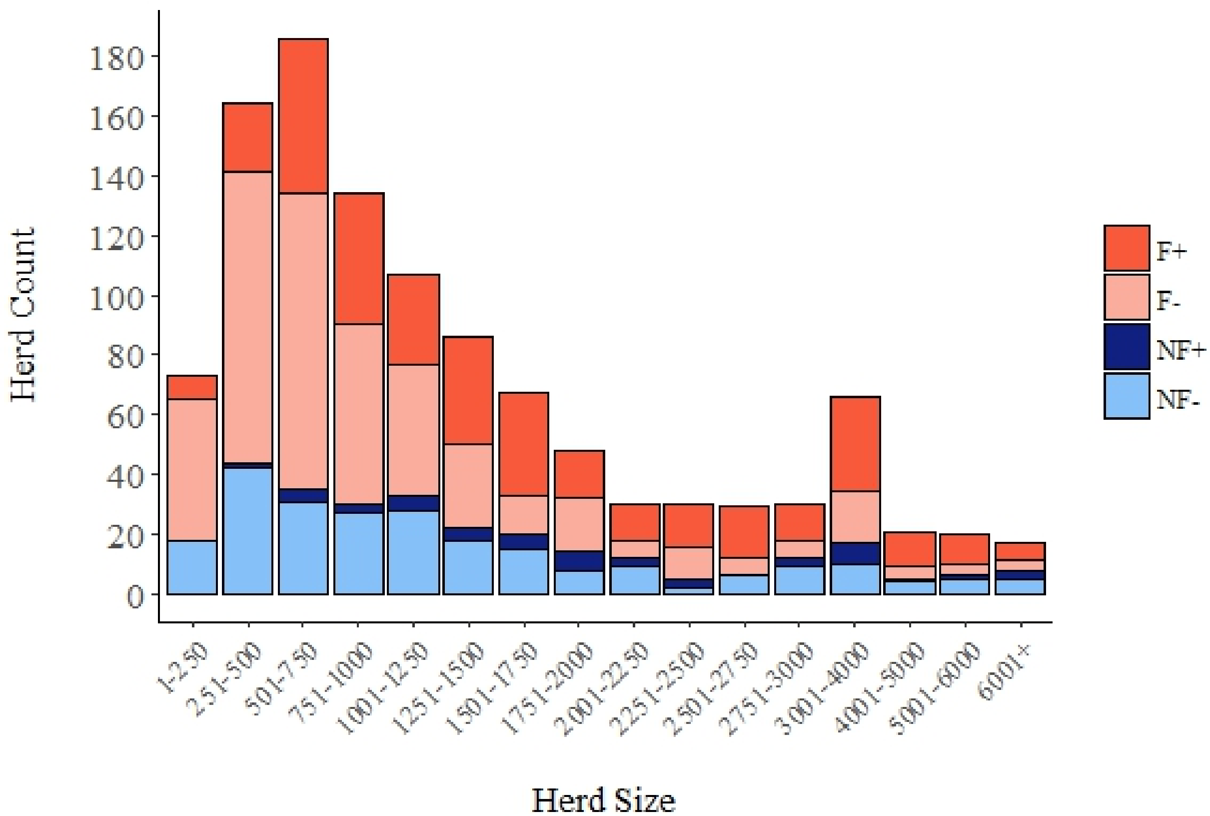


Figure 1.5 Herd size distribution in Region 5 dairies by presence (+) or absence (-) of mechanical separator for dairies with freestall housing (F) and non-freestall housing (NF). Pasture-based dairies not included.

Dairies in Region 5 mostly use freestalls for lactating cow housing (74.10 percent) compared with those dairies that have no freestalls (25.90 percent, Table 1.2). Animals housed at facilities that have freestalls make up 71.29 percent of the Region's dairy herd. Note, not all of these animals (particularly dry cows) are typically housed in freestalls when freestalls are present. Herd population and animal counts are summarized in Table 1.3 by separating out the lower and upper two decile groups of mature cows. Statewide, the lower two deciles of herds resides on dairies with 385 mature cows.

Table 1.2 Percent of herd and mature cow (animals) and distribution by housing type for Region 5 (Central Valley) dairies.

Lactating cow housing type	Herds	Animals
Freestall	74.10	71.29
Non-freestall	25.90	28.71

Table 1.3 Distribution of mature cows by herd size in Region 5 (Central Valley; includes eight pasture herds).

Mature cows per herd	Number of herds	Percent of herds in category	Mature cows	Average herd size (standard deviation)
36 to 1,035	573	51.34	322,153	562 (255)
1,040 to 4,100	487	43.64	966,726	1,985 (799)
4,120 plus	56	5.02	326,134	5,824 (1,518)

Task 1.2 Determine the use of mechanical or gravity separation systems, liquid manure storage impoundments or anaerobic digesters on farm related to facility size and type; and Task 1.3 Evaluate and analyze herd size by manure collection, treatment and storage categories.

Dairies in Regions 1 and 2 utilize a variety of animal housing and manure collection techniques. Professional experience based on farm visits to one-third to one-half of these dairies is the basis for the information herein. Liquid manure is generated from harvesting milk and washing down milk contact surfaces. Flushing to collect manure from animal housing areas is uncommon in these Regions. Typically, manure in animal housing areas (loafing or freestall barns) is scraped and stored as a solid, semi-solid or slurry. Manure is land applied by spreader, honey wagon or irrigation.

Dairies in the northern part of Region 1 utilize pasture for most of the year (Humboldt and Del Norte Counties). The cooler climate, longer rainy season and shallow depth to groundwater allow for greater pasture season and use. Presence of groundwater provides water for pasture irrigation when needed. Dairies in the southern part of Region 1 or in Region 2 use pasture for less than 6 months per year (Sonoma and Marin Counties) unless irrigated. Water is scarce for most dairies in this area. Summer pasture is virtually non-existent. The exception is dairies that use municipal treated water for irrigation. Typically, rainfall is greater for dairies in Region 1 and 2 than in other parts of California. Predominantly, manure is scraped and stored as a slurry, semi-solid or solid, or it is not collected (land applied by animals on pasture).

Few dairies in Regions 1 and 2 continue to use mechanical separators. Two dairies in these Regions have operational anaerobic digesters.

Dairies in Region 6 (Lahontan) and Region 8 (Santa Ana) minimize parlor water use. Liquid manure is generated from harvesting milk and washing down milk contact surfaces. Cattle are housed in corrals and no freestall facilities are present. Animal housing areas utilize scraping and solar drying as the primary manure management practice. South Coast Air Management District

Rule 1127 (SCAQMD, 2004) is applicable to dairies in Region 8. Rule 1127 requires solid manure be cleaned out four times per year. At one point there was an anaerobic digester on a Region 6 dairy.

Dairies in Regions 7 (Imperial) and 9 (San Diego) are non-freestall facilities with dry manure scraped and hauled two to four times per year. Feed apron manure is scraped in these areas and does not enter liquid anaerobic storage system. Manure from the harvesting milk and washing down milk contact surfaces enters liquid manure storage. One dairy in Region 7 has an anaerobic digester.

The majority of California's dairy cattle (90.99 percent) reside in Region 5 (Central Valley). Animals in this region are housed in freestalls with access to corrals, or in corrals with or without shade structures. Specific practices are required to mitigate particulate matter (dust) and volatile organic compound emissions for dairies in the SJVAPCD jurisdiction (SJVAPCD, 2004; SJVAPCD, 2010). Dry manure from corrals is removed four times per year. For many dairies with freestalls where manure is collected via flush, flushing occurs more frequently than the milking schedule. Based on SJVAPCD information, 24.23 percent of non-freestall dairies utilize flush with scrape systems for manure collection. The remaining non-freestall dairies utilize scrape systems for manure collection. No differentiation was made in these permits regarding the percent of manure collected via flush versus scrape activities.

Baseline data from 2016 identified 1.16 percent of dairies used vacuum collection (partial or complete) of manure from mature cows. Flushing may also occur at these dairies. Five dairies outside of the SJVAPCD had digesters installed in recent years. Some are still functional. Twelve dairies within the SJVAPCD identified digesters present, although some were not functional (personal knowledge) at the time data were collected. These anaerobic digesters were installed prior to 2015, the beginning of the Dairy Digester Development and Research Program. Definitions of weeping walls and aerators were not included in the SJVAPCD permitting process. Yet, 1.01 percent and 1.52 percent of herds identified at least one weeping wall or the presence of aerators.

Solid liquid separation occurs with different manure handling techniques. Liquid manure will gravity flow through a gravity separation system. Systems are designed based on frequency of clean-out. Settling basins are typically concrete lined structures with three sides and a bottom. Water enters, is slowed, and then exits. This allows dense particles to settle along with some fibrous material. Clean out frequency is typically less than 45 days. Larger gravity settling systems are cleaned out less frequently (3 months to 2 years). Greater retention times allow for greater accumulation of solids when compared to smaller gravity separation systems. The 2019 benefit calculator used for AMMP applications does not incorporate the use of these systems. Microbial decomposition does occur in these cells; yet, volatile solids are physically removed at the time of clean out from gravity separation cells. The regularity of solids removal is design and management dependent.

For Region 5 dairies, 58.16 percent use some type of gravity separation system; 36.49 percent have a mechanical separator; 25.69 percent use no solid separation system; 20.34 percent use both gravity separation systems and a mechanical separator (Table 1.4). Previous research (Arndt et al., 2018) indicated methane emissions did occur from gravity separation systems.

The focus of detailed analyses of herd distribution by separation type focused on mechanical separators. Use of mechanical separators by herd size and by housing type (Figure 1.5) are presented. Presence of mechanical separators increased as herd size expanded beyond 1,250 milking and dry cows. Roughly 10 to 15 percent of herds (range 1 to 250, 251 to 500 milking and dry cows) had mechanical separators present. Mechanical separators were present on 32.32 percent of herds in 501 to 1,250 milking and dry cow range. Mechanical separators were present on 53.74 percent of herds greater than 1,251 milking and dry cows. The combinations of gravity separation system type (small or large) and mechanical separator by housing type are presented (Figures 1.6 and 1.7). Facilities with no separation system (gravity or mechanical) are presented (Figures 1.8 and 1.9).

Table 1.4 Percent of herds with solid liquid manure separation by manure treatment system for dairies in Region 5.

Use of mechanical separator	Use of gravity separation system	
	NO	YES
NO	25.69	37.82
YES	16.15	20.34

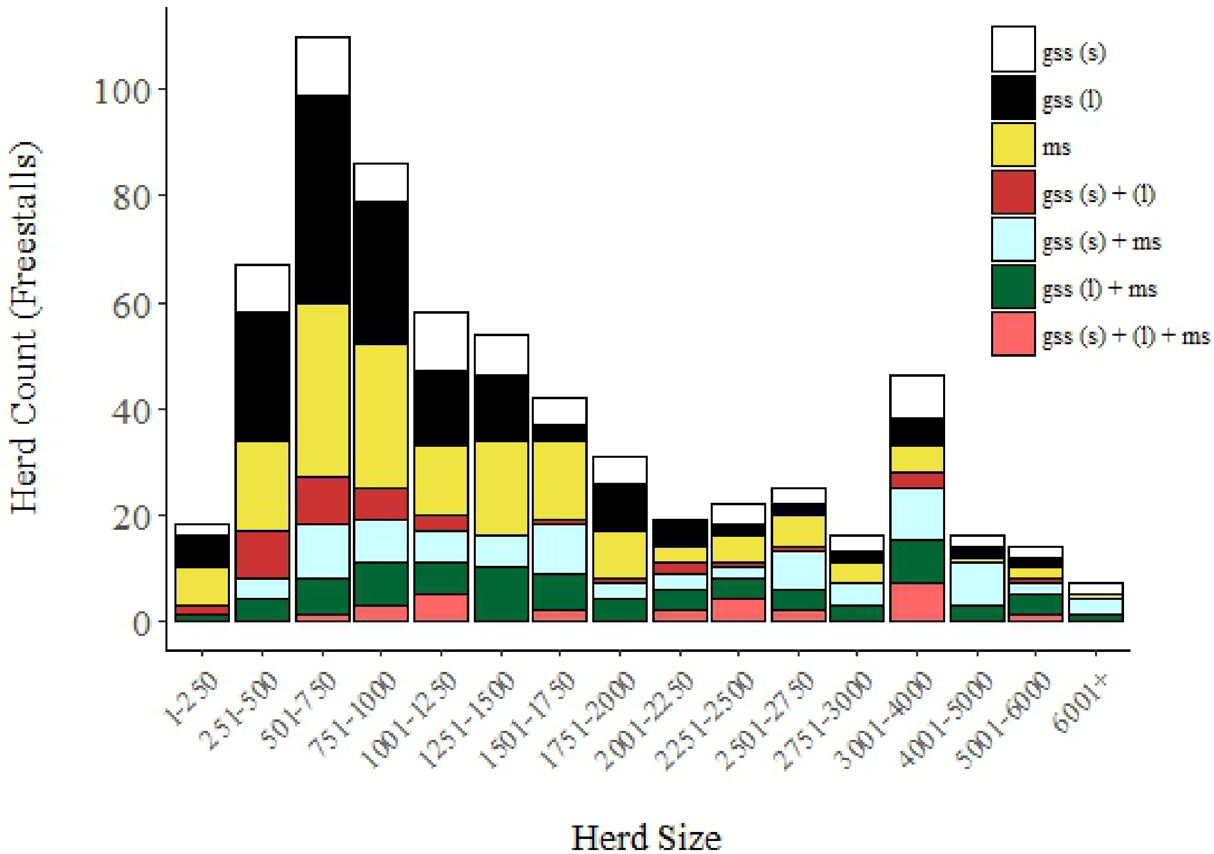


Figure 1.6 Herd size distribution in Region 5 dairies by presence of small (gss (s)) or large (gss (l)) gravity separation system and or mechanical separator (ms) for dairies with freestalls.

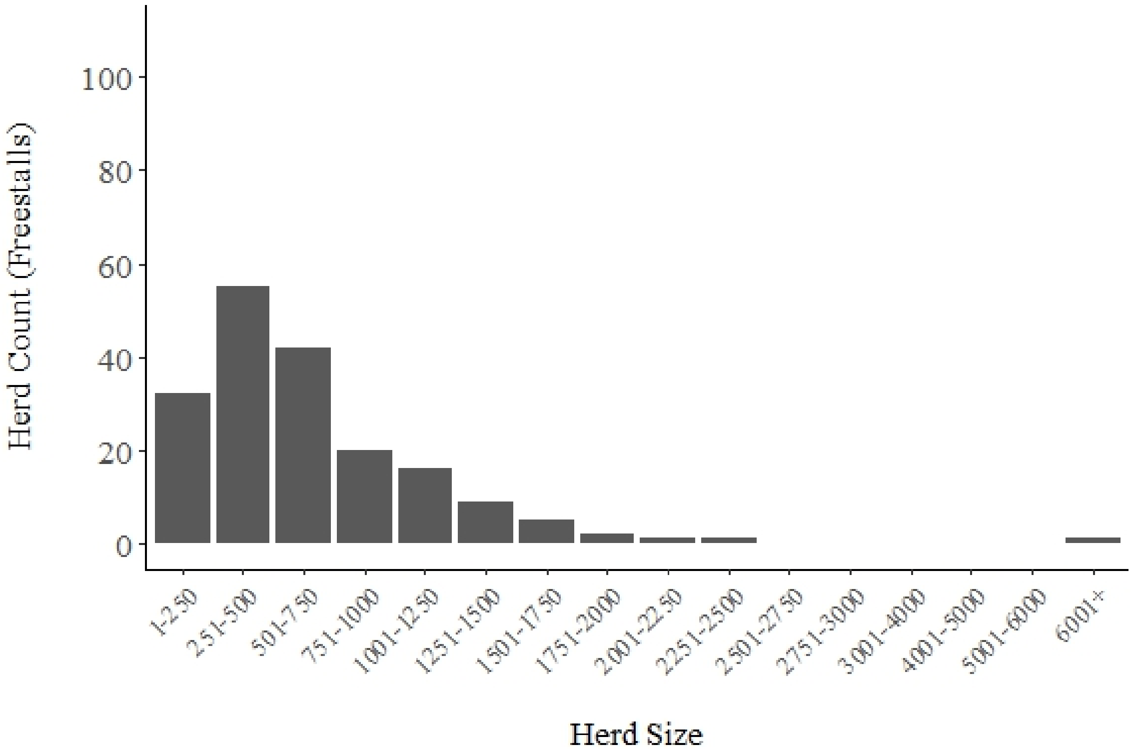


Figure 1.7 Herd size distribution in Region 5 dairies by absence of gravity separation system and mechanical separator for dairies with freestalls.

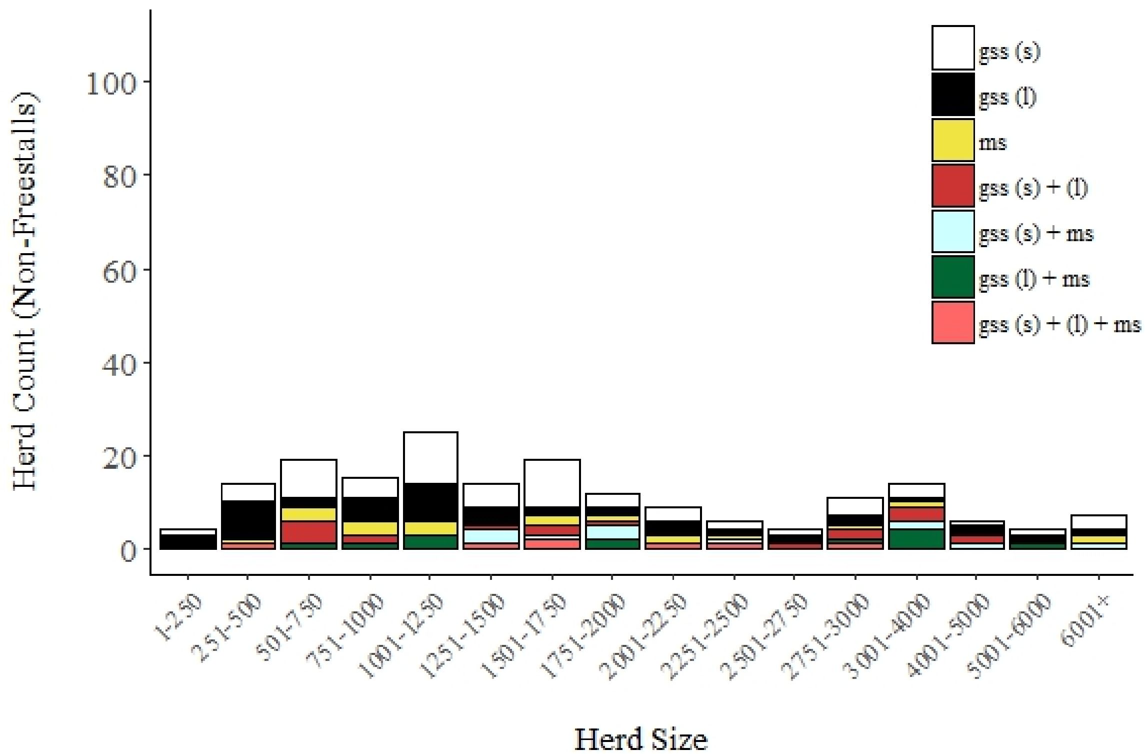


Figure 1.8 Herd size distribution in Region 5 dairies by presence of small (gss (s)) and or large (gss (l)) gravity separation system and or mechanical separator (ms) for non-freestall dairies.

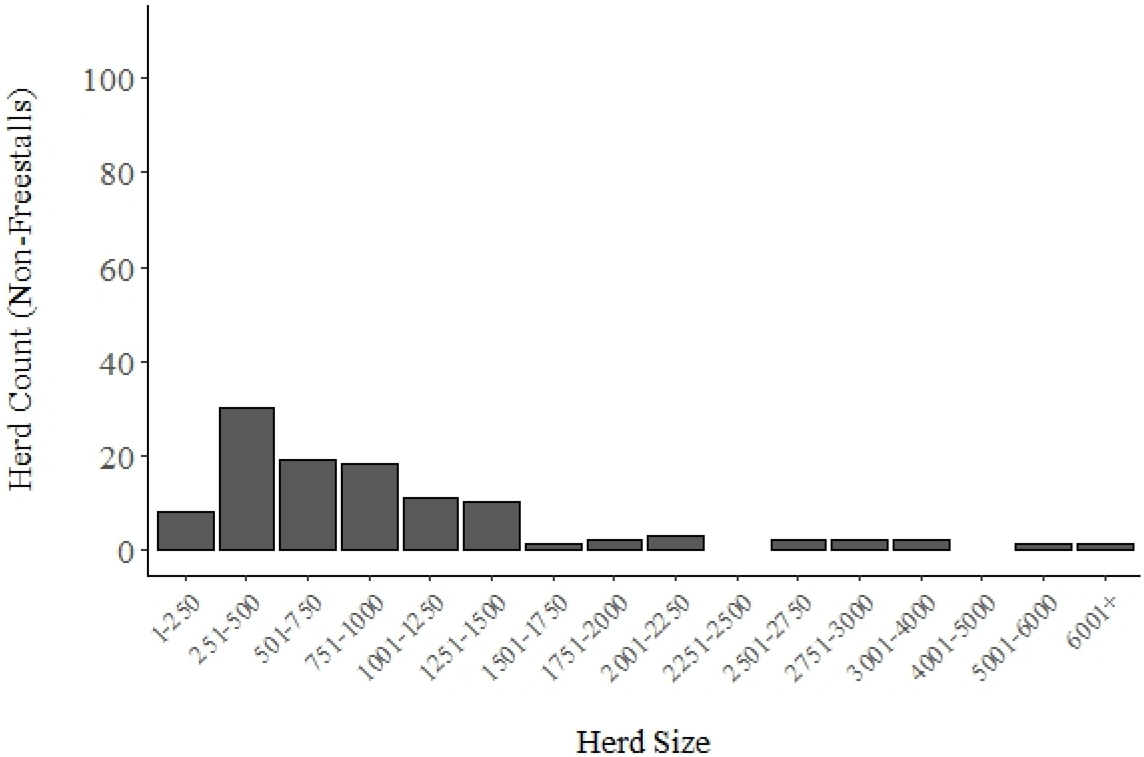


Figure 1.9 Herd size distribution in Region 5 dairies by absence of gravity separation system and mechanical separator for non-freestall dairies.

Task 1.4 Waste Management Plan evaluation.
A random subset of Waste Management Plans was evaluated to determine if greater understanding of the manure handling system could be obtained. Difficulties arose as each engineering firm utilized its own process. Plans were not consistent in determining loading rates. Some identified base assumptions for manure collection. Most did not include calculations for volatile solids collected. All had detailed information or assumptions used for water generated at facilities being collected through the liquid system. Most firms included volume of gravity separation cells in total storage calculations. Inconsistencies existed (due to lack of uniform definition) in description of gravity separation cells. Tremendous variability existed in storage pond design depending on soil type and depth to water table. In some areas, ponds were partially above ground. In other areas, ponds were completely in ground. Storage volume and surface area were variable. Some larger surfaced ponds (shallow) were similar in surface area to deeper ponds regardless of herd size. Historic information for each facility including design criteria at original build with animal numbers and productivity and additional cattle and manure collection/treatment/storage capabilities added over time may have improved interpreting information in Waste Management Plans.

Discussion
Data harmonization activities were challenging as each agency maintained their list of individual operations with permits, and these lists do not always have a common variable for cross reference purposes. The list of dairies maintained by a specific agency serves the agency's need.

No universal variables were included in these lists. Dairies were identified by the owner and or operator. The address was a physical address or a mailing address. Addresses were associated with where to send fee bills, where to send compliance information or where to go to make a site inspection. Some lists used names of owners and not names of operator or herd name. Names were not consistently spelled the same on all lists. Tremendous effort was used to harmonize the information. Since lists were predominantly obtained from Regional Water Quality Control Board sources, the geographic references used in the results refer back to Regional Water Quality Control Board jurisdictions. Within the Central Valley (Region 5), the eight counties comprising the SJVAPCD represented the San Joaquin Valley and the remainder of dairies were located in the Sacramento Valley. Dairies and animals were predominantly located in the Central Valley (90.99 percent) with most of these in the San Joaquin Valley. Primary focus of data analysis was Region 5 and Region 8 as these two Regions contained 94.33 of the California dairy herd.

Herd size distribution for California dairies is not normally distributed. In all major dairy areas (Region 5, 8, 1 and 2) dairies' herd size distribution curves had positive skew and were leptokurtic (Figures 1.2 through 1.4). There was no straightforward way to define smaller and larger sized dairies based on distribution curves. Furthermore, the United States Department of Agriculture National Agricultural Statistics Service (USDA NASS) provides no definitions. From an environmental perspective, when animal facilities were first permitted through the Clean Water Act (1972), large dairies were defined as over 700 mature cows. Although herd sizes have changed since 1972 no modifications to these size definitions have occurred.

The Reauthorization of the Coastal Zone Management Act (1990) identified specific categories of nonpoint source pollution for each coastal state to incorporate into their programs. Small dairies were defined if there were 20 to 69 head (28 to 97 animal units). Large dairies were categorized with 70 or greater head (greater than 98 animal units). Separate Federal Regulations, the Clean Water Act as amended (1972), defined small (less than 200), medium (between 200 and 699) and large (700 and more) herds with mature dairy cows whether milked or dry. Although many modifications to the Clean Water Act have occurred since 1972, these categories and their numeric definitions have remained (US EPA, 2012).

Clearly, the definition of small, medium or large is relative to a population at a given time and for a specific reason. The 1974 USDA NASS agricultural census identified dairies with more than 500 milking cows as their largest category and included both medium and large dairies as defined by the Clean Water Act. This category was less than .2 percent of dairies and 5.7 percent of dairy cows in the United States (USDA NASS, 1974). The average herd size (total cows/number of herds in category) was 914 cows. The 2017 census category of 5,000 cows and greater contained 15 percent of the United States dairy herd on 0.4 percent of herds (USDA NASS, 2017). The 2017 USDA NASS statistics for California were used as a comparison for our dataset. The USDA NASS data and the data we obtained from individual agencies were similar enough, understanding differences in comparing these datasets. This is due in part to our analysis for the lower two and upper two deciles calculated for Region 5 dairies alone. Whereas USDA data include all dairies in CA. The USDA NASS dairy population statewide was 17.25 percent in herds of 1,000 milking (a slightly smaller herd size than 1,035 mature cows; the upper boundary for the lower two deciles) and 14.97 percent in herds with more than 5,000 mature dry cows. The latter category did not include herds between 4,100 and 5,000 mature cows, included in the upper two deciles of the current dataset. Analyses of USDA NASS data emphasized that a categorization of herd size is time dependent and therefore reflects the industry at any specific point in time.

Data on herd size distribution are provided herein for staff at the California Department of Food and Agriculture. For our analytical purposes, the upper and lower two deciles of mature cow population were identified.

Manure management for non-freestall dairies varies by geographic area. Dairies in Regions 6, 7, 8 and 9 scraped manure. The majority of non-freestall dairies in Region 5 scraped manure. For these cattle, manure was dry scraped or managed to enhance solar drying and then handled dry. A small amount of non-freestall dairies in Region 5 flushed lanes. Also uncertain based on this analysis was the end fate and disposition of heifer and dry cow manure as no set of available data sufficiently delineated management of manures from these categories of animals.

Previous work conducted for the California Air Resources Board analyzed time on concrete on two freestall and two non-freestall dairies in the San Joaquin Valley. These analyses were conducted during three seasons representing winter, spring/fall and summer conditions. Results indicated lactating cows housed in freestall dairies spent 78.2 and 69.8 percent of their time on concrete (Cohen-Davidyan et al., 2020). Lactating cattle on non-freestall dairies spent 31.0 and 37.0 percent of their time on concrete. Assuming time on concrete was a surrogate for percent of manure collected through the liquid system (freestall dairies) and potentially collected through the liquid system (non-freestall dairies) this provided an upper boundary for the amount of manure collected. Dry cows and replacement animals spent 21.0, 25.1, and 23.8 percent of their time on concrete for three of these dairies (one freestall and two non-freestall). The fourth dairy reared replacement animals at a separate location. Manure from replacement animals was flushed on the freestall facility, inconsistently flushed on one non-freestall facility and not flushed on the other non-freestall facility.

Manure management at any given snapshot in time is a function of the initial design of the facility and subsequent growth in animal population, infrastructure and management. Manure management in the 1970s was often a function of scraping concrete lanes with tractors. As facility infrastructure improved and freestalls were built, flush lanes were introduced to the California dairy landscape. Water used to clean milk contact surfaces was re-used to clean concrete lanes. Water drained to manure lagoons for biological treatment. This reduced challenges associated with tractor scraping of lanes and potential injuries to animals and people. Further advances in manure management, the concern to separate out solids to manage manure better within the production facility as well as during fertigation, have gained momentum over the last two decades.

Mechanical separators were present on 43.61 percent of freestall and 17.07 percent of non-freestall dairies. Presence of mechanical separators differed by lactating cow housing type and herd size (Figures 1.6 and 1.7). As herd size increased, dairies had an increased percent of facilities with mechanical separators present. A higher percent of freestall facilities had mechanical separators across all categories when herds were binned by 1,000 mature cow intervals. Mechanical separators were present on 29.53, 52.97, 64.48, 65.31 and 66.67 percent of dairies with <1,001, 1,001 to 2,000, 2,001 to 3,000, 3,001 to 4,000, and >4,001 mature cows. The corresponding values for presence of mechanical separators on non-freestall dairies was 7.09, 22.47, 25.71, 35.29, and 27.27 percent of dairies with <1,001, 1,001 to 2,000, 2,001 to 3,000, 3,001 to 4,000, and >4,001 mature cows. Dairies likely collecting more manure through a liquid system (freestall dairies) had a larger percent of herds with mechanical separators and dairies likely collecting less manure through the liquid system (non-freestall dairies) had a lower percent of herds with mechanical separators present.

Integration of these results (Figures 1.6 and 1.7; Table 1.3) with results from previous work (time on concrete) allowed calculation of approximate amount of lactating cow manure collected in liquid form and potentially subjected to mechanical separation. Approximately 36.93 percent of manure from lactating cows was estimated to be collected in a liquid form where a mechanical separator was present. This value was approximate as it assumed all animals produce the same amount of manure regardless of herd size and housing design.

It is important to note that the analysis is the presence or absence of a mechanical separator and does not imply it is always operational. Once a separator is installed, operation and maintenance of the equipment is important to keep it functional. Also, resources (labor and equipment) must be allocated to solids management to be successful.

Solids removed from mechanical separators were stackable (due to particle size) and moisture content. Standard stationary inclined screens had an additional pressure roller on the end of the conveyor belt to reduce moisture. Moisture content of solids just separated was near 83 to 85 percent (professional experience). The solids were handled (labor and equipment) to distribute for open solar drying, creation and turning for compost windrows, or relocated for temporary storage and subsequent handling (common in winter). Solids may be stockpiled wet or dry for subsequent application to fields between crops.

Gravity separation systems (58.16 percent) were more common than mechanical separation (36.49 percent). Standard gravity separation systems (settling basins, settling ponds) were not included as part of the Alternative Manure Management Program practice list although weeping wall systems were included. The 2019 GHG benefit calculator did not allow input for project baseline or project use of standard gravity separation systems. These vary on farm from concrete lined settling basins that were cleaned out on a 4 to 8 week cycle to earthen impoundments that were cleaned annually or every other year. Separated solids were handled in both mechanically and gravity separated systems. Often, farm labor and equipment (tractor, manure slinger wagon) were used to manage separated solids. Solids from gravity separated system were handled similarly to mechanically separated solids in some cases. More often, these solids were handled through contracted services. The services used a dredger to remove solids and supplied manure trucks to haul manure to fields or drying areas.

Use of vacuum or scraped collection of manure was low. A devoted and specialized management system was used to collect and subsequently manage vacuumed or scraped manure. This material does not stack when collected from lactating cattle areas. Different management techniques were used to handle vacuumed manure and included addition to an already existing solid manure pile or incorporating it into other dry material prior to composting, storing it in its wet form, or doing some open solar drying before it was managed further.

Conclusions

California dairies were analyzed by herd size, animal housing, manure treatment and storage practices. Herd distributions by geographic regions were identified. Ninety-one percent of mature cows (milking and dry) were on dairies in Region 5. Herd distribution between those with freestalls and those without were 74.10 and 25.90 percent. This represented 71.29 and 28.71 percent of animals. The lower and upper two deciles of dairy cattle in the Central Valley were on dairies of less than 1,035 or over 4,120 mature cows. The lower two deciles of herds were on dairies with 385 mature cows. Manure treatment technology and storage practices were described for dairies in Region 5. No definitive practices were used based on herd size or housing type. Some 25.69 percent of herds in Region 5 used neither mechanical separation nor gravity separation systems. The remaining 74.31 percent used gravity separation system only (37.82 percent), mechanical separation system only (16.15 percent) or both (20.34 percent). Mechanical separators were present on 43.61 percent of freestall and 17.07 percent of non-freestall dairies. Approximately 36.93 percent of lactating cow manure was estimated to be collected in a liquid form where a mechanical separator was present. Dairies in Regions 1, 2, 8 and 6 comprised 2.14, 0.81, 1.25, and 4.33 percent of mature cows in California. Liquid manure from dairies in these regions was associated with milking parlor activities and any associated rain runoff. Manure management on dairies with housing in Regions 1 and 2 was wet scraped (slurry) or dry scraped (semi-solid or solid). Manure was managed as a dry solid on dairies in Regions 6 and 8. These results provide useful information should targeted implementation of manure management practices be desired to reduce GHG emissions.

Recommendations

Any designation of small or large herd size selection is Region and time specific and requires re-evaluation over time as herd size distributions change. It would be useful to evaluate the 2013 greenhouse gas emissions inventory to determine if values used for dairy cattle manure emissions reasonably represented herd design and manure collection processes.

CHAPTER 2 QUANTIFY ESTIMATED METHANE EMISSIONS AS LOW, HIGH AND AVERAGE BASED ON HERD SIZE (SMALL AND LARGE), HOUSING DESIGN AND MANURE HANDLING CATEGORIES.

Introduction

The purpose of the AMMP program is to divert volatile solids from anaerobic conditions conducive to methane formation. The percent of emissions reduced with each project type is a function of herd size, animal housing, and manure management.

Methane emissions from manure is a function of the amount of volatile solids excreted, subsequently collected and handled under anaerobic conditions (IPCC, 2006). Bedding and wasted (animals drop feed into manured areas) or spoiled feed may be added to the manure stream (ASAE, 2004). Volatile solids that enters anaerobic conditions may contribute to emissions (IPCC, 2006). Animal housing (freestall versus non-freestalls) is a key factor in the percent of excreted manure likely to be deposited on a concrete surface and be handled in anaerobic conditions. Time animals spend on concrete serves as a surrogate to estimate amount of manure potentially collected in a liquid or slurry form. Design and environmental management of freestalls, including barn directional orientation, feedline soakers/misters and fans over freestalls impact animal use of freestalls. Animal management, specifically animal access to corrals, impacts how much time animals spend on concrete. As previously indicated, another project evaluated time on concrete for sentinel pens of cattle at four commercial dairies (two freestall; two non-freestall) (Cohen-Davidyan et al., 2020). These analyses were conducted during three seasons representing winter, spring/fall and summer conditions. Results indicated that lactating cows housed in freestall dairies spent 78.2 and 69.8 percent of their time on concrete (Meyer et al., 2019). Lactating cattle on non-freestall facilities spent 31.0 and 37.0 percent of their time on concrete. Assuming time on concrete was a surrogate for percent of manure collected through the liquid system (freestall dairies) and potentially collected through the liquid system (non-freestall dairies) this provided an upper boundary for the amount of manure potentially collected in the liquid system. Some dairies scraped concrete lanes to a transfer lane where wash water from the milking parlor or other flushing water would ultimately mix with slurry and convey the material to the liquid storage structure. Other dairies scraped concrete lanes into corrals where manure was distributed for solar drying. Dry cows and replacement animals spent 21.0, 25.1, and 23.8 percent of their time on concrete for three of these dairies (one freestall and two non-freestall facilities). The fourth reared replacement animals at a separate location. Manure from replacement animals was flushed on the freestall facility, inconsistently flushed on one non-freestall facility and not flushed on one non-freestall facility. Collection of manure on concrete varies by facility infrastructure and manager preferences for resource (labor and tractors available for manure management) use. This is why it is important to consider site specific practices when estimating baseline and project emissions.

Manure handling differs by region within California. Manure is handled (in order of amount of manure) by manure consistency as: slurry, solid or liquid, Regions 1 and 2; liquid, solid or slurry, Region 5; solid or liquid, Regions 6, 7, 8 and 9.

The objective was to quantify estimated methane emissions as low, high and average based on herd size (small and large), housing design and manure handling categories. Suggested modifications to the 2019 GHG benefit calculator are provided based on use during these analyses.

Materials and Methods

Task 2.1 Quantify estimated methane emissions as low, high and average based on herd size (small and large), housing design and manure handling categories

Results of Task 1.3 inform regional dairy populations (categorized by Water Quality Control Board) and manure treatment technology presence (specific in detail to Region 5). Essential for this analysis was information submitted in AMMP applications to define the percent of manure volatile solids (VS) collected through a liquid or non-liquid stream as well as the estimated percent of VS removed by practices. Quantification of GHG emissions was calculated with the 2019 GHG benefit calculator for AMMP practices (CARB, 2019).

Data from individual AMMP applications were sought to normalize applications and compare results of baseline and post project emissions across projects within and between farms. A public records request was made to obtain copies of AMMP applications submitted to CDFA. Additionally, some individual dairy producers and technical assistance providers were contacted to obtain copies of submitted applications. Some technical assistance providers were contacted to gain greater insight into the AMMP application process and obtain additional information and impressions about their understanding of the effectiveness of select practices.

Hypothetical analyses. Baseline emissions and post AMMP installation emissions were determined by analysis and interpretation of project narratives from 2017 and 2018 AMMP applications. Tulare County was used for this hypothetical analysis. Inputs included: project location, baseline livestock population by category, baseline data (manure collection, solid separation, storage/treatment practice for separated or scraped solids) and project manure collection and solid separation specific information was not available for changes in energy use (electricity and diesel fuel consumption) pre and post AMMP. Statewide data for average values for milk production and composition were used to estimate project emission reductions (CDFA, 2018). These data populated the Project Date Input tab in the 2019 GHG benefit calculator. Emissions were estimated for herd sizes 250, 750, 1250, 1750, 2250, 3250, and 3750 (freestall and non-freestall) for baseline and select AMMP projects. This normalization was necessary for comparison purposes. The resultant analysis provided comparison of individual AMMP practices within and between dairy herd sizes and housing types. Single project analyses were conducted. No allowance was made for dairies with gravity separation systems in their baseline management. Scrape to flush narrative indicated an unknown number of days of collection (data redaction). A value of 30 percent collection (70 percent remaining in flush) was used. This overestimates reductions if manure is collected 104 days a year. Results from low and high emissions were selected. Averages were calculated by AMMP practice categories for solid separation and flush to scrape systems as the sum of the emissions by herd type and size divided by the number of rows used to contribute to the sum.

Results

Application specific information was necessary to normalize individual applications and compare results between farms. Initially, the intent was to obtain application specific information from AMMP applications submitted to CDFA and received through a public records request. This process required CDFA staff to redact out confidential business information. Unfortunately, herd size, milk production and composition information were deemed confidential and not provided, per Government Code Section 6254(k) and Evidence Code Section 1060. Additionally, percent of manure collected and efficiency of AMMP practice values were redacted from these applications. This was crucial information to normalize data. The 2017 and 2018 GHG benefit calculators allowed applicants to modify the percent of manure collected and the effectiveness of a particular practice. Facility energy use for baseline and post AMMP implementation was also redacted from applications. These important pieces of information were essential to do a more precise analysis of baseline GHG emissions and GHG emissions reduction for each facility. In the absence of important project-specific information (animal numbers, milk production and composition, manure collection and effectiveness of AMMP practices), project summary information had limited value for comparison purposes. Summaries did not consistently reflect actual project practices as GHG benefit calculator spreadsheets used in 2017 and 2018 allowed user justified modifications along with the explanation of the modifications. Without full application information or justification of user modifications, it was difficult to evaluate the final GHG emissions reduction results in context of each dairy or determine whether the reduction values represented each facility appropriately. Selection of baseline and project solid liquid separation (sections 4c and 7c respectively in the 2019 GHG benefit calculator) were consistent in these analyses for analytical purposes. It was not possible to determine if these were selected consistently in applications as this information was redacted.

The project team reached out to individual producers and industry contacts to obtain AMMP applications directly from dairy producers who submitted applications in 2017 and 2018. Less than 12 application packages were received. Although these provided more precise information for those applications received, too few applications were received and there was an insufficient number of applications received for any specific AMMP practice category to conduct the analyses on directly acquired producer information.

<u>Hypothetical analyses.</u> After detailed discussions with CDFA staff, it was determined a streamlined analysis was appropriate. Emissions were estimated using the 2019 GHG benefit calculator for herd sizes 250, 750, 1250, 1750, 2250, 3250, and 3750 (freestall and non-freestall) for baseline and select AMMP projects. Herd sizes were identified as the upper threshold for bins of cattle described in Chapter 1. Assumptions for the amount of volatile solids collected and removed by different AMMP practices is not readily accessible in the application process. The 2019 GHG benefit calculator served to standardize calculations based on percent of manure collected and effectiveness of different AMMP practices.

Analysis of baseline conditions indicated the 2019 GHG benefit calculator assumed freestall manure collection was 2.4 times greater than manure collection at non-freestall facilities. Differences in solid separation with open solar drying or composting were impacted more by the type of separator used and not the type of drying identified. Weeping walls had the greatest emissions reductions (about 43 percent) based on the 2019 GHG benefit calculator. Stationary inclined screens (about 16 percent) and screw press separators (about 24 percent) were more comparable to one another than weeping wall separation. Partial flush to scrape conversion (at 30 percent of manure scraped; 70 percent of manure flushed) achieved more GHG emissions reductions (about 24 percent, freestall; 18 percent non-freestall) when compared with emissions reductions from stationary inclined screens and similar emissions reductions when compared with emissions reductions from screw press separators. Emissions reductions were similar within a practice category and herd size regardless of housing type (freestall or non-freestall) for solid liquid separation. Emissions reductions were about 33 percent greater for flush to scrape systems and compost bedded pack barns on freestall facilities when compared with emissions reductions from non-freestall facilities. Region 5 AMMP funded dairy projects (project years 2017-2019) were in herds with mature cows in the lower two deciles of (n=35; less than 1,035), middle six deciles (n=49, between 1,035 and 4,200) and upper two deciles (n=2, above 4,200)

Low and high emissions analyses were identified and average emissions reductions were calculated by AMMP practice categories for mechanical solid liquid separation and flush to scrape systems. The results reflected the imbedded assumptions used in calculations for each specific AMMP category. Results of these analyses are summarized in Table 2.1. Conversations with individuals assisting producers with AMMP applications identified the primary GHG savings for compost bedded pack barn and pasture improvements was due to differences in diesel use for facilities where baseline manure collection was solid manure.

Table 2.1 Estimated greenhouse gas emissions for flush manure collection and no solid separation (baseline) and project estimated emissions after implementation of Alternative Manure Management Program practice (units are MTCO2e per year).

Herd description (number of animals)																
Dry cows	37.5		112.5		187.5		262.5		337.5		487.5		562.5		637.5	
Lactating cows[1]	212.5		637.5		1062.5		1487.5		1912.5		2762.5		3187.5		3612.5	
Total cows	250		750		1250		1750		2250		3250		3750		4250	
Housing[2]	F	NF	F	NF	F	NF	F	NF	F	NF	F	NF	F	NF	F	NF
Baseline	1334	551	3999	1650	6663	2750	9327	3850	11991	4950	17319	7149	19983	8249	22647	9349
Conversion to solid separation with open solar drying from:																
F/WW[3]	752	321	2253	962	3755	1603	5256	2244	6757	2885	9760	4166	11261	4807	12762	5448
F/SS[4]	1114	464	3339	1390	5564	2317	7789	3243	10014	4170	14463	6023	16688	6949	18913	7875
F/SP[5]	1011	423	3029	1268	5047	2113	7065	2958	9083	3802	13119	5492	15137	6337	17156	7182
Conversion to solid separation with composting (passive or intensive windrow) from:																
F/WW	747	319	2240	956	3732	1594	5224	2231	6716	2868	9700	4143	11192	4780	12685	5418
F/SS	1113	463	3334	1388	5555	2313	7777	3238	9998	4163	14441	6014	16662	6939	18884	7864
F/SP	1008	422	3021	1265	5034	2108	7047	2951	9060	3793	13086	5479	15099	6322	17112	7165
Low	747	319	2240	956	3732	1594	5224	2231	6716	2868	9700	4143	11261	4780	12685	5418
Average	958	402	2869	1205	4781	2008	6693	2811	8605	3614	12428	5220	14340	6022	16252	6825
High	1114	464	3339	1390	5564	2317	7789	3243	10014	4170	14463	5492	15137	6337	17156	7182
Partial conversion to scrape with open solar drying[6]																
	1012	450	3032	1350	5052	2249	7073	3149	9093	4048	13133	5847	15153	6746	17174	7646
Partial conversion to scrape with composting (passive or intensive windrow)[6]																
	1003	447	3005	1341	5008	2235	7010	3129	9012	4023	13017	5811	15020	6705	17022	7598
Low (composting)	1003	447	3005	1341	5008	2235	7010	3129	9012	4023	13017	5811	15020	6705	17022	7598
Average	1008	449	3019	1346	5030	2242	7042	3139	9053	4036	13075	5829	15087	6726	17098	7622
High (open solar)	1012	450	3032	1350	5052	2249	7073	3149	9093	4048	13133	5847	15153	6746	17174	7646
Compost bedded pack barn																
	179	191	536	573	894	955	1251	1337	1608	1719	2323	2482	2680	2864	3037	3246

[1]Assumed milk production 75 lbs, fat 3.85, true protein 3.43, and lactose 4.97; [2]F – freestall, NF – non-freestall; [3]Flush collection, weeping wall separation; [4]Flush collection, slant screen separation; [5]Flush collection, screw press separation; [6]30 percent flush/70 percent scrape (annualized) after AMMP project implementation.

Discussion

Baseline emissions were always greater than project emissions for all scenarios evaluated. If energy consumption was increased for the project (not included in our analyses) it is possible for project emissions to exceed baseline emissions if sufficient emissions decreases do not occur from manure management. The assumption that the manure entering lagoons at 2.4 times the rate for freestall versus non-freestall facilities for lactating cattle was greater than 2.2, the ratio of average time on concrete from freestall (74.0 percent) and non-freestall (34.0 percent) facilities. Comparing high and low time on concrete the ratio of manure collection from freestall versus non-freestall facilities ranged from 2.5 to 1.9 (Cohen-Davidyan et al., 2020). Animal management practices at freestall dairies impacts time on concrete. Animals with restricted time in corrals spend more time where manure is deposited on concrete and therefore a greater amount of manure would encounter manure treatment technologies. Data provided in Table 2.1 are useful to those estimating GHG emissions reductions or interested in comparing project emissions from different sized herds within or across AMMP practices. Actual herd calculations will vary when herd specific milk production and composition data, animal and manure management and energy use data are available. As anticipated, baseline emissions on dairies with freestalls are greater at a specific herd size than at dairies with no freestalls. This reflects the fact that dairies with freestalls collect more manure on a concrete surface that is handled in liquid form under anaerobic conditions when compared with dairies with no freestalls.

Neither baseline calculations nor project calculations allowed for inclusion of gravity separation systems. These separation systems do exist on farm (as presented in Chapter 1) and should be included in both baseline and project emissions calculations.

Anomalies could occur when using the 2019 GHG benefit calculator. This is not an exhaustive list. If baseline manure collection is flush and baseline solid separation is none, there is no need to have a storage/treatment practice for separated or scraped solids. A different example is that once a Category 4 practice is selected (2 Project data inputs) then 4a should be flush and 7 should only include scrape/vacuum options. Since many applications were for partial vacuum (i.e. 104 days a year) it is unclear why an option for 7a is flush when the new practice identified in 2 already selected a scrape/vacuum option. Additionally, 7c allows selection of separation type. It is not clear if this project separation is for the 70 percent of manure that is not vacuumed or if it is for the 30 percent of manure that is vacuumed (assuming a partial collection via vacuum at 30 percent).

Conclusions

A hypothetical analysis of baseline conditions was compared to post AMMP emissions with an assumption that collection of manure from freestall dairies was 2.4 times greater than from non-freestall dairies. As calculated, estimated emissions differences in solid separation with open solar drying or composting were a function of the type of separator used and not the type of drying identified. Weeping walls had nearly twice the emissions reductions than mechanical separators. The 2019 GHG benefit calculator emissions reduction estimates were greater for screw press separators than for stationary inclined screens. Emissions reductions from partial flush to scrape conversion (at 30 percent of manure scraped) was similar to emissions reductions for screw press separators and greater than stationary inclined screens. Actual project emissions reductions will vary when herd specific milk production and composition data, animal and manure management and energy use data are available.

Recommendations

Baseline assumptions used in the GHG benefit calculator for percent of manure collected should be clearly defined within the benefit calculator so users may better understand how well a specific practice will work given their herd animal and manure handling practices.

Gravity separation systems that are cleaned frequently should be incorporated into baseline and project descriptions (sections 4c and 7c of the 2019 GHG benefit calculator) to more closely reflect practices on farm and reductions in volatile solids entering liquid storage systems.

Consideration should be given to lock some cells based on practice selected to minimize potential errors in data entry.

Refine the emissions estimate GHG benefit calculator to improve data entry for unusual combinations of manure management.

Review the GHG benefit calculator inputs for stacked practices and provide examples of how to include multiple practices within an application so applications are calculated similarly.

Modify the GHG benefit calculator to allow input of compost bedded pack barn manure collection and clearly define fate and management of manure dropped on transfer lanes and while at the milking parlor as well as feed apron manure.

Retain flexibility in the application process to allow use of different practices for different groups of cattle.

CHAPTER 3 REVIEW STRATEGIES AND TECHNOLOGIES CURRENTLY OR POTENTIALLY USED TO REDUCE MANURE METHANE EMISSIONS FOR APPLICABILITY TO SMALL AND LARGE DAIRIES.

Introduction

Improving manure management on dairies in California has been an important topic for over two decades. An analysis of manure treatment technologies was conducted (SJVDMTFAP, 2005). Representatives from regulatory agencies, academia, industry and environmental/conservation organizations came together to evaluate and identify technologies potentially able to improve manure management in the San Joaquin Valley. This review was conducted through an open solicitation to vendors with known products as well as to potential vendors not yet involved in dairy manure management. Technologies were organized in broad categories that included: thermal conversion (combustion, gasification and pyrolysis); solid-liquid separation and filtration; composting; anaerobic digestion; aerators/mixers; covers for lagoons and compost piles; microbial cultures, enzymes, and other additives; feed management; nitrification/denitrification; and miscellaneous. Of great importance during the review process was the need to identify potential benefits and detriments of individual technologies to air and water emissions. A useful outcome of the group's effort was a uniform scorecard developed to assess individual technologies. Insufficient data from unbiased research resulted in most scorecard analyses relying on best professional judgment on behalf of panel members based on known practices, chemistry and physical conditions present on dairy farms. Few companies had data beyond anecdotal. Of particular interest to panel members at that time, and all concerned with manure management at this time, is the ultimate fate and form of manure constituents as they enter, move through and exit potential processing technologies.

More recently, many dairy processors in the United States came together to form Newtrient. Newtrient seeks to evaluate and identify technologies that advance manure management and technology adoption related to energy production and nutrient recovery. Newtrient creates a space where technology providers can provide proprietary information (including efficacy, maintenance costs and location on dairies) to a panel for review. Similar to the previous effort in California, Newtrient has found that many vendors have insufficient data from actual field trials to allow detailed scientific review.

The AMMP application process established practice categories to reduce methane emissions. These practices were reviewed recently through California Air Resourced Board's Dairy and Livestock Greenhouse Gas Emissions Working Group Subgroups 1 (Fostering Markets for Non-digester Projects) and 3 (Research Needs, Including Enteric Fermentation). The purposes of the Subgroup analyses were to assemble a comprehensive overview and discussion on available non-digester methane emissions reduction alternatives (CARB, 2018a) and to identify research needs, better understand mitigation strategies to achieve emissions reductions and better understand options for reduced enteric emissions (CARB, 2018b).

These recent endeavors to evaluate effectiveness of non-digester manure treatment technologies have identified similar technology categories as the work from 2005. Subgroup 1 had a presentation by Newtrient to share information on new technology assessment. Familiar technologies were discussed (mechanical separation) with addition of polymers and diffused air filtration to improve separation capability. Newtrient also discussed use of membranes to remove salts, centrifuges, vermiculture, evaporative systems, torrefaction and hydrothermal carbonization. The end products from more intensive treatment technologies were identified as humus, custom fertilizers, biochar, algae, worm castings and fuel. Few of these newer technologies were or are being tested or demonstrated in California. In state demonstrations are critical to understand how effective technologies may be under California animal and manure management conditions. Additionally, these technologies repartition nutrients into other products. Markets for end products must be identified to determine technology economic feasibility. The information obtained through the two Subgroups and continued information from Newtrient's data collection methodologies are useful for directionality of potential nutrient and emission changes.

Our objective was to review strategies and technologies currently or potentially used to reduce manure methane emissions for applicability to small and large dairies.

Materials and Methods

California AMMP proposal data were used when possible to inform current and future manure management conditions.

Task 3.1: Obtain information included in AMMP proposals regarding strategies and technologies currently used to reduce manure methane emissions

Data from individual AMMP applications were obtained through a Public Records request. Additionally, some individual dairy producers and technical assistance providers were contacted to obtain copies of submitted applications. Some technical assistance providers were contacted to gain greater insight into the AMMP application process and obtain additional information and impressions about their understanding of the effectiveness of select practices.

Task 3.2: Evaluate reduction strategies applicability to small and large dairies for San Joaquin Valley and North Coast dairies based on associated manure collection, treatment and storage categories.

AMMP application analyses of practices. Redacted project narratives, budget sheets and GHG benefit calculator results were used to obtain information on pre-AMMP manure management and proposed post-AMMP manure management. For those herds with multiple practices (solid liquid separation and composting as well as a compost bedded pack barn) the solid liquid separation was used as there was no way to differentiate percent of manure destined for each of the AMMP categories. Often solid liquid separation and composting of manure were to be implemented on one animal class and compost bedded pack barn was for a different class of animals. Project type information was extracted from 2017 and 2018 applications. Herd size (milking and dry cow numbers; harmonized information Chapter 1) and average milk production and composition data were used consistent with Chapter 2 (CDFA, 2018). Data from each AMMP funded project from 2017 and 2018 were input into the 2019 GHG benefit calculator to estimate baseline emissions and emissions reductions for gross practice level. No data were available for energy use to include in the analysis. Each dairy appeared only once even though some applied in both 2017 and 2018. Additionally, some dairies identified multiple practices would be implemented. Each of these was assigned to what was understood as the primary manure treatment practice given the available information. When possible data from 2019 applications were included. The AMMP information for 2019 was from the summary of applications and not necessarily from actual applications as all 2019 files were not obtained prior to the analysis.

Percent of dairies seeking AMMP funding was determined by dividing the number of dairies in each herd range and housing category seeking funding by the total number of dairies in each herd range and housing category and multiplying the results by 100.

Average emissions estimates were estimated by funded project and averaged within AMMP category. Percent reduction was calculated as the value of baseline emissions minus project emissions divided by baseline emissions, multiplied by 100.

AMMP emissions reductions. Information from herd narratives was extracted to identify manure management pre and post AMMP project implementation. Statewide data for average values for milk production and composition were used to estimate project emission reductions, normalized with the 2019 GHG benefit calculator (CDFA, 2018). Results of emissions reduction by project type were summarized by AMMP practice for those herds in the lower two deciles of cows for herds in Region 5. Note, the definition of the lower two deciles was a mere snapshot in time and will change as herd sizes change.

Results

AMMP application analyses of practices. Distribution of herds by housing type is in Figure 3.1. In 2017, Region 5 funded AMMP dairies were predominantly freestall (n=12; 2 non-freestall facilities). In 2018, 33 freestall facilities were funded in Region 5. In 2019, 38 dairies were funded in Region 5; 7 were non-freestall. Applications from herds with animal population in the lower two deciles represented 52.42 percent of total applications from Region 5.

More applications were received from dairies with freestalls than dairies without freestall. Distribution of herds applying for AMMP funds was somewhat different than the population distribution of herds in Region 5 (Figure 3.1 and Chapter 1 Figure 1.5). More dairies with less than 1,035 milking and dry cows applied for AMMP funds. This was consistent with herd distribution in that 51.34 percent of herds had less than 1,035 milking and dry cows. Percent of dairies seeking AMMP funding by herd size range and housing category is presented in Figure 3.2.

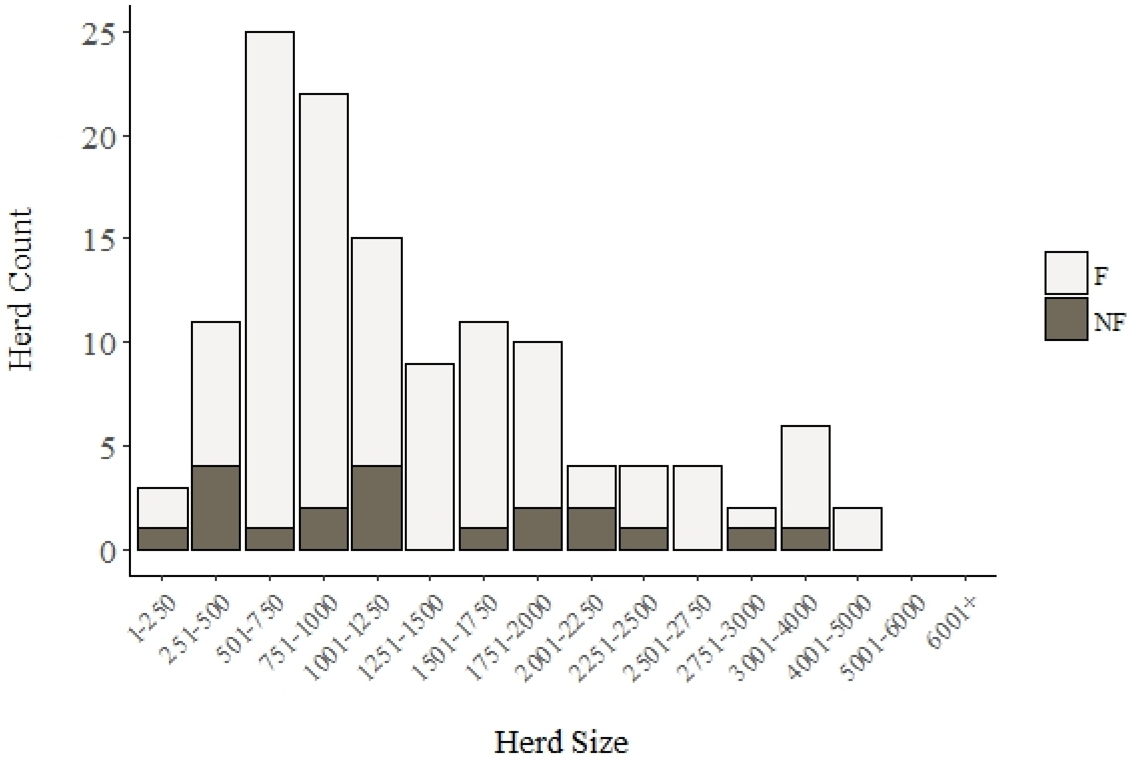


Figure 3.1 Region 5 AMMP dairy project applications in 2017, 2018 and 2019 by herd size and housing type (F=freestall; NF=non-freestall). Individual dairies are represented once even though they may have applied multiple times. Pasture based dairies not included.

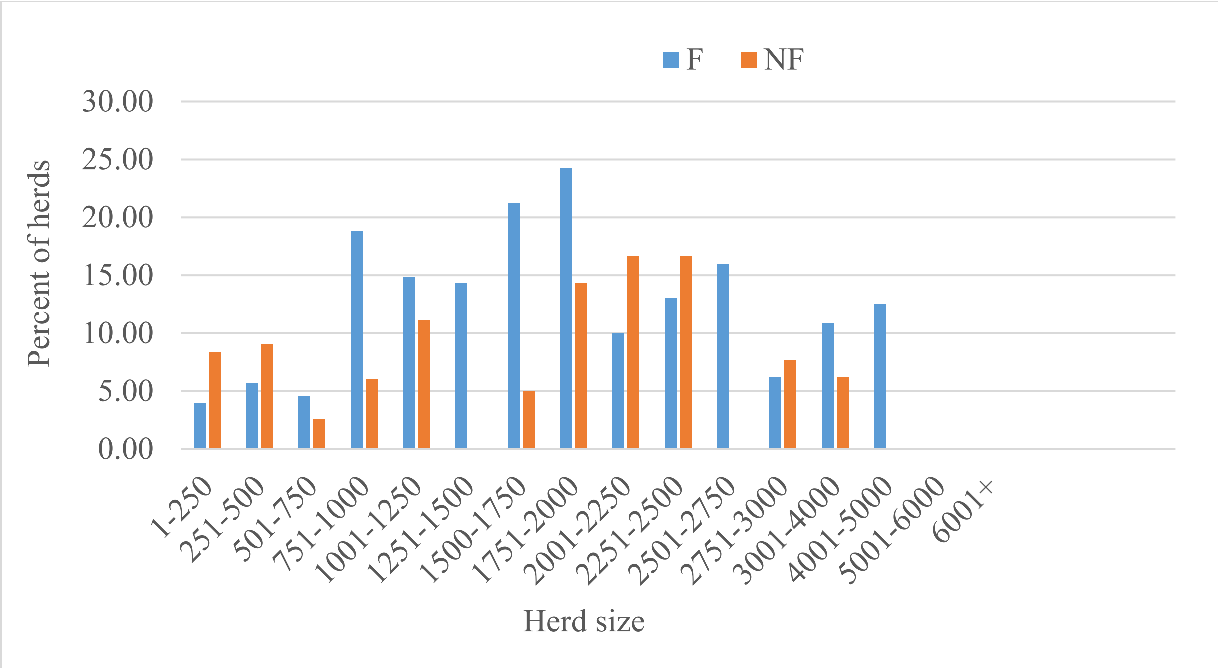


Figure 3.2 Percent of Region 5 herds by housing type (F=freestall; NF=non-freestall) and herd size seeking AMMP funding in 2017, 2018 or 2019. Individual dairies are represented once even though they may have applied for AMMP projects multiple times. Pasture based dairy not included.

Three rounds of funding have occurred for the AMMP process. Descriptions of each project category for the 2019 application cycle are provided (Table 3.1).

Table 3.1 Project category descriptions

2019 Project Category	Project Description
1a	Pasture based management
2a	Compost bedded pack barn
3	Solid separation without project narrative to determine category (2019 applications)
3a	Solid separation with open solar drying
3e	Solid separation with solid storage
3g	Solid separation with composting (passive or intensive windrow)
4a	Scrape conversion with open solar drying
4g	Scrape conversion with composting (passive or intensive windrow)

AMMP applications submitted by dairies from 2017, 2018, and 2019 were analyzed to determine which project category applied to each proposed project in the Central Valley (Region 5) and North Coast (Region 1 and 2 combined). Baseline manure management practices for AMMP applicant dairies is identified (Table 3.2). Nearly all of the applicants collected manure in flush systems (n=36, 2017; n=50, 2018), and mechanical separation technology was absent as a baseline practice (58.3 percent 2017; 82.3 percent 2018).

Table 3.2 Baseline conditions for Region 5 dairies at time of AMMP application (funded (Fd) and unfunded (UF) projects) for 2017 and 2018 applications.

	Application Year			
	2017 Fd	2017 UF	2018 Fd	2018 UF
Manure collection				
Flush	14	22	32	18
Scrape	0	0	0	0
Scape/Vacuum	0	0	1	0
Treatment				
None	10	11	27	15
Solid separation				
Stationary screen	3	7	6	3
Vibrating screen	1	1		
Roller drum		1		
Screw press		1		
Weeping wall		1		

Dairy herd demographics are provided for 2017 (Table 3.3), 2018 (Table 3.4) and 2019 (Table 3.5) projects in Region 5. Most applications submitted (85.7 percent) and funded projects (89.8 percent) were on dairies with freestalls. Solid liquid separation was identified as the primary or only practice on 63.8 percent of applications submitted. Compost bedded pack barn requests were involved with 19.8 percent of applications followed by conversion from flush to scrape on 16.3 percent of applications. All funded projects for solid separation with open solar drying, solid separation with compost, and flush to scrape with open solar drying were on dairies with freestalls. Most funded compost bedded pack barns (76.5 percent), solid separation with solid storage (76.0 percent) and flush to scrape conversion with composting (60.0 percent) were on dairies with freestalls. Summary of funded AMMP projects for Region 5 dairies is in Figure 3.3. Management strategies that reduce methane emissions used on dairies that applied for AMMP funding included some form of solid separation from the liquid waste stream. A general Category 3 solid separation (unable to decipher management practice used post separation) was used for 2019 funded projects as most files were not available for analysis.

Table 3.3 Summary of 2017 funded dairy AMMP project herd demographics by housing design for Region 5[1].

		Housing[2]		Herd Size	
2019 Project category[3]	Number	F	NF	Range	Average
1a	1	1	0	795	
2a[4]	3	2	1	950-1992	1521
3a	1	1	0	1898	
3e	1	1	0	940	
3g	4	4	0	1225-3330	2164
4a	2	2	0	890-900	895
4g	3	2	1	2237-3090	2642
Summary of 2017 non-funded dairy AMMP project herd demographics					
2a	1	0	1	510	
3a	10	7	3	182-3385	1175
3e	2	2	0	441-1600	1021
3g	9	9	0	345-3215	1758

[1] Applications received across species and across California: 53. Region 5 dairy applications awarded: 15. Dairies initially awarded that did not utilize funds: 2 (not counted in funded applications). Region 5 dairy applications not awarded: 24. Region 5 non-dairy applications not awarded: 4. Applications outside of Region 5: 8.

[2] Freestall, F; non-freestall, NF.

[3]Project categories: 2, compost bedded pack barn; 3 solid separation with a. open solar drying; e. solid storage, g. solid composting (passive or intensive windrow); 4, partial conversion from flush to scrape with a. open solar drying; g. composting (passive or intensive windrow).

[4]Two of these are in conjunction with other projects (i.e. 2a/4g, 2a/4a).

Table 3.4 Summary of 2018 funded dairy AMMP project herd demographics by housing design (freestall, F; non-freestall, NF) for Region 5.[1]

		Housing[2]		Herd Size	
2019 Project category[3]	Number	F	NF	Range	Average
2a[4]	4	4	0	610-2730	1948
3a	13	13	0	330-1800	1053
3e	2	2	0	515-1356	936
3g[5]	11	11	0	322-2095	1005
4a	2	2	0	1207-1520	1364
4g	1	1	0	2400	
Summary of 2018 non-funded dairy AMMP project herd demographics.					
2a[6]	2	2	0	858-941	900
3a	11	9	2	785-2000	1175
3e	2	2	0	193-505	349
3f	1	1	0	980	
3g	2	2	0	792-1272	1032
4a	1	1	0	1040	

[1]Applications received across species and across California: 63. Region 5 dairy applications awarded: 33. Dairies initially awarded that did not utilize funds: 2 (not counted in awarded applications). Region 5 non-dairy project awarded: 1. Region 5 dairy applications not awarded: 19. Region 5 non-dairy applications not awarded: 0. Applications outside of Region 5: 8.

[2]Freestall, F; non-freestall, NF.

[3]Project categories: 2, compost bedded pack barn; 3 solid separation with a. open solar drying; e. solid storage, g. solid composting (passive or intensive windrow); 4, partial conversion from flush to scrape with a. open solar drying; g. composting (passive or intensive windrow).

[4]Three of these are in conjunction with other projects (i.e. 2a/4g, 2a/1a, 2a/3g).

[5]Two of these are in conjunction with other projects (i.e. 3g/3a, 3g/3a).

[6]Both are in conjunction with other projects (i.e. 2a/3g, 2a/4g).

Table 3.5 Summary of 2019 funded dairy AMMP project herd demographics by housing design for Region 5.[1]

2019 Project category[3]	Number	Housing[2] F	Housing[2] NF	Herd Size Range	Herd Size Average
2a	10	7	3	575-4200	1558
3	12	12	0	345-1840	1054
3a	10	7	3	430-4750	1539
3e[4]	2	2	0	941-3185	2063
3g	5	5	0	644-1600	1099
4a	1	0	1	920	920
Summary of 2019 non-funded dairy AMMP project herd demographics					
2a	7	5	2	149-1020	565
3	7	6	1	182-3515	1211
3a	4	3	1	530-1160	815
3e	1	0	1	345	
3g	4	3	1	580-2400	1114
4	3	2	1	450-1469	803

[1]Applications received across species and across California: 91; Region 5 dairy applications awarded: 40 . Dairies initially awarded that did not utilize funds: 0 based on information available at time of report. Region 5 non-dairy project awarded: 2. Region 5 dairy applications not awarded: 26. Region 5 non-dairy applications not awarded: 3. Applications outside of Region 5: 20.
[2]Freestall, F; non-freestall, NF.
[3]Project categories: 2, compost bedded pack barn; 3 solid separation with a. open solar drying; e. solid storage, g. solid composting (passive or intensive windrow); 4, partial conversion from flush to scrape with a. open solar drying; g. composting (passive or intensive windrow).
[4]Two of these are in conjunction with other projects (i.e. 2a/4g, 2a/4a).

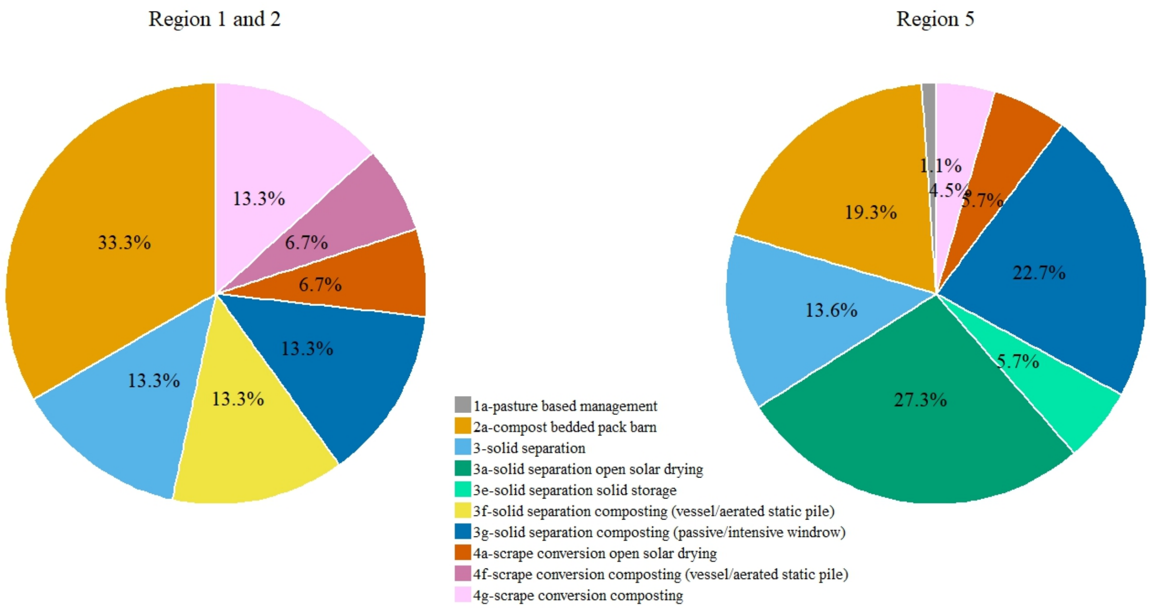


Figure 3.3 Percent of AMMP projects in each project category funded 2017 through 2019 on dairies in Regions 1 and 2 (left) and in Region 5 (right).

Fewer dairies reside in Regions 1 and 2. A summary of herd size (HS) demographics by application year, project type and project status (funded or unfunded) for milking and dry cows is provided (Table 3.6). The most requested AMMP practice was compost bedded pack barn and solid liquid separation (34.48 percent of applicants each) for applications from Regions 1 and 2. Conversion of flush to scrape was requested by five applicants (17.24 percent). Funded projects are compared with Region 5 in Figure 3.3.

Table 3.6 Summary of funded (Fd) and unfunded (UF) dairy AMMP project herd demographics in Regions 1 and 2.

	2017		2018		2019	
2019 Project category[1]	Fd	UF	Fd	UF	Fd	UF
1a	--	--	--	1	--	3
HS range						330-575
HS average				260		463
2a	2	--	--	--	3	5
HS range	290-690				299-500	
HS average	490				433	
3	--	--	--	--	2	--
HS range					375-900	
HS average					638	
3f	--	1	1	--	1	3
HS range						275-600
HS average		1120	1120		1700	387
3g	--	--	1	--	1	--
HS range						
HS average			290		290	
4f	--	--	--	1	1	--
HS range						
HS average				189	405	
4g	1	1	1	1	--	--
HS range						
HS average	550	189	400	280		

[1]Project categories: 2 compost bedded pack barn; 3 solid separation with a. open solar drying; e. solid storage; g. solid composting (passive or intensive windrow); 4 partial conversion from flush to scrape with a. open solar drying; g. composting (passive or intensive windrow).

AMMP emissions reductions. Estimated project emissions and percent of emissions reduction from baseline emissions are shown in Table 3.7 for dairies in the lower two deciles of animal populations in Region 5. One project in these herds was to manage manure in compost bedded pack barns. This project assumed great reductions in manure handled in anaerobic conditions. Those projects on facilities seeking to implement mechanical separation with some form of subsequent solids drying (open solar, n=6; solid storage, n=1; passive or intensive composting, n=4) were most prevalent. Emission reductions from these projects ranged from 8.78 to 86.78 percent. Two facilities had flush to scrape conversions. One had lower emissions reduction of 8.78 percent and one had higher emissions reduction 81.90 percent.

Table 3.7 Estimated AMMP project emissions[1] and percent reduction of emissions from baseline for Region 5 funded projects with herd population less than 1035 mature cows.

Project category[2]	Project description	Count	Project emission ($MTCO^2e/yr$)	Average percent reduction
2[3]	2a	1	429	86.78
3	3a	6	2288	21.43
	3e[4]	1	DNC	DNC
	3g	4	2360	23.45
4	4a[5]	1	3628	8.78
	4e	1	429	81.90

[1]Calculation for reduction based on baseline project emissions using the 2019 GHG benefit calculator.
[2]Project categories: 2, compost bedded pack barn; 3 solid separation with a. open solar drying; e. solid storage, g. solid composting (passive or intensive windrow); 4, partial conversion from flush to scrape with a. open solar drying; g. composting (passive or intensive windrow).
[3]Compost bedded pack barn projects were for dry cows, heifers and or special needs cattle.
[4]Data do not compute (DNC). Herd project transitioned manure management from scrape with deposition into liquid storage area, to vacuum and process through a screw press separator. Assumptions could not be made for percent of manure collected and percent of collected manure diverted from anaerobic conditions.
[5]Project converts from flush with mechanical separator to vacuum and open solar drying. Assumed 104 days a year of vacuum collection with flush the remaining time (30 percent collection).

Discussion

AMMP application analyses of practices. By default, the primary AMMP applications submitted and funded were for practices already functioning on California dairies. A few self-motorized vacuum systems (dedicated machine not tractor driven) were funded. This was a new practice for California dairies. A few applications requested funding for unique technologies, including vermicompost or solid liquid separation with additional effluent stream treatment post separation. Although new technologies for enhanced nutrient removal exist (available for viewing at the World Ag Expo in 2018, 2019 and 2020) they have not fully entered the California market place, yet. It is anticipated that once some of these technologies have been demonstrated in California their use will increase, assuming financial opportunities are present. These more advanced separation technologies remove additional nutrients (beyond standard mechanical separators) and yield pelleted or other solids. This additional carbon removal comes with additional capital as well as operation and maintenance costs.

Using redacted files had some limitations as essential project information was unavailable making it difficult to fully understand how emissions reductions were influenced. A few examples are provided here regarding potential GHG benefit calculator assumptions. Many applications indicated they were installing a mechanical separator (stationary inclined screen or double screen system). Some indicated a screw press with auger or conveyor was included.

Based on project narratives and information provided within applications, the purpose of the screw press was to remove moisture not to remove solids. This was interpreted as the screw press received the solids from the stationary inclined screen and produced an effluent that went to anaerobic storage. One application proposed to vacuum manure and then send it through a screw press separator to remove solids. The fate of effluent was not described. In this circumstance, the GHG benefit calculator would assume all vacuumed manure was diverted from anaerobic storage although effluent from the screw press likely would end up in anaerobic storage.

Within a Region, no specific trends or tendencies existed between use of different practices and herd size. Different practices were preferred by Region. Compost bedded pack barns were funded on a higher percent of dairies in Regions 1 and 2. Compost bedded pack barns (34 percent) and solid liquid separation (39 percent) were nearly equal in funded projects for Region 1 and 2 dairies. Over two-thirds of Region 5 projects were solid liquid separation. Differences in manure collection, treatment and storage can explain why such a large percent of Region 5 dairies applied for solid liquid separation compared with dairies in Regions 1 and 2. Liquid manure is more dilute on Region 5 dairies than dairies in Regions 1 and 2. Knowledge of specific facility information may elaborate why tendencies did not exist. Information about facility age, previous herd (animal) or facility (infrastructure) expansion, acres available for infrastructure development, herd economics, age of operator and succession planning may have contributed to interest in AMMP. Additional barriers for participation may exist. Considerable time was needed to complete AMMP applications and get all documentation necessary uploaded for review. Construction costs changed between the time proposals were submitted and awarded. This may explain why some awarded projects were not utilized. In application years 2017 and 2018 two Central Valley dairies each were awarded projects and did not construct them. Clearly, interest did exist from those who applied for the AMMP program. As funded projects move forward and come on-line more individuals may be interested in seeking AMMP funding to contribute to GHG emissions reductions. Future participation will depend in part on fund availability for the program and dairy economics.

One of the many goals on dairies is to produce high quality milk. To achieve this goal, attention is given to animal housing and resting areas. Manure management on concrete surfaces is an essential tool to provide cattle with a clean environment to produce a high quality product. As such, attention to freestall beds and concrete lanes and alleys is important. Since cattle spend more time in freestalls their manure is deposited on a concrete surface that is either flushed or scraped and typically destined to anaerobic storage. The nature of freestall dairies requires that more manure be managed daily at a given herd size as this manure is dropped on concrete surfaces animals frequent. The 2019 GHG benefit calculator assumed 2.4 times more manure was collected from freestall facilities than from non-freestall facilities and was subject to treatment and or storage under anaerobic conditions thereby contributing to methane production. In any given herd size range below 3,500 mature cows more dairies with freestalls applied for funding than non-freestall. It does not appear that this was a function of amount of manure collected and managed. It may be a function of facility size, age, profitability and probability of continuing in the dairy business. It may also be a function of awareness of herd owners to access AMMP funds.

As identified in Chapter 1 mechanical separators were present on 53.74 percent of herds greater than 1,251 milking and dry cows and present in 32.32 percent of herds with 501 to 1,251 milking and dry cows. However, presence does not mean functionality.

Prior to AMMP compost bedded pack barns were uncommon in California. These barns require daily management and incorporation of fresh manure into the bedded pack. Sufficient labor and equipment must be available daily on dairies to incorporate fresh manure into bedded packs. As of November 2019, there were five completed compost bedded pack barns, six partially completed, and two not yet started. No energy inputs were available for pre and post AMMP implementation. The manure emissions reductions for animals in compost bedded pack barns should account for time away from barns during milking. It is unclear how the manure on feed aprons would be managed without analyzing barn design. If feed apron manure is scraped daily and incorporated into the bedded pack then the reduction seems reasonable. If feed apron manure is not incorporated daily into the bedded pack then the emissions reduction may be an overestimate.

Vacuum systems were used in select facilities in California (Region 5) prior to AMMP. Prior to AMMP, vacuum systems were predominantly tractor driven tanks with a vacuum component attached to the tractor through a power take off device. Introduction of fully operated equipment (no need for tractor as tank and engine are on the same piece of dedicated equipment) was attractive to a few dairy producers interested in modifying their manure management practices. Management of vacuum equipment requires dedicated labor to operate equipment. Additionally, this activity is subject to potential challenges as the equipment operator needs to dismount to open and close gates and the activity requires synchronization with milking schedule to ensure to minimize animal stress. Many of the flush to scrape projects proposed to vacuum 104 days a year (personal communication) in some or all lactating pens, then subsequently air dry or compost manure. A value of 30 percent of manure vacuumed was assumed. In herds where manure is vacuumed twice weekly and no flushing occurs, then near total collection of the manure from concrete feed aprons will be collected. In herds where manure is vacuumed twice weekly and flushed the other days of the week, markedly less manure will be diverted from liquid storage compared with the previous example. Some residual manure remains in concrete grooves after vacuuming. Manure defecated while cows travel to and from the milking parlor or at the milking parlor is not likely collected via vacuum.

Dairies located in Regions 1 and 2 pasture cattle for part or much of the year (southern or northern locations, respectively). Pasture based dairies manage manure and wash water collected from the milking parlor daily. Additional manure is managed from animal housing areas. Climatic conditions (high rainfall and extended rainy season) result in minimal flushing associated with manure collection so less wash water is generated for subsequent storage. Mostly, manure is scraped from animal housing areas and stored as a slurry or solid. Requests for compost bedded pack barns and solid liquid separation were consistent with the climate and current management conditions. Daily attention is necessary for proper maintenance of the compost bedded pack barn. The advantage for organic producers in Regions 1 and 2 was the end product should have markedly fewer weed seeds and required fewer additional management considerations when land applied on pasture.

AMMP emissions reductions. Emissions reductions for any given project implemented were evaluated on the subset of manure it treats. As used, the 2019 GHG benefit calculator asks for specific practices and may focus only on the part of the herd receiving the practice. Complex combinations of multiple classes of animals and multiple practices for manure management were submitted by some application. For some facilities, modifications to different classes of animals and their associated manure management may yield greater emissions reductions than merely focusing on one class of animals. Flexibility in the application process is important to allow subscription of different practices for different groups of cattle. As an example, one AMMP project will have a compost bedded pack barn for one group of animals and manure from other animals at the facility will be flushed and be subject to mechanical separation. It is critical to take into consideration the percent of emissions reduction from a specific practice with a specific class of animals compared with the total emissions from the farm. It is the actual reduction in emissions across all dairies that is necessary to achieve the 2030 target of 40 percent reduction from 2013 inventory emissions values.

Conclusions

The primary applications for AMMP were for known and existing practices already on farms in California. More dairies in the lower two deciles of lactating and dry cow population applied for AMMP funds. This represented a smaller percent of dairies in each herd size category for freestall (4.76 percent) and non-freestall (6.38 percent) dairies with less than 750 milking and dry cows. Funded AMMP projects were predominantly solid separation (Category 3) in Region 5 and solid separation or compost bedded pack barns in Regions 1 and 2. Continued funding of AMMP provides opportunity for producers to participate actively in GHG emissions reductions. This is critical given the current economic outlook for dairies.

Recommendations

Continued funding of AMMP provides opportunity for producers to participate actively in GHG emissions reductions. This is critical given the current economic outlook for dairies.

CHAPTER 4 THE ECONOMIC MODEL, SIMULATION APPROACH, AND DATA USED TO ASSESS THE ECONOMIC IMPACTS OF METHANE EMISSION REDUCING PRACTICES FOR SMALLER AND LARGER CALIFORNIA DAIRIES

Introduction

Chapter 4 describes a conceptual model, a simulation framework and the data used to implement the model.

This chapter provides background to the simulation model results contained in Chapters 5, 6 and 7. Therefore, this chapter itself does not offer specific results or practical conclusions, but rather is an input to such results and conclusions.

The first part of Chapter 4 documents the modeling framework developed to assess impacts and describes the simulation methodology. The detailed computation model, written in R is available from the authors.

The second part of Chapter 4 provides data and parameter values used for the simulations. This provides a detailed list of manure management practices, and their effects on costs and therefore are used in specifying cost equations and shifts in cost equations that are part of the model developed in the first part of the chapter.

Materials and Methods

4.1 Economic Modeling Framework

Economic modeling was applied in the context of technical change or policy changes to better understand economic and related implications of such variables as prices, quantities and environmental outcomes. A novel approach was developed in the context of manure management practices and impacts on size distributions of farms. Similar simulations have been used to address issues in environmental, resource and agricultural economics. See for example, Lee, Sumner and Champetier (2019); Perrin (1980); and Rickard and Sumner (2008) and the articles they cite.

4.1.1 Overview of the modeling framework

An economic model was developed representative of dairies for operations of different sizes and manure handling types where manure and methane management costs may be adjusted to reflect the implementation of methane emissions reduction practices. Each dairy size/type was characterized by a herd size and associated costs and emission factors for current and alternative practices.

In order to simulate the response of the whole dairy industry, each representative dairy model was scaled up by multiplying each specific outcome by the number of operations in each group type. Milk production was matched to the demand for milk products for all of California. This scaling up allowed the model to assess the methane emissions abatement in California's inventory and to track market adjustments in milk supply and demand.

In the model, a shift upwards in production costs from increased methane abatement efforts results in a shift upwards of supply on the milk market. Given a stable demand for milk, these cost shifts result in an increase in milk price, decrease in quantity produced and consumed.

Thus, the complete model reflects the full production and market effects of policy on the dairy sector while allowing differences in costs and emission reductions among different sized dairies and as well as among freestall and non-freestall operations.

Four time horizons were considered: 1 year, 5 years, 10 years and 20 years. These horizons differ in terms of the values of parameters that reflect the extent and pace of adjustments in producer and consumer behaviors (i.e. supply and demand elasticities) including the extent of entry and exit for dairy operators.

4.1.2 Groups of dairy operations according to size and other characteristics

Dairy operations of California were assigned to one of seven groups. For non-organic dairies each group was characterized by a combination of three herd size ranges and two current housing systems that affect manure handling. The seventh group represented organic dairies which represented substantial differences in costs, revenues and production practices.

In the equations below, the notation "*z*" indicates the group index. All operations within one size category were assumed to have the same production costs including the same cost changes related to methane abatement practices. Treating operations as homogenous within group allowed considering a representative operation for each size-group and building a detailed economic model of farm choice, profitability and methane emission.

4.1.3 The treatment of marginal cost, abatement practice adoption and representative operations in size-practice groups

The model has one representative set of parameters per group. The model does not include an explicit mechanism for progressive adoption of practices among dairies of one group. The model produces a step-wise methane abatement cost curve. The model and parameterization faced the standard trade-off between model complexity, available parameter estimates and robustness. Adding heterogeneity in costs within groups can be readily added when data and parameter estimates are available to calibrate such patterns of heterogeneity.

Importantly, this simplified model specification is unlikely to generate systematic bias related to size distribution implications. Adoption of manure management practices is implicitly random within each group, which is expected if factors other than abatement marginal cost, such as location, access to information, or other farm-specific management drive dairy farms to adopt abatement practices.

4.1.4 Bio-economic model of a representative dairy

A representative dairy operation was characterized with the help of a set of biophysical variables. The number of milking cows in the herd, c, indicated size. If data were available, the model would be robust to other size measures. The quantity of milk produced was denoted Q and the quantity of methane emitted through manure management was denoted GE.

In addition to biophysical variables and parameters, operations were characterized by a set of economic metrics. On the income side, these included the price of milk, which was denoted by P;

the milk revenue R = P*Q; and non-milk revenue OtherR. The costs included feed, FeedC; hired labor, LabC and costs specific to manure management that are discussed in detail below. Table 4.2 lists notation starting with those representing the income size, then variable costs, then capital investment costs, management and finally the economic summary concepts marginal cost and total costs.

Many of the biophysical and economic variables can be usefully considered on a per unit basis with several units in the denominator. Costs and revenues are defined per unit such as: per cow, per hundredweight of milk or per dairy operation. Subscripts and superscripts used to facilitate the tracking of units for each variable are in table 4.2

Table 4.1 List of symbols used in the equations and the description of economic characteristics of dairy operations in the model

Symbol	Interpretation
P	Price
R	Revenue
OtherR	Other revenues (not milk)
FeedC	Feed costs
LabC	Labor costs (hired)
MaOpC	Manure management operations costs
OtherOpC	Other operations costs
OpC	Total operations costs
MaInvC	Manure management capital investment costs
OtherInvC	Other (non-manure related) investment costs
InvC	Total investment costs
MgC	Management costs
MC	Marginal cost
TC	Total costs

Table 4.2 Subscripts and superscripts for model variables and parameters

Symbol	Interpretation
c	Per cow
m	Per cwt of milk
o	Per dairy operation
g	Total for a group of operations
T	Total for California
z	Indicator for size/type group
Conv, Org	Indicates conventional and organic markets

The subscript c, represents a measure per cow, m represents a measure per hundredweight of milk, and o represents a measure per dairy farm operation. The index g, refers to a group as specified above and T represents the total for the California dairy industry. Index z will be used as a subscript when considering groups of operations and the entire industry.

Using this notation, for example, Q_c would be the quantity of milk produced per cow in a representative operation and GE_m the amount of methane emitted per cwt of milk. Note that not all combination of variables and indexes are useful to consider. All equations and variables are yearly measures unless otherwise specified.

Equipped with this notation, the rest of this subsection describes the main economic tradeoffs involved in a representative dairy operation. The next few equations were used to characterize the important economic and methane-related mechanisms and tradeoffs in our representative operation.

The dairy operation produces Q_o cwt of milk per year from its C_0lactating cows. The sales of the milk production generate the revenue given by

$$R_o = P_m * Q_o + OtherR_o. \tag{1}$$

Note that P_m the price is per cwt of milk and was assumed to be the same for all operation sizes, with organic milk in a separate group. The farm revenues not accruing from milk sales were accounted for in the term $OtherR_o$.

The quantity of milk produced is a function of the number of lactating cows:

$$Q_o = C_o * Q_c \tag{2}$$

where Q_c is the amount produced per cow in this representative dairy size and manure management group.

The amount of methane emissions for the operation reflects the manure management practice and the characteristics of the operation size/type:

$$GE_o = GE_c^i * C_o \tag{3}$$

where superscript "i" indicates the methane mitigation practice.

A more intensive effort of methane emission reduction means that the amount of methane per lactating cow GE_c^i is smaller (emission factor). It is this index i which allowed linking the methane abatements to the corresponding manure management costs on the operation. As with other parameters of the simulation, the emissions factors for a given manure management practice were allowed to differ across dairy sizes. Note that equation (3) tracks the emissions from lactating cows in the calculation of amount of methane per lactating cow GE_c^i. As discussed in sections 4.2 and 4.3, the emission factor includes the dry cow as well as the cows that are currently lactating. The heifers are not included.

The economic costs of milk and manure management for the operation were represented in the equation for costs of production. The total costs of an operation (calculated per year) were split in three main categories: operations costs, capital investment costs, and management costs. This is represented by the following relationship per operation:

$$TC_o = OpC_o + InvC_o + MgC_o. \tag{4}$$

These costs were converted to costs per cow or cwt of milk produced by dividing by the number of cows or milk production and would then have subscripts "c" or "m". We track the different cost types separately to allow them to differ across time horizon, which is important in the relevant simulations, as well as for the composition of costs to differ across dairy types.

Operating costs can be thought of as costs applying on a per unit of milk basis or per cow basis. Investment costs will vary depending on the lifetime of the investment considered and the opportunity cost of capital (equivalent to the interest rate). Management costs will vary across dairy sizes reflecting differences in the number, behavior, and capacity of owner/managers.

We incorporated the details of the cost implications of methane abatement practices, which required a further break down of each cost category.

Costs of operations were split into four items:

$$OpC_o = FeedC_o + LabC_o + MaOpC_o(i) + OtherOpC_o \tag{5}$$

which tracks feed costs, labor costs (excluding manure management operations), manure management operations, and other miscellaneous costs. Feed and labor costs are functions of the number of cows in the herd and the amount of milk produced and are tracked separately in order to assess the effect of long-term trends in dairy profitability related to potential changes in labor and feed prices over time (see Task 7).

The manure operations costs include the fuel, labor and materials for scraping and other manure management operations but do not include the initial capital investment or the time and effort spent by the operation management. Operating costs for manure are a function of the amount of manure to be processed and the methane abatement practice indicated by the index i. Both parameters were allowed to vary across dairy size/types.

For investment costs, we only differentiated between investments related to manure management (machinery, storage infrastructure, etc.) and all other investments:

$$InvC_o = MaInvC_o(i) + OtherInvC_o \tag{6}$$

where Ma stands for manure. These investment cost for manure infrastructure *MaInv* do not include the opportunity cost of the manager's time.

The annualized cost of investment in manure management capital such as infrastructure or specialized machinery were represented by $MaInvC$ and other annualized capital investment costs were represented by $OtherInvC$. The cost of manure-related infrastructure and equipment depends on the methane practice adopted as well as the amount of manure to be processed, which is captured in the choice of parameters for each dairy size group. Annualization means that the one-time expenditure for purchase of material and building is spread over the useful lifetime of the infrastructure or equipment. The investment cost also includes the payment of interest on the capital required for the initial investment. Thus, annualization requires two assumptions: the lifetime of the infrastructure or equipment and the underlying interest rate.

This itemization of costs and distinction between operation, investment, and managerial costs related to manure management practices is important to the extent that these cost components are expected to differ across farm sizes. This level of detail also allows a careful representation of differences across the practices discussed in Task 3. Each methane management practice identified by index "i" was characterized in our simulations by methane emissions per cow GE_c^i from equation (3) and its corresponding costs $MaOpC_o$ and $MaInvC_o$.

The third term in equation (4) is the cost of management MgC_o and represents the time and effort of the managers of the dairy. For hired managers, this term could be calculated like other hired labor costs and an increase in management effort resulting from the adoption of methane abatement practices could be represented by simply increasing the amount of manager time needed. However, the management and ownership organization of dairies varies greatly across dairy sizes as well as idiosyncratic characteristics and therefore a systematic accounting of management costs is practically impossible. In fact, in many dairy operations, the managers are also owners and the compensation for their labor as managers cannot be separated from the returns to their investment as owners of the operation. For that reason, most datasets on dairy operation costs only report total costs excluding management costs.

In equation (4) we included management costs explicitly to emphasize that these costs affect dairy profitability directly. However, given the difficulty in quantifying management costs and their change in relation to new methane abatement practices, we did not include them in the rest of the modeling. We do nevertheless account for their potential effect when modeling exit decisions as discussed below. We argue that increases in management effort could greatly affect small operations where there is only one operator/manager who is unable to increase management effort through hire or dedicating more of his or her time.

The profit margin for the operation is the difference between revenue and total costs:

$$\Pi_o = \mathrm{R}_o - \mathrm{TC}_o \tag{7}$$

In addition, if the equipment maintains some salvage value at the end of the useful lifetime, this value, adequately discounted, should be subtracted from the initial total costs of the investment. Here, salvage values are likely to be very small and are ignored.

This profit margin is a central indicator of economic profitability in our simulation framework and in the literature on the economics of dairy operations (see for instance MacDonald, Cessna and Mosheim (2016), Bouchard (2016), Bragg and Dalton (2004) and others).

All equations presented so far were characterizing one representative operation and all variables were measured in units per operation or per cow (e.g. tons of CO2-equivalent of methane per operation, dollars of revenue per operation, and etc.). Below, we now expand the model to include all groups of operations adding up to the entire industry. In each group, all operations were assumed to be identical to the representative operation. Each group was characterized by a different set of values for its representative operation.

4.1.5 From representative dairy operations to groups and industry

The notation introduced in tables 4.1, and 4.2 allowed the model to scale up from representative dairy operations to the size groups and to the industry as a whole where the market mechanisms are at play in the determination of milk prices and quantities produced and consumed.

Given the assumption of representative operations for each size group, the equations (1) to (7) above given for each operation can be scaled up for their respective group by multiplying each variable with subscript "*o*" by the number of operations in each group N_z. The revenue, quantity of milk produced and all other variables for each group were indicated by subscript *g*. The variables introduced for representative operations above are now superscripted with *z* to reflect differences across groups. For instance, Q_o^A is the amount of milk produced by an operation in group A, while Q_c^D is the amount of milk per cow in group D.

As a result, equations (1) and (3) above become:

$$R_g^z = P_m * Q_g^z + OtherR_g^z = N_z * [P_m * Q_o^z + OtherR_o^z] \quad (8)$$

$$GE_g^z = N_z * [GE_c^i * C_0] \quad (9)$$

Cost and profit equations (4) to (7) can be aggregated for the groups of operations in the same fashion.

The next step is to add variables across groups to obtain milk production and methane emissions for the two milk markets as well as the corresponding economic returns, costs and profit margins.

The total quantity of milk produced is the sum of the quantities from each group:

$$Q_T^{conv} = \sum_z Q_g^z = Q_g^A + Q_g^B + \cdots + Q_g^F \quad (10)$$

$$Q_T^{org} = \sum_z Q_g^z = Q_g^G + Q_g^H \quad (11)$$

where "T" indicates the industry's total production and equation (11) allows for more than one organic group if needed.

Methane emissions can be calculated in a similar manner:

$$GE_T = \sum_z GE_g^z, \tag{12}$$

which combines emissions from producers in the organic and conventional milk markets.

4.1.6 Characterizing the response of dairies to changes in prices and costs.

Equations (1) to (12) above provide an organized description of costs of production and revenues for the production of milk with a breakdown of how methane-related practices might affect the operations of dairies. However, these equations do not provide a model of how producers will adjust their operations to changes in milk prices or costs of production through the adoption of new manure management practices.

The profit margin equation in (7) provides a useful benchmark as it allows modeling the behavior of operators as maximizing profit. We first present this profit optimization model before showing how it can be enriched with additional and more complex behaviors relating for instance to uncertainty about prices or investment diversification.

The profit of an individual operation from a group of size *z* is given by equation (7) above. To highlight the economic trade-off underlying profit maximization, we included the quantity of milk produced:

$$\Pi_o^z(Q_o^z) = \mathrm{R}_o^z(Q_o^z) - \mathrm{TC}_o^z(Q_o^z) \tag{13}$$

The profit is maximized by the quantity of milk that brings the marginal profit to zero, which means setting the marginal revenue to the marginal cost:

$$\frac{d\mathrm{R}_o^z}{dQ_o^z}\Big|_{Q_o^{z*}} = \frac{d\mathrm{TC}_o^z}{dQ_o^z}\Big|_{Q_o^{z*}} \text{ or } P_m = \mathrm{MC}_o^z(Q_o^{z*}, i) \tag{14}$$

using expression (1) for the revenue of the operation and where the star in Q_o^{z*} indicates the profit maximizing quantity. Index i indicates that the marginal cost of production will depend on the manure and methane management practice. A higher operation cost per hundredweight of manure will result in a higher marginal cost per hundredweight of milk.

The important intuition in equation (14) is that the quantity of milk will respond to price changes according to the shape of the marginal cost function. If the marginal cost changes substantially for a small change in the quantity of milk produced, the managers will not adjust production significantly for even large changes in prices. In contrast, if marginal costs differ only a little over a range of milk production volumes, a small price change will require the manager to adjust output quantity by a greater amount.

In a similar fashion, the equations in (14) captured adjustments that would follow from changes in the prices of feed, labor and other factors affecting costs. Equation (14) is the inverse of the supply equation where quantity of milk produced is given as a function of price as shown in (15):

$$Q_o^z = S_o^z(P_m, i). \tag{15}$$

We indicate that the supply function depends on the set of methane management practices implemented with the index i.

The supply function for the representative operation in each group (15) can be aggregated to the group in equation (16):

$$Q_g^z = S_g^z(P_m) = N_z * S_o^z(P_m, i) \tag{16}$$

The supply function for the industry is in (17):

$$Q_T = \sum_z Q_g^z = \sum_z N_z * S_o^z(P_m, i). \tag{17}$$

The slope (or derivative) of this supply function with respect to the price determines how much the industry will adjust milk output to price changes. A common way to represent different time horizons in this setting is to assume that this derivative is larger when more time is given to producers to adjust to price changes.

This profit maximization model has been expanded in the economics literature on dairy production, to better account for the dynamic nature of production decisions as well as the behavior of dairy manager/owners who may pursue profit as well as other objectives.

First, production decisions in the dairy industry carry significant inertia. Given that infrastructure determines to a large extent the size of the herd and the amount of milk produced, investment decisions lock in producers for long periods of time, in the range of years. Over the course of weeks or months, only limited adjustment for output and costs can be made to herd size or by changing feed and other practices. As a result, the response of dairy producers to changes in input costs or milk price is lagged and based on profit margins averaged over months or years.

MacDonald et al. (2007) Tauer (2006), Foltz (2004) and others show that dairy operations have remained in production when revenues fall below total costs but above the salvage value of the invested capital. This range of prices where profits margins are negative but dairy operators do not exit is called a zone of hysteresis or asset fixity. This zone depends on farm characteristics as well as regional factors such as opportunity cost of land.

A second important aspect of the economic behavior of dairy operators relates to asset investment and opportunity cost of management effort. When dairy owners are also the operators, investment decisions in the dairy and labor decisions by the owners are tied. For instance, Bragg and Dalton (2004) find that higher off-farm income opportunities and greater diversification of farm income were more likely associated with dairy exit decisions.

There was no available economic model of dairy exit that was specific to the California industry and context. The development of such model, which would require extensive data collection through surveys, was beyond the scope of this study. Accordingly, we used a heuristic model that combines a standard supply function for individual operations with a pattern of exit calibrated on observed trends in California.

The supply functions were specified by an elasticity (representing the slope of the supply) and shifts. The value of the elasticity parameter reflects the amount of adjustment that operators can implement for the 5, 10 and 20-year horizon. The shifts represent the change in costs due to the adoption of methane emission abatement practices as well as feed price and labor and are calculated using the cost equations (4), (5) and (6).

In parallel to this standard supply specification, the number of dairy operations in each group was adjusted for each simulation period considered. As discussed in the parameterization section 4.2 below, trends of exit observed over the last two decades for each size group were used to build projections of exit over the next two decades. This was implemented by changing N_z in equation (16), which aggregates individual operations to groups. With this composite model of standard supply and exit, the supply side with heterogeneous dairy operations is complete.

We now turn to the demand for milk.

4.1.7 Characterizing milk demand facing California dairies.

We used two demand equations to represent the behavior of consumers on the conventional and organic milk markets. For the conventional market, an aggregate demand for raw milk facing the industry that combines the ranges of processed products and the demands and policies affecting those products. This simplified representation of the demand for dairy products is suitable for the purpose of our analysis. Individual producers face prices that vary by month and over which producers have little influence except in the characteristic of their milk (components and quality). Prices received by producers are determined to a large extent by the quantity of milk produced in California and elsewhere. Thus, our specification captures the main mechanism of equilibrium adjustments to a methane emission change. Since prices for organic milk are much higher and determined by a different demand segment, we represented the organic market separately despite its relatively small size.

Accordingly, we captured the response in the aggregate demand functions for conventional and organic milk:

$$Q_D^{Conv} = D(P_m^{Conv}) \text{ and } Q_D^{Org} = D(P_m^{Org}) \tag{18}$$

where D( ) is the demand function giving the quantity demanded annually Q_D in hundredweight per year for a given price P_m.

The shape, and in particular the slope of this function, characterizes how quickly the quantity demanded and consumed will change when price changes.

The supply and demand equations are connected by “market clearing conditions”, which recognize that buyers and producers respond to the same price P_m and that, adjusting for a limited amount of storage over time, the quantity produced Q_t must be equal to the quantity demanded Q_D.

$$Q_D = Q_T \tag{19}$$

The demand function in (18), and the supply functions in (17), provide a complete model that tracks how implementation of methane abatement measures will impact production costs of dairies of different sizes and through market adjustment, the price and quantity of milk.

Figure 4.1 is a schematic representation of how the supplies of the different groups of dairies and the conventional and organic demands are connected in the model. The diagrams labeled “organic” represent two groups of dairies supplying the organic milk market. The three diagrams along the right side of Figure 4.1 represent the other 6 groups, housing systems are combined for each of three size groups.

Figure 4.1 helps illustrate how farm groups categorized by herd size relate to industry supply and demand conditions that determine market prices. When changes in manure handling practices affect costs of farms they affect the overall supply function in that market and therefore affect price and the demand facing the categories, which, in turn, affects milk production of farms in that size category.

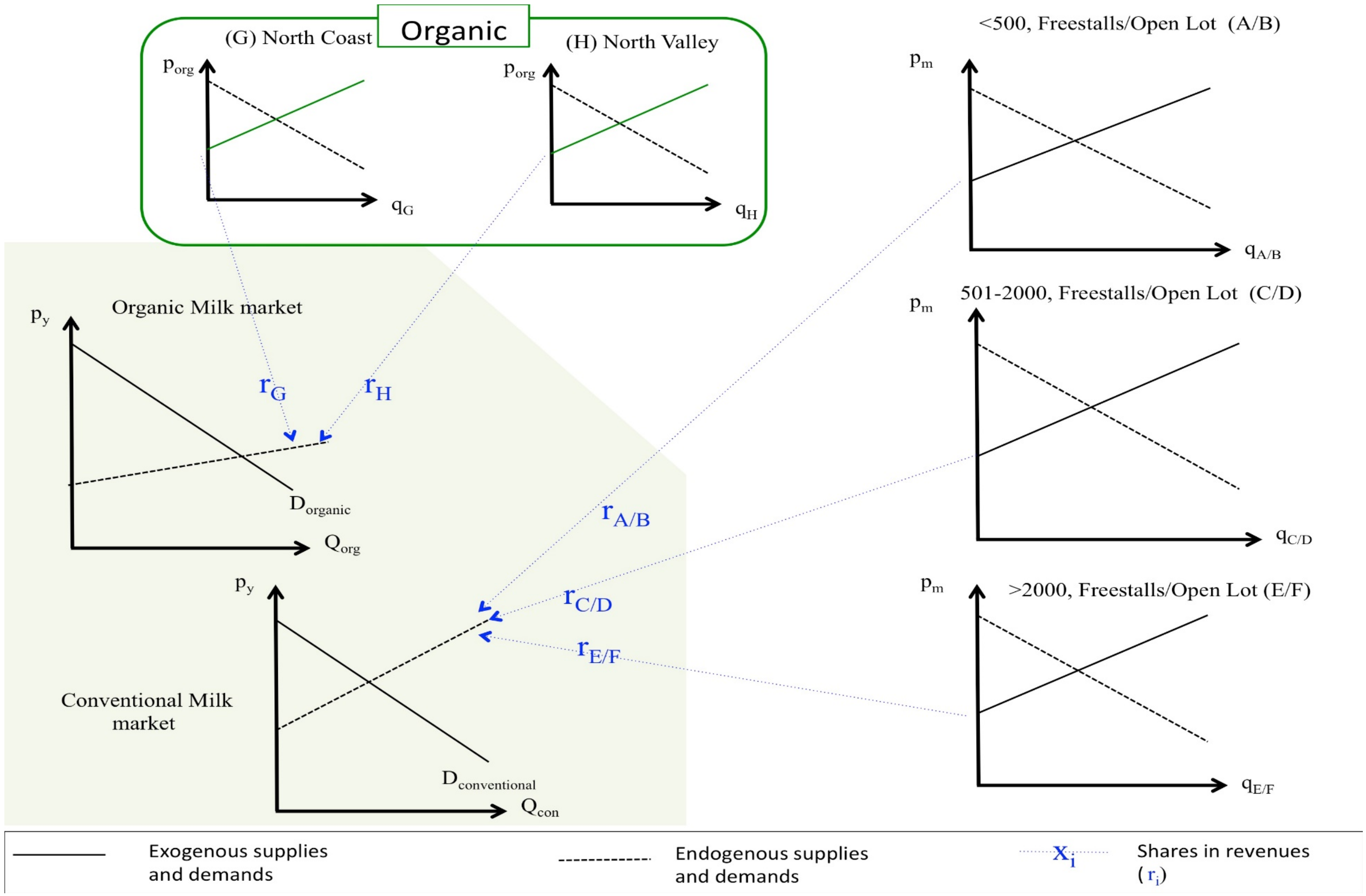


Figure 4.1 Break down of milk markets by dairy groups

4.1.8 Definition of scenarios in the economic model

Equipped with this sectorial model of the dairy industry in California, the impact assessment of the methane abatement policies can be implemented through scenarios, which show how economics and emissions outcomes would change under the adoption of different practices. The scenarios as defined by pattern of adoption of certain methane abatement practices which results in both an increase in production costs and a reduction in methane emissions.

We illustrate the effect cost increases in the economic modeling in Figure 4.2 and focus on dairy operations in group A. The diagram shows the demand for milk D_T (conventional here) as well the supplies for group A alone, S_A and for the whole industry, S_T. These supplies, which correspond to equations (16) and (17) above reflect the costs of operating before any new practice adoption. The starting price and quantity for the market is found where the total industry supply S_T meets the demand D_T and is labeled P_m, Q_T the figure. At that price, the quantity produced by group A is where the supply of the group S_A meets the dotted line indicating price P_m. By construction, the vertical distance between Q_A and Q_T is the sum of milk quantities produced by all other groups in the market (B through F).

When group A adopts a new methane abatement practice, the supply curve of the group "shifts up", reflecting a cost increase. In cases where some operations also exit the industry, the supply function also shifts left, since the total production of the group is reduced. The net effect of the shifts is a new supply for the group S'_A. Similarly, other groups may or may not see their supply move and by different amounts according to the specific patterns of adoption costs for different dairy sizes and types. The aggregated effect of these supply shifts is visible in Figure 4.2 in the new supply for the market S'_T.

The new market price and quantity is where the new total supply meets the demand and is the point (P'_m, Q'_T). Where S'_A, the new supply for group A meets the new price line P'_m determines the amount of milk produced by group A, after the adoption of new practices and market readjustment. It is labeled Q'_A and the horizontal different between Q_A and Q'_A is the change in quantity produced by group A. The vertical different between P'_m and P_m is the increase in price resulting from cost increases throughout the industry. Note however that producers are for the most part not benefiting from this price increase since they see their cost increase at the same time. The net effect will vary from group to group depending on how cost shifts affect different groups.

Implementation of this model includes several operation groups, three different time horizons (5 years, 10 years and 20 years) and the alternative methane abatement practices. The values of the supply and demand elasticities differ across time horizons and recognize that longer time horizons tend to allow for more score adjustment in practices, production and consumptions in response to changes in prices and costs. We also incorporate observed and projected trends in dairy farm exit, hired labor costs, and dairy feed costs.

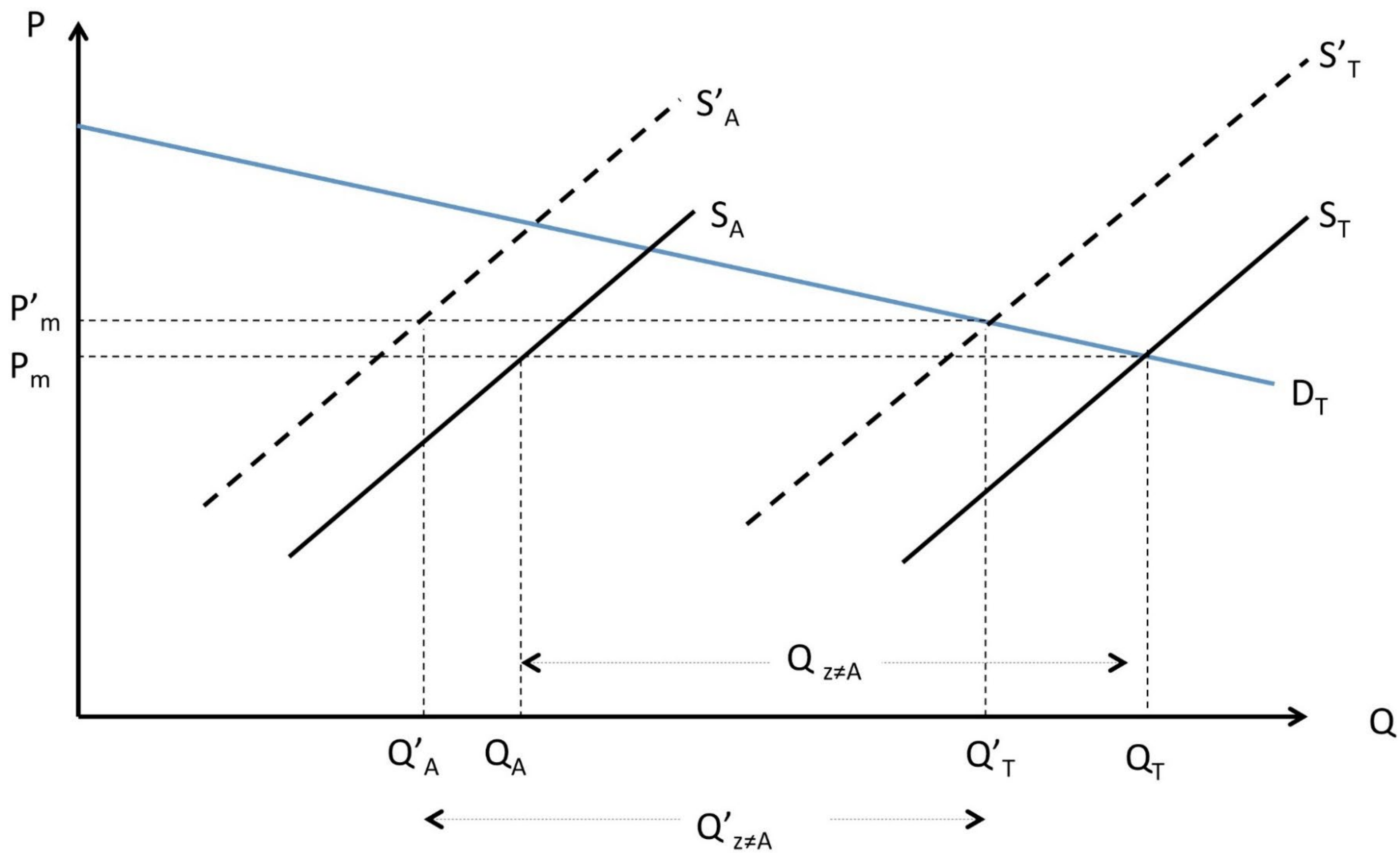


Figure 4.2 Equilibrium displacement in the milk market due to a production cost increase

Our simulations focused on modeling implications of costs of manure management patterns among groups and how these have changed and may change. These differ by dairy size and types. The patterns of adoption of practices used in our simulations are specified the second half of this chapter.

We considered four time-horizons and included dairy farm exit patterns across sizes based on historical experience. Furthermore, we allowed adoption to be partial within a group meaning that in the same group, some dairies adopt and others not. This means we did not impose an assumption that all operations in a group behave identically. There are several ways to model and explain differences in adoption or exit among operations and we discuss them when necessary when presenting simulation results.

4.1.9 Framework of equilibrium displacement model expressed in logarithmic differentials

We adopted a standard method to significantly reduce the requirements of parameterization in which we focused on changes or displacements induced by a policy or other scenario. Rather than calculating the operating costs (or another variable of interest) before and after implementation of a methane regulation policy, we tracked *by how much*, in percentage terms, the operating costs have changed. Similarly, instead of calculating quantity of milk, price of milk and profit margin before and after practice adoption, we estimated the percentage change in each of these variables. This methodology is commonly used in economics and is sometimes called an equilibrium displacement model.[1]

We used the notation *dln* to represent the percentage change of the variables. For instance, the percentage change in quantity of milk produced by the industry is noted $dlnQ_T$ and is calculated as the change in quantity dQ_T divided by the quantity before the equilibrium change (or the initial quantity) Q_T. Here we lay out the model using notation for the non-organic milk market. The organic market follows the exact same derivations.

The relationships above can be rewritten in percentage terms. For instance, equation (17) becomes by differentiation:

$$dQ_T^{Conv} = \sum_z dQ_g^z \tag{20}$$

which can be divided by dQ_T^{Conv} can be rewritten as:

$$dlnQ_T^{Conv} = \frac{dQ_T}{Q_T^{Conv}} = \sum_z \frac{Q_g^z}{Q_T^{Conv}} * \frac{dQ_g^z}{Q_g^z} = \sum_z s_g^z * dlnQ_g^z \tag{21}$$

where s_g^z are the shares of milk production from each group of dairy sizes in the total output of the conventional milk market.

Equation (21) reflects that the percentage change in total output is the average of the changes in each group weighted by the share of each group in the total production.

[2] To directly implement the full model as characterized by the set of equations in levels as written above would requires that each equation be fully parameterized against data. Furthermore, functional forms, which would typically be non-linear, must be chosen to represent all relationships.

The demand equation for conventional milk in (18) can similarly be transformed in a dln form by making a first order approximation of the demand function:

$$dlnQ_D^{Conv} = \eta^{Conv} * dlnP_m^{Conv} \tag{22}$$

where η is the elasticity of demand (the percentage change in quantity for a percentage change in price), and $dlnP_m$ is the percentage change in milk price.

The demand elasticity is a negative number, reflecting that quantity demanded moves in opposite direction to price facing consumers.

The implementation of the equilibrium displacement method for the supply equations requires additional steps because the supply side is where the assumptions about cost changes and exits come into play.

The basic supply functions for individual dairies from equation (15) is first transformed similarly to the log differential demand equation:

$$dlnQ_o^z = \varepsilon_z \, dlnP_m, \tag{23}$$

where ε_z is the supply elasticity, which represents the slope of the marginal cost function in log differential terms.

Next, we introduce the change in costs resulting from the adoption of practice i. We combine equations (4), (5) and (6) so that we write a detailed expression of the total costs for a given practice i:

$$TC_o = FeedC_o + LabC_o + MaOpC_o(i) + OtherOpC_o + MaInvC_o(i) + OtherInvC_o + MgC_o \tag{24}$$

Notice that when comparing this cost expression before and after the adoption of a new practice j, only the terms with index (i) change. Therefore, the change in total costs are:

$$dTC_o = MaOpC_o(j) - MaOpC_o(i) + MaInvC_o(j) - MaInvC_o(i) \tag{25}$$

This expression can be converted in proportional change as well by dividing by the initial total cost and introducing the cost shares of the manure operations costs and the manure investment costs.

$$dlnTC_o = cs_{MaOp} dln\, MaOpC_o + cs_{MaOp} dlnMaInvC_o \tag{26}$$

where *cs* stands for cost share and the change considered, the *dln,* refers to the change from practice i to j.

For clarity of expression, in these expressions, we have not tracked the group index z. Each of the equations in log differential form for each group has different parameters for cost shares and changes in manure related costs. These are laid out in detail in the model parameterization section below. Furthermore, each supply-side equation has been written for the operation as indicated by index "o". In the context of a displacement model, these equations apply to costs per hundredweight of milk, or per cow, since the changes in production of milk per operation are in the first order approximation.

Another use of equation (24) is in the simulation of the effect of trends in labor and feed costs for each horizon. When these costs are expected to change over time, the terms $FeedC_o$and $LabC_o$ do not cancel each other and two additional terms appear in the dln expression of the cost change (26) which becomes:

$$dlnTC_o = \delta_Z \ = cs_{MaOp} dln\ MaOpC_o + +cs_{MaOp} dlnMaInvC_o + cs_{Feed} dlnFeed_o + cs_{Lab} dln\ Lab_o \tag{27}$$

For clarity in notation, we call δ_Z this expected proportional change costs, understanding that it will take different expressions depending on the scenario and the time horizon considered.[2]

The last step to implementing the displacement framework is to aggregate the individual supply responses into group supply responses. This is done following equation (16), which multiplies the individual responses by the number of operations in each group. However, the number of operations in each group (N_z) may change both following exit trends and additionally in response to management costs, especially for some small operations. As a result, the N_z is not just a parameter but a variable and is therefore present in the *dln* form:

$$dlnQ_g^z = \ \varepsilon_z\ dlnP_m - \varepsilon_z \delta_Z \ + \ dlnN_z \tag{28}$$

The implementation of methane abatement practices was therefore represented by a change (upward shift) in the marginal cost curves of dairy operations as well as a change in the number of operations in the group in the relevant cases. The cost shift δ_Z are percentage increases in costs (percentage calculated at the baseline costs and prices). Note that the shifts in costs were converted in quantity shifts by multiplying by the elasticities. The sign was also inverted since an increase in marginal cost is a vertical shift up for the cost curve (positive in price dimension) but horizontal left (negative in quantity dimension).

This supply equation for individual groups (28), combined with equation (21) which aggregates group outputs into the industry milk output constitutes the supply side of the market equilibrium displacement model.

The market clearing condition in equation (19), which states that the total quantity produced is equal to the quantity consumed, translates directly in proportional changes:

$$dlnQ_D = dlnQ_T \tag{29}$$

This market clearing conditions connects the demand side (22) with the supply side (28) and (21) and completes the model in its proportional change form. The derivations detailed here for the conventional milk market are identical for the organic market.

Once the displacement market equilibrium has been solved for and the changes in milk price and quantities determined, the other variables of interest, including methane emissions, can be calculated.

---

[3] We considered all financial variables and parameters in inflation adjusted terms, so only trends in relative prices would be of interest.

4.1.10 Solving of the system of equations and computational methods.
In its *dln* form, the model is linear and solving for the changes in prices and quantities involves solving a system of linear equations. Separation between the supply and demand of organic milk from that of conventional milk means that we have used two independent sets of equations. The market for organic milk is small (a few percent of production) and concentrated in select products (liquid and soft milk products) that tend to stay within California. Therefore, we simulate the displacement of the two markets separately.

For the conventional market, there are several group supply equations (28) in which quantity supplied related to the market price and one equation that aggregates the group supplies into the industry's total (21). There is one aggregated demand equation (22). The market clearing condition (29) is not useful for the resolution of the model as the quantity demanded and the total quantity produced are the same by construction of the group functions and do not need to be tracked separately in aggregated form.

Given the large number of scenarios of practice adoption as well as time horizons simulated, it was practical to write the system of equations in a matrix forms that can be easily inverted numerically. We use the programming language R to implement the numerical simulations. (An appendix with the operative computational program is available upon request.)

4.2 Information and Data About Manure Handling Used to Implement Economic Simulations

To allow manageable modeling, dairy farms in California have been categorized in to seven groups: three herd size groups each with freestall and non-freestall housing, plus an organic category. Farms in each of these groups have a set of engineering, management, and capital situations that determine, in part, the manure management practice chosen.

In the following summary, we report the manure methane emission baseline in 2013 from which all adjustments are referenced. We also report how much manure methane emissions have declined since 2013 as a result of the AMMP and DDRDP funded projects.

Next, we document and explain the engineering, management, and capital considerations that affect responses to manure management incentive and policy implementation. This explanation is based on available data and related documents. These considerations include the technologies that are most common, the inputs used by those practices, and other characteristics that vary by farm and farm operator.

These considerations are relevant to and affect responses of farms across size and therefore relate to dairy farm size distribution for several reasons.

First, scalability of capital. Some dairy equipment and facilities have discrete capacities. These capabilities are sometimes related to economic considerations, but have physical limits as well.

Second, suitability of technology and practices to scale. Manure management practices are chosen for how well they integrate into existing farm infrastructure, including available management. Practices with higher methane reductions may not be adopted on farms that are constrained in their adoption by capital, land, and management time.

Third, avoided costs of the baseline practice. The baseline manure practices were costly when adopted on the farms. The process of changing practices implies new investments and farms would not shift if such a shift would make obsolete or require replacement of significant recent investments that have a long useful life. The cost-benefit calculation of manure handing investments must be done in the context of existing investments and their useful life.

Fourth and finally, the section documents and explains some areas where we lack verifiable widespread data about practices and uses of technologies, but for which there is anecdotal evidence about costs and benefits of specific practices. For example, there seems to be information that compost bedded pack barns increase cow comfort and hence increase milk yield per cow. However, we lack a statistical study that verifies this observation. Each of these four points: scalability, suitability, baseline costs, and anecdotal information about costs and benefits, are discussed, where relevant, in the sections below.

4.2.1 Baseline Practices

Conventional Milk Production – Freestall Facility

We base the cost of the freestall facility on flushed manure collection. In addition to the electricity and maintenance cost of the flush operation, the facility also has labor costs associated with occasional scraping of the alleyways. This is necessary where bedding material and manure cake on edge of the alleyway freestall and is not washed away with the flush. There is the labor and equipment cost of maintaining the freestall bedding. In the baseline practice, flushed manure will be processed through gravity separation cells for solid liquid separation. The liquid fraction is then recycled through the flush system.

Findings in Chapter 1 show that 58 percent of region 5 facilities use some form of gravity separation technique and 36 percent use some form of mechanical separation. Separation practices are therefore an established practice on many dairies. Furthermore, the practice of using well dried manure solids as bedding in freestall facilities is common practice. Meyer et al. (2011) reported that 80 percent of freestall facilities use dried manure bedding. Alternatively, freestall facilities using sand will recycle sand separated and dried from the manure as bedding. From this perspective, utilization of manure solids as bedding is a familiar practice on most facilities. We use the gravity separation cells in the baseline cost for flushed freestalls and flushed non-freestall facilities.

Based on data from a 2,200-cow herd in the Central Valley, farm operations pay a contractor to come to the farm to excavate and transport the separated solids from the separation cells. Based on invoice data, excavation costs $27 per load with each cow producing the equivalent of 0.6 loads of solids per year. The excavation cost varies between $26 to $28 per load throughout the year (Meyer, D. personal conversation, March 2020a). Depending on the season the solids will be land applied, a cost we do not consider, or taken for solar drying to be used for bedding. The solar drying component involves labor and equipment costs in the frequent turning of the windrows and stacking of the material for winter storage.

The cost of excavating these separation cells is removed in the alternative management practice.

Conventional Milk Production – Non-freestall Facility

Data for the labor cost of non-freestall manure management were collected from an 1,800-cow Central Valley dairy (Meyer, D., personal conversation, March 2020b). Manure management costs on a non-freestall facility of 1,800 equates to the equivalent cost of one full time member of staff plus the equipment and fuel costs. The labor costs break down as two workers spending eight hours per day, three days a week for seven months of the year on manure management. Then for the other five months of the year the labor equivalent is one worker spending eight hours for three days a week on maintaining the pens. In addition, there is the equivalent of 20 hours per week spent on maintaining the dry cow and heifer pens. The tasks that occur every second day are using a tractor mounted tine cultivator to incorporate the manure into the surface of the pen and scraping the feed aprons even where flush systems are used. The less frequent tasks involve the use of a tractor mounted box scraper to gather the decomposed manure from the surface of the pen, loading, and transporting the material. If flush is the primary method of manure collection for the feed apron, there is also the cost of operating that flush system, and the labor and equipment cost of loading, transporting, and stacking the separated solids from the gravity separation cell.

Organic

In the baseline cost of manure management, we based our cost estimate on housing cows for six months. This represents months of November through March for which the majority of farms house cows 100 percent of the time plus the equivalent of one extra month to represent times when cows are housed at night. We understand that some farms choose to house cows during the night during some of the grazing season. Farms may also provide supplementary feeding post milking. These practices further increase the amount of manure collected. The decision to house or supplement the ration is driven by forage availability and how close the farm is to achieving 120 days on pasture with 30 percent dry matter intake required for the organic status.

From an extension farm advisor working in the North Coast region, we understand most organic facilities are deep-bedded freestall barns (~75 percent) or mattress freestalls (~20 percent), with a small number providing no housing or bedded pack barns. Within the freestall organic facility, scrape collection is most common. It is estimated that 25 percent of facilities will use flush in some capacity and go over with a tractor mounted scrape when necessary (UCANR Dairy Adviser, personal conversation, March 2020).

4.2.2 Alternative Practices

From DDRDP funded projects from 2015 through 2019 and AMMP funded projects from 2017 through 2019, the majority of the emission reductions have been from DDRDP funded projects. Further to the data reported in Table 4.3, the industry has seen a reduction of 65,326 milking cows in the state herd between 2012 and 2017 (National Agricultural Statistics Service, USDA Agricultural Census, 2017). Ceteris paribus, herd reductions further contribute to manure emissions reductions.

Table 4.3 DDRDP and AMMP Contribution to Reductions

	CDFA Contribution ($Million)	Private Contribution ($Million)	Annual Emissions Reduction (Million $MTCO_2e$/yr)	Contribution to Reduction (percent)
DDRDP Estimated Reduction (107 Projects, 2015 - 2019)*	183.3	369.4	1.98	89.92
AMMP Estimated Reduction (107 Projects, 2017-2019)**	62.3	9.0	0.22	10.08
Estimated Total Reduction From Projects			2.20	100
2013 Dairy Manure Methane Emissions***			9.84	
percent Reduction			22.35	

*DDRDP data from CDFA, (2020b), excludes two projects funded and canceled.
** AMMP data from CDFA, (2020a)
***(CARB, 2020)

Table 4.4 Projects awarded and respective subsidy value and matching funds by year.

	Count of Projects Awarded		Awarded ($ M.)	Matching Funds ($ M.)	Awarded ($ M.)	Matching Funds ($ M.)
	DDRDP	AMMP	DDRDP	DDRDP	AMMP	AMMP
2015	6		11.1	23.4		
2017	16	18	30.7	74	9.6	2.1
2018	42	39	72.4	102	21.3	2.7
2019	43	50	69.1	170	31.4	4.2
2020*			22.1		10.2	

*2020 Values are based on a 65 percent, 30 percent, 5 percent split between DDRDP, AMMP, and admin costs for the $34 million Budget act appropriation.
AMMP Data from CDFA, (2020a), DDRDP data from CDFA, (2020b).

Table 4.5 Annual GHG reductions by herd size/funding group

Herd Size Grouping		Annual GHG Emissions Reduction (Million $MTCO_2e$/yr)	Percentage contribution of each group to total funded reductions
<500	AMMP	10,021.00	0.5
500-2000	AMMP	154,622.80	7.0
>2000	AMMP	57,019.40	2.6
500-2000	DDRDP	169,447.70	7.7
>2000	DDRDP	1,807,446.80	82.2
Total	AMMP+DDRDP	2,198,557.70	100.0

AMMP Data from CDFA, (2020a), DDRDP data from CDFA, (2020b).
Facilities were grouped by matching the awardee in the CDFA data to the best available data of facility herd size.
Authors calculations based on table 2.1 in chapter 2. Columns for herd sizes 250, 1250 and 3250 were used to represent herds within the <500, 500-2000 and >2000 herd size groupings respectively. In the case of organic the column for herd size 250 was used and prorated to reflect 180 days housed.

4.2.3 Manure collection and technologies after adoption of alternative practices

Flushing

Flushing remains the most common method of manure collection because of cost and convenience. For these reasons, facilities continue to flush in many cases and separate solids after collection. Costing post adoption of 3a, 3g and lagoon digesters continues to incur the cost of flush manure collection. This follows the practice detailed in chapter 2.

Vacuum Scrape

Vacuum scraping has previously been found to be the most expensive method of manure collection on farms of less than 750 lactating cows (Kaffka et al, 2016). Farmers of all herd sizes need to consider whether the concrete alleyways are strong enough to support the weight of the equipment. Farmers may encounter future expense where this equipment breaks through alley way concrete that subsequently has to be replaced.

Costs include the capital expense, operational cost, and maintenance cost of one self-propelled vacuum scraper per farm. However, large facilities will consider two vacuum scrapers, to fit with the farm logistics and as backup. A 4,300-gallon tanker can be filled in approximately five minutes depending on the length of the alleys (Vacuum scraper manufacturer engineer, personal conversation, March 2020). Emptying the tank takes less time. While labor time is small and scraping can be achieved in the time that a group is out for milking, the vacuum scrape adds labor costs above the baseline flush method. It remains unclear whether the task of bedding the freestalls and vacuum scraping can be achieved with the existing labor allocation. We expect that on large farms additional labor will have to be allocated to operating the vacuum scrape, while existing labor maintains the freestall bedding. Once the scraping task is complete, the operator is available for other tasks, like bedding, before the next group goes to milking.

Automatic Scrape

There are some examples of AMMP applicants who propose automatic scrape manure collection. The installation of automatic scrape is a scalable cost because 70-80 percent of the costs are construction costs with equipment costs as the remainder (Kaffka et al 2016). The equipment costs comprise of an electric drive motor that can drive scrapers on two lanes up to 500 feet long, plus the scraper and cable components. Freestall barns that are too long, or have an insufficient gradient, are likely to be unsuitable for this practice.

Tractor Mounted Scrape

Like a vacuum scraper, a tractor mounted scraper is used in the time that cows are at milking. A scraper has a fixed volume of manure that it can push at a time. Because of this, a tractor mounted scrape is only suitable for small dairies. Where scrape replaces flushing on small dairies, it remains unclear if the scraping and bedding activities can be achieved with the existing labor allocation in the time that the group is at milking. We expect that on smaller dairies the farmer will make necessary adjustments to achieve the scraping and bedding with the existing labor. These adjustments may be the order in which the alleyways are scraped and beds are maintained, or holding cows at a feed barrier for a longer time before the freestalls are ready and cows can get access again.

Compost Bedded Pack Barns

Compost bedded pack barns (CBPs) are a feasible option for small dairies, both organic and conventional. A CBP facility collects manure in two forms. The majority of manure is collected on the pack where cows spend most of their time. The remainder of manure is collected on the concrete feed apron and walkways to the parlor and from the parlor area. The daily cost of operating a CBP includes the cost of kiln dried wood shavings that is incorporated into the pack. Our cost estimates are for a $2,000 load of dried wood shavings every two weeks for a 280-cow herd in the conventional dairy. This cost is highly variable through the season, with humid months requiring more wood shavings. The cost can also be reduced with the addition of cheaper materials like almond shells. Included in the cost estimate are labor and fuel costs for 30-minute aeration of the pack, twice per day while the cows are at milking, plus fuel and labor for the scraping of the feed apron (UCANR Dairy Advisor, personal conversation, March 2020).

CBP provides increased cow comfort and there is some evidence to suggest that it provides economic benefits from lower lameness rates and improved milk yield (AMMP application narrative).

Mechanical Separation

There are several options for type and capacity of mechanical separation equipment. Despite this, we find that equipment costs increase for small facilities. This is especially true for small non-freestall facilities that have collected ~70 percent less manure than the freestall facility of equal size and therefore require equipment of proportionately less capacity.

Open Solar Drying

The practical operation of open solar drying of scraped manure remains ambiguous. We understand that farms will deposit scraped manure, either from the vacuum scrape or pumped from the collection cell, into shallow concrete curbed channels. This requires zero participation so is practical for eight months of the year. Once dry enough to stack, the solids can be put in to piles or windrows.

For solid separation with open solar drying, the separated solids are transported from the separator to drying pad daily. These separated solids can be stacked and dried faster than the scraped manure without separation.

The area for concrete drying pads was informed by Kaffka et al. (2016) and the cost per square foot of constructing the drying pad was informed by the AMMP applications.

Composting

The cost of composting is highly dependent upon the management decision of how composting should be carried out. The options open to the manager are to intensively manage the composting process, with aeration or frequent turning to speed up the process. Intensive management reduces the area required because once composting has occurred the material can be stacked on a smaller area. Alternatively, the windrows can be turned less frequently, requiring a larger area. In-vessel composting remains an option at higher energy and capital cost but requiring less area.

The area for concrete drying pads was informed by Kaffka et al. (2016) and the cost per square foot of constructing the drying pad was informed by the AMMP applications.

Lagoon Digesters

Herd size is not the sole determinant of the suitability of a digester on a dairy facility. To pipe methane from the digester, by low pressure pipes, to the centralized gas cleaning and injection site, the dairy facility location plays an important role.

Third party project developers are responsible for the matching funds, construction, and operation of the lagoon digester. Each lagoon digester has a solid liquid separation system installed to process manure before the liquid fraction enters the digester. Installation of this separation system is part of the capital cost of the lagoon digester system. The farm owner is thereafter responsible for the operation and maintenance of the separation system while the project developer operates the lagoon digester (DDRDP application narrative).

Manure management cost of the lagoon digester therefor includes the continued operation of the flush system, all freestall or non-freestall bedding labor and equipment costs, plus the labor and equipment costs for handing the separated solids during the solar drying process.

Alternative Practices – Non-freestall Facility

The scalability question is particularly pertinent to the case of non-freestall dairies. Non-freestall facilities collect 30 percent of the daily manure compared to the volume of manure collected on a freestall facility of equal size (see chapter 2 for detailed discussion). Manure is collected on the feed apron and walkways to and from the parlor. The remainder of the manure is deposited on the corral and is handled separately in an aerobic process. The non-freestall facility therefore has a need for equipment with 30 percent of the capacity of a comparable freestall facility. Small non-freestall facilities are therefore in the position where they need equipment that does not scale down linearly to their required size. This imposes a higher capital cost per unit of manure handled than the comparable freestall facility.

Table 4.6 Baseline emissions per cow and reductions in emissions

			Percentage reduction after implementation of alternative practice				
Herd Size Grouping	Housing System and manure collection *	Baseline Emissions Per Cow ($MTCO_2e/yr$)	2a. Compost Bedded Pack Barn	3a. Solid separation with open solar drying, Screw Press	3g. Solid separation with composting, screw press	4a. Scrape conversion with open solar drying	Lagoon Digester
<500	Freestalls - Flushed	5.34	86.6	24.2	24.4	59.1	82.5
<500	Non-freestall – Flushed	2.20	65.3	23.2	23.4	44.6	-
500-2000	Freestalls – Flushed	5.33	86.6	24.3	24.4	59.1	82.5
500-2000	Non-freestall – Flushed	2.20	65.3	23.2	23.3	44.5	-
>2000	Freestalls – Flushed	5.33	-	24.3	24.4	59.1	82.6
>2000	Non-freestall - Flushed	2.20	-	23.2	23.4	44.5	86
<500	Organic (Freestall) - Scrape	2.59	86.0	21.9	22.2	-	-

*On non-freestall facilities 30 percent of manure is collected by flush in the baseline.

Source: Authors calculations based on table 2.1 in chapter 2. Columns for herd sizes 250, 1250 and 3250 were used to represent herds within the <500, 500-2000 and >2000 herd size groupings respectively. In the case of organic the column for herd size 250 was used and prorated to reflect 180 days housed.

Table 4.7 Adoption of alternative manure management practices and digesters and the average emissions per cow in each group once the new practices are operational in 2021.

	Herd Size Grouping	Housing and Collection	Count of Digesters*	Count of Other Alternative Practices**	Percentage adoption rate of digesters	Percentage adoption rate of other alternative practices	Average Percentage reduction emissions among adopting farms of Digesters	Average Percent. reduction emissions among adopting farms of Other Alternative Practices (excludes Digesters)	2021 Interim baseline emissions per cow (average among group)	Percent. reduction emissions per cow (between 2013 baseline and 2021 interim baseline)
A	<500	Freestall	0	8	0	4		60	5.21	2
B	<500	Non-freestall	0	6	0	9		60	2.09	5
C	500-2000	Flushed	14	53	3	11	82	30	5.03	6
D	500-2000	Non-freestall	1	18	1	15	60	30	2.09	5
E	>2000	Flushed	82	14	41	7	82	30	3.43	36
F	>2000	Non-freestall	10	1	25	3	60	30	1.85	16
G	<500	Organic	0	7	0	7		50	2.50	4

*(CDFA, 2020a) **(CDFA, 2020b). Facilities were grouped by matching the awardee in the CDFA data to the best available data of facility herd size. Average percentage reductions, interim baseline and emission reduction per cow are authors calculations based on the practices funded. The 2013 baseline emissions per cow can be found in table 6.

Taking the baseline emissions per herd size/housing type group presented in Table 2.1 of chapter 2 the baseline emissions per cow in each group were calculated. We use this baseline emission per cow to represent the 2013 emissions per cow by assuming that no methane reducing manure management practices were adopted on farm without AMMP or DDRDP subsidy support. Then, as shown in Table 7, the 107 AMMP and 107 DDRDP projects funded from 2015 through 2019 were matched to a group using the best available data on farm herd sizes and housing type.

Among the awardees of AMMP funding in each group, farms were funded to install one of eight distinct project types (2a or 3a etc.). From this we produced the best estimate of a percentage reduction in emissions among adopting farms of alternative practices. For digesters, the best estimate of average percentage reduction in emissions among adopting farms of digesters was calculated.

Knowing the number of farms in each group and the adoption rate in each group, we calculated for each group the 2013 baseline emissions per cow and the average percentage reduction in emissions from adoption the 2021 interim emissions per cow. By 2021 we expect the 2015 through 2019 funded projects will be operational and providing reductions in manure emissions. The reduction in emissions that results from our approximations is commensurate with the 22 percent reduction in emissions described in Table 4.5.

4.2.4 Cost Parameters

Practices chosen for the economic analysis are versions of practices discussed in chapter three. The choice of practices was informed by chapter three and constrained by the data availability.

Capital costs of AMMP installations were determined by analysis of 2017 and 2018 project applications. No information was available for the volume of manure the project will process or the number of cattle from which the manure will be processed. Instead we inferred the capacity of the project from dimensions of buildings or by inferring information from the application narrative (e.g. whether the project was for lactating, heifer or dry cow groups). When a farm included multiple project practices, we included only the costs relevant to our analysis. We used publicly available information on the capacity of equipment and contacted equipment manufacturers where required for further details. We also used publicly available data to match a herd size to the application. From here we estimated the number of cows from which manure will be processed by the AMMP project and estimated a capital cost per cow.

Given the subsidy limit, farms in the small herd group were at the subsidy limit. Further analysis was conducted to achieve a similar cost structure in the small herd group as in the medium and large herds.

We recognize that 36 percent of Central Valley facilities have mechanical separators in operation. Therefor the change in operation and maintenance costs will be less on these facilities.

Table 4.8 Capital Cost Calculations

Name of practice	Calculation and Assumptions
2a - Installation of compost bedded pack barn	By analysis of the AMMP applications budgets we found the same capital cost per cow for small herd size both converted from freestall and non-freestall and organic. Costs include construction of roofed barn to required dimensions for herd size including all metal gates and feed barriers plus all electrical and water installation.
3a - Solid separation with open solar drying	Costs for all herd sizes both freestall and non-freestall were based on mechanical separation plus concrete collection pits, concrete pad for manure solids collection, construction and installation costs. The concrete solar drying pads were costed as an area sufficient for drying manure for relevant herd size. In the case of non-freestall this is the equivalent to a drying pad large enough for manure solids for the 30 percent of manure collected from the relevant herd size.
3g - Solid separation with composting (passive or intensive windrow)	Costs include construction and installation of concrete collection pits, all required mechanical separation equipment, and concrete pad for separated manure solids collection. Larger concrete composting pads are required compared to the equivalent herd size using open solar drying because of the longer time composting takes compared to solar drying. The small herd use existing farm tractor to operate the compost turner.
4a - Scrape conversion with open solar drying: vacuum truck	Includes the purchase of a vacuum scraper and the construction of solar drying pads of suitable dimensions for handling all manure collected. Includes the cost of compost turning equipment and the purchase of a tractor for dedicated compost management activities.
Lagoon Digesters	Assessment of the DDRDP applications indicate that the third-party digester developers contribute all of the matching funds capital cost towards the lagoon digester installation.

Table 4.9 Operational and Maintenance Cost Calculations

Name of practice	Note
2a - Installation of compost bedded pack barn	All manure management costs associated with freestall housing and non-freestall housing are replaced with labor costs for managing the pack barn and scraping concrete areas. Costs are dominated by payment for kiln dried wood shavings which cost $0.71/cow/day as an annual average. For organic, we take 180 days housed.
3a - Solid separation with open solar drying	Freestalls: Continue to incur the cost of flushing and bedding freestalls. Non-freestall: Continue to incur the cost of flushing all concrete areas where manure collects, and the maintenance of the non-freestall pens. The size of the separator installed is one with capacity to handle the equivalent of 30 percent of manure from the herd. Organic: 180 days housed. Continue to incur the cost of scraping, bedding freestalls. All groups: The cost of excavating and solar drying the manure solids from separation cells is replaced with the cost of solar drying the mechanically separated manure solids for use as freestall bedding. Includes the operational and maintenance costs associated with the mechanical separator.
3g - Solid separation with composting (passive or intensive windrow)	Non-freestall: Continue to incur the cost of flushing all concrete areas where manure collects, and maintenance of the non-freestall pens. In addition, operation and maintenance of the mechanical separator continues. The separator must have capacity to handle the equivalent of 30 percent of manure. We include the cost of composting the separated solids.
4a - Scrape conversion with open solar drying: vacuum truck	All flushing costs are replaced with labor and maintenance costs of vacuum scraping. Labor and equipment costs for bedding freestalls remain. Costs of excavating and solar drying manure solids from separation cells are replaced with cost of solar drying. Fuel use and labor time data were provided by vacuum scraper manufacturer and other industry sources.
Lagoon Digesters	Continue to incur the cost of flushing and bedding freestalls. The cost of excavating and drying manure from separation cells has been replaced with the operation and maintenance cost of mechanical separator plus the cost of solar drying separated solids.

Results

The results of this chapter is a set of equations that are implemented in a simulation model that can characterize responses in the California dairy industry to changes in manure management practices. Using the descriptions and data provided in the second part of the chapter, and other baseline data and supply and demand parameters, the simulation model generates impacts on dairy industry aggregates, including implications by herd size categories. These impacts are developed fully in Chapters 5, 6 and 7.

Discussion

We have explained the economic rationales and implications of model equation as they were developed in the first part of the chapter. We have explained the information and data about manure handling practices and underlying assumptions in the second part of the chapter.

Our simulation approach is one that is often employed by economists to investigate impacts of changes in farm practices that affect demand or cost conditions. The approach is grounded in economic principles that recognize incentives that changes in cost conditions created for producers, processors, and buyers. The approach traces the implications through the affected markets. Thus, the model is well grounded in economic theory and practice. Our implementation relies on changes in logarithmic form, essentially percentage changes. This allows the model to rely on cost share and percentage changes as inputs.

Broad industry level baseline information is used to characterize shares. The key unique input to this study related to the alternative manure handling practices. Our detailed information presented in this chapter was drawn from the sources to which we refer that are specific the California situation.

Conclusion

The outcome of this chapter is the model ready to be applied in subsequent chapters.

Recommendations

We have not recommendations from this chapter alone. Any recommendations come from applying the model and data to the situations discussed in the following three chapters.

CHAPTER 5 WHOLE-FARM ECONOMIC AND ENVIRONMENTAL IMPACTS OF METHANE EMISSION REDUCTION STRATEGIES ON SMALLER AND LARGER DAIRIES

Introduction

This chapter uses our economic model and simulation framework to consider how methane strategies affect dairy farm choices, profitability and economic feasibility. It uses the data base developed in the second part of Chapter 4 and additional parameters that are discussed in this chapter. We present a set of simulation results for six scenarios of adoptions and for a 5-year horizon. Other time horizons are covered in Chapters 6 and 7. The simulation results show the effect of practice adoption on emissions and costs and tracks these cost effects through the milk markets, including adjustment in quantity demanded for dairy products.

The economic modeling framework presented in Chapter 4 includes a complete economic model of farm economics and accounts for revenues from milk and other sources. We include the economic tradeoff related to sustainability of the whole farm. Because practices designed to reduce methane emissions from collected manure are not likely to have major effects on non-milk revenues, such revenues do not appear in the equilibrium displacement model, since they remain mostly unchanged by practice adoption.

Many dairy farms in California have some degree of vertical integration. For example, some are integrated with forage production (silage or hay), upstream of the milk production operation. They are also commonly (about 80 percent) members of marketing and processing cooperatives and therefore are vertically integrated downstream. These forms of whole farm output are tied directly to milk production and revenues and in that way do not alter the results of our simulations, which are presented in terms of percentage changes in milk production and revenue.

Some farms have additional crop enterprises such as tree nuts. The methane emission reduction practices that we simulated and present in this chapter have relatively small impacts on these enterprises. The investments in other farm or non-farm businesses have relatively small effects on the direct economics of the dairy enterprise. If other investments are attractive relative to dairy farming, capital and management will move toward those investments whether or not current dairy farms currently have such investments. When considering exit and consolidation decisions (Chapter 7), we explain how other revenues may affect exit decisions.

Materials and Methods

In the second part of Chapter 4, we identified a shortlist of practices for each of the dairy farm groups and estimated the cost increases and methane emissions abatements resulting from their adoption on each of the seven dairy farm groups that we have used to categorize farms by size and other characteristics. As presented in the economic framework in Chapter 4, these costs combine operation and management costs, as well as fixed capital investment costs related to the constructions of infrastructure for instance.

Scalability considerations were captured in two ways, in that both components of the costs were allowed to vary across farm groups that are defined by herd size. Operation and maintenance costs were adjusted to reflect differences in labor requirements for the same practice across farm sizes and other characteristics. The capital cost of initial investment also captured non-divisibility, as it was calculated on a per farm basis rather than a per cow basis and therefore is often larger per cow for smaller herds.

In addition, the economic impact on the whole-farm was tracked through the size of manure management costs relative to total costs on the farm. This share of manure handling costs in total costs varies across farm sizes and characteristics in our model. As a result, the adoption of a practice having the same cost across farms, would still have different impacts on each farm size. Typically, larger operations tend to have costs of manure handling representing a smaller share of total costs, relative to smaller operations. Accordingly, our calibrated model reflects differences of practice adoption on whole farm economic sustainability consistently by adjusting operation and management costs, capital investment costs, and share of manure to the herd size.

The methane emission reduction resulting from a given practice adoption also varies according to farm size and other characteristics. Table 5.1 summarizes information discussed in detail in Chapter 4 about the costs and emissions per farm size and other group-defining characteristics for practices that define the emission-reduction strategies considered. Table 5.1 lists the methane reduction practices that represent typical options used by herd size and initial manure collection groups. Table 5.1 then lists the emission per cow for each practice if adopted by dairies in that group. The annual manure management cost per cow and capital cost per cow for that practice group combination is then provided. These data are key inputs into the simulation models that determine economic outcomes and imply emission reductions. As shown in Table 5.1, costs are high on a per cow basis for the farms with fewer than 500 cows. Table 5.1 lists high per cow capital cost for pack barns. Notice that we listed zero for capital cost for digesters because, we understand that under current arrangements between farms and digester operation companies, these costs are covered by the companies that use the methane collected to produce and sell natural gas and profit from renewable and low-carbon fuel credits.

In Chapter 4 we described six scenarios of patterns of adoption of methane-reducing practices across the seven groups. These scenarios were based on already observed adoption and AMMP and digester program data. For clarity, these scenarios are organized in Table 5.2. For each scenario we show the list of practices for each dairy farm group and an assumed percentage rate adoption of that practice among farms in the group.

Table 5.1 Costs and emissions for manure reduction practices by farm groups

Herd Size	Animal housing	Methane reduction practice	Emissions per Cow	Yearly Manure Management Cost per Cow	Capital Cost per Cow
<500	Freestall	2a - Installation of compost bedded pack barn	0.72	315.45	1728.00
<500	Freestall	3a - Solid separation with open solar drying	4.04	110.45	586.00
<500	Non-freestall	2a - Installation of compost bedded pack barn	0.76	315.45	1728.00
<500	Non-freestall	3g - Solid separation with composting (passive or intensive windrow)	1.69	111.52	574.00
500-2000	Freestall	3a - Solid separation with open solar drying	4.04	89.39	525.00
500-2000	Freestall	Lagoon Digester	0.74	89.39	0
500-2000	Freestall	4a - Scrape with open solar drying, Vacuum scrape	2.18	78.07	625.00
500-2000	Non-freestall	3a - Solid separation with open solar drying	1.69	65.04	517.00
>2000	Freestall	4a - Scrape with open solar drying, Vacuum scrape	2.18	54.15	500.00
>2000	Freestall	Lagoon Digester	0.93	56.55	0
>2000	Non-freestall	3a - Solid separation with open solar drying	1.69	56.22	496.00
>2000	Non-freestall	Lagoon Digester	0.93	56.55	0
Organic*	Scrape	2a - Installation of compost bedded pack barn	0.36	133.87	1728.00
Organic*	Scrape	3a - Solid separation with open solar drying	2.02	87.06	586.00

*Organic operations are assumed to have fewer than 500 head in this analysis.

Table 5.2 Group share of cows and supply and demand elasticities in the 5-year time horizon.

Group	Share of Cows (%)	Supply elasticity, 5-year horizon
A <500 Freestall	3.6	2.0
B <500 Non-freestall	1.3	2.0
C 500 -2,000 Freestall	32.9	2.0
D 500-2,000 Non-freestall	8.2	2.0
E >2,000 Freestall	43.9	2.0
F >2,000 Non-freestall	8.8	2.0
G Organic	1.3	2.0
		Demand elasticity, 5-year horizon
Conventional		1.0
Organic		0.5

Table 5.3 Practice adoption and rate of adoption per group in 6 scenarios

Group	Practice	Rate adoption per group (%)	
		Scenario 0	
<500 Freestall	2a - Compost bedded pack barn	4.0	
<500 Non-freestall	2a - Compost bedded pack barn	9.0	
500-2000 Freestall	4a - Vacuum Scrape, solar drying	14.0	
500-2000 Non-freestall	3a - Solid separation, solar drying	16.0	
>2000 Freestall	Lagoon Digester	46.0	
>2000 Non-freestall	Lagoon Digester	25.0	
Organic	2a - Compost bedded pack barn	7.0	
		Scenario 1	Scenario 2
<500 Freestall	2a - Compost bedded pack barn	30.0	40.0
<500 Non-freestall	2a - Compost bedded pack barn	30.0	40.0
500-2000 Freestall	3a - Solid separation, solar drying	30.0	40.0
500-2000 Non-freestall	3a - Solid separation, solar drying	30.0	40.0
>2000 Freestall	4a – Vacuum Scrape, solar drying,	30.0	40.0
>2000 Non-freestall	3a - Solid separation, solar drying	30.0	40.0
Organic	2a - Compost bedded pack barn	30.0	40.0
		Scenario 3	Scenario 4
<500 Freestall	2a - Compost bedded pack barn	30.0	5.0
<500 Non-freestall	2a - Compost bedded pack barn	30.0	10.0
500-2000 Freestall	Lagoon Digester	30.0	20.0
500-2000 Non-freestall	3a - Solid separation, solar drying	30.0	15.0
>2000 Freestall	Lagoon Digester	30.0	60.0
>2000 Non-freestall	Lagoon Digester	30.0	30.0
Organic	2a - Compost bedded pack barn	30.0	10.0
		Scenario 5	
<500 Freestall	3a - Solid separation, solar drying	5.0	
<500 Non-freestall	3g - Solid separation, composting	10.0	
500-2000 Freestall	Lagoon Digester	20.0	
500-2000 Non-freestall	3a - Solid separation, solar drying	15.0	
>2000 Freestall	Lagoon Digester	66.0	
>2000 Non-freestall	Lagoon Digester	35.0	
Organic	3a - Solid separation, solar drying	10.0	

Additional Environmental concerns

California faces pressures related to a range of environmental issues. With most California milk production located in the San Joaquin Valley, most dairy farms face similar environmental concerns. (Remaining dairies in Southern California and the organic farms located mostly in the North Coast region are the main exceptions.) Major concerns are related to local air and water quality.

As a first order approximation, given any set of abatement practices already adopted, the environmental impacts are roughly proportional to milk production. The practices we considered as ways to reduce methane emissions do not seem to have major negative implications for local environmental concerns. That means simulations that capture changes in cows and milk quantity are likely to capture the most important other environmental implications.

For the analysis presented here, we have not separately simulated local environmental impacts for the scenarios or for specific dairy groups or methane emissions management practices. These practices directly affect methane rather than other environmental outcomes. Non-climate-related environmental impacts may result from these practices. However, as documented below, the economic scenarios do not imply major impacts on total number of cows in California or the quantity of milk they produce.

Results

The scenarios are summarized in Table 5.3. We now turned to the results from the simulations of estimated effects, which are reported in Tables 5.4 to 5.9.

Scenario 0.

The results of this scenario are discussed in detail. The other scenarios will only be clarified in comparison with relatively little repetition.

The set of methane reduction strategies and adoption rates in Scenario 0 are representative of adoption patterns observed between 2013 and 2021. The projects set to be completed between today and 2021 are included in the estimates. The effects of this pattern of adoption are summarized in Table 5.3. The first two numerical columns report the effect of practice adoption on farms that adopt. The installation of pack barns for smaller herd size dairy operations brings a reduction of 86.6 percent of methane emissions. Emission reductions in non-freestall are smaller than in freestall operations because manure recovery rates are smaller.

Pack barns are expensive both in terms of capital investment and management and operation costs and result in increases in total production costs for the dairies. Conventional smaller herd size dairies who adopt packed barn see their total cost per unit of milk increase by around 9 percent, whereas organic dairies see a smaller increase in total costs due to the fact that they operate at higher total costs to start with. Note that the cost shift is almost identical per cow or per unit of milk in our model since the differences are in costs per cow or milk across size groups, but not within one group or one representative operation.

For medium size dairies, vacuum scrape with open solar drying brings some reductions at moderate costs for freestall operations, while solid separation brings limited methane abatement at a low cost for the non-freestall operations.

For larger operations, digesters bring large abatements when manure recovery rates are elevated. Here the costs of adoption are shown to be small because subsidies are accounted for and only a moderate increase in operation and management costs is accrued to the change in total costs of production.

Table 5.4 Effect of practices of Scenario 0 in 5-year time horizon

		Practice adoption pattern			Percentage changes for group in:				
Group	Practice	Emission reduction per cow, adopting farm (%)	Cost per cow increase, adopting farm (%)	Percent adoption per group	Costs per cwt milk (%)	Price of Milk	Quantity of milk	Methane Emission	Group's share of methane reduction
<500 Freestall	2a	-86.6	9.0	4.0	0.36		-0.57	-4.0	0.7
<500 Non-freestall	2a	-65.3	9.3	9.0	0.84		-1.53	-7.3	0.2
500-2000 Freestall	4a	-59.1	1.1	14.0	0.15	0.07	-0.16	-8.4	13.6
500-2000 Non-freestall	3a	-23.2	1.0	16.0	0.16		-0.17	-3.9	0.6
>2000 Freestall	Digester	-82.6	0.1	46.0	0.04		0.06	-37.9	82.1
>2000 Non-freestall	Digester	-57.8	0.1	25.0	0.03		0.08	-14.4	2.6
Organic	2a	-86.2	3.2	7.0	0.22	0.18	-0.09	-6.1	0.2
Total California								-22.9	100

The third numerical column in Table 5.4 reports the adoption patterns for each group as presented before in Table 5.3. These are useful as they help understand the next column where the average increase in total costs per group is reported. This change in cost is the percentage increase in total production costs per unit of milk averaged across adopted and non-adoptees in each group. For instance, in the smaller herd size freestall dairies, only 4 percent of operations adopt the methane mitigation practice and incur the 9 percent increase in total cost. Thus, the average increase in total costs for the whole group is only 0.36 percent (the product of adoption rate and cost increase). For smaller herd size non-freestall operations, the average cost increase is of 0.84 percent because both adoption rate and cost shift per operation are near 9 percent.

Note that because manure management costs rarely exceed two or three percent of total production costs, even expensive practices like pack barn do not result in very large increases in total costs. In turn, this means that adjustments in price and quantities in the market will be relatively small throughout all scenarios.

The last two columns of Table 5.4 report the effect of the scenario on methane emission in two related measures. First, the group methane emission percentage abatement column reports by how much in each group have methane emissions been reduced, relative to the initial emissions in that group. The largest reduction there is for the group of larger freestall operations where 46 percent of operations have adopted digesters, which reduce emissions by 82.6 percent on adopting operations. The bottom line is a 22.9 percent abatement in methane emissions relative to the baseline for the California dairy industry as a whole. In other words, Scenario 0 achieves a reduction of 22.9 percent in the emissions of manure methane. Second, the last column in Table 5.4 reports the contribution of each group to this total abatement. There, larger freestall operations dominate since they are both the largest source of emissions initially and experience the largest reduction of emission as a group. Large non-freestall operations only contribute 2.6 percent in the aggregate abatement because their contribution to initial emissions is relatively small and despite an average abatement for the group itself of 14.4 percent of its emissions.

Scenarios 1, 2 and 3.
Recall that the scenarios each apply a different pattern of adoption rates to alternative practices as described in Table 5.3. Scenario 1, applies a uniform 30 percent adoption rate to the same practices as in Scenario 0, except that it does not include digesters for the two groups with more than 2,000 cows. The detailed results of Scenario 1 are in Table 5.5. Increasing adoption rates to 30 percent for the smaller dairies raises their costs, and thereby lowers their quantities by about 5 percent. Together they reduce emissions by about 25 percent.

The group of dairies with freestalls and 500 to 2,000 cows now uses the practice 3a, which includes open solar drying and vacuum scrape. This practice yields less emission reduction for this group than Scenario 0, even with adoption increasing to 30 percent from 14 percent. However, the big difference is that this scenario does not include digesters for the larger dairies. This scenario includes 30 percent of the larger freestall dairies using practice 4a, which reduces methane by 59 percent. Therefore, this group has a reduction in methane of almost 18 percent and contributes the majority of emission reduction (64.3 percent). Overall this scenario yields a methane reduction of 13.6 percent statewide (Table 5.5).

Scenario 2 simply increases the adoption rate to 40 percent. The results, shown in detail in Table 5.6, are proportional and the impact on quantity, costs per cwt of milk, and milk output per group change in proportion to the assumed adoption rate. As shown in the last row of Table 5.6, for scenario 2 methane declines by 18.1 percent, which is one-third more than the reduction for scenario 1 reported in Table 5.5.

Scenarios 3 uses 30 percent adoption, but includes digesters for the mid-sized freestall dairies and both the larger herd size groups. The results for Scenario 3, detailed in Table 5.7, are that methane reduction decreased by about 24 percent statewide. As shown in Table 5.7, about 90 percent of the emission reduction is contributed by the midsized and larger freestall dairies, where most of the state's cows are located. Large emission reduction per dairy also occurs on the smaller dairies, in part because their higher costs reduce production on these farms by more than 5 percent. The results in Table 5.7 show that organic dairies maintain production because their cost increase is almost wholly matched by the consequent higher price in the organic market, which tends to be within California, and therefore has a more inelastic demand.

Scenarios 4 and 5.
Scenario 4 has an adoption rates that differ across farm categories for the same set of practices as scenario 3. In scenario 4 the adoption of pack barns for the smaller herd size dairies is lower. As shown in the details of Table 5.8, smaller herd size dairies have lower cost increases compared to scenario 3 in Table 5.7 and therefore reduced the rate of decline in their milk production. The assumed rate of digester adoption for the midsize freestall dairies was also lower than 30 percent to reflect the fact that there are fewer digesters among that group currently compared to the larger freestall dairies. To compensate for these differences, we assume a higher rate of digester adoption on the larger freestall dairies of 60 percent, about one third higher than are currently implemented or under development on dairies in this category. As a result, as shown in Table 5.8, the overall methane emissions decreased by 32.1 percent statewide.

Finally, in scenario 5 we assume that smaller dairies use the practice of solid separation with solar drying (practice 3a) rather than the expensive pack barns. As Table 5.9 shows, assuming that this technology is adopted causes reduced costs of manure handling and just about eliminates the implied decline in milk production for smaller dairies. Table 5.9 shows that under this adoption assumption, smaller dairies now contribute very little to statewide emission reductions. In addition, scenario 5 assumes higher digester adoption on the larger farms compared to scenario 4. In scenario 5, a 66 percent adoption rate is assumed for larger farms with freestalls and a 35 percent adoption rate is assumed for larger non-freestall farms. Table 5.9 shows that under scenario 5 the total methane emissions decreased by 34.5 percent from the base, with 78 percent of the reduction contributed by the larger freestall dairies and another almost 19 percent contributed by the mid-sized freestall dairies.

Table 5.5 Effect of practices of Scenario 1 in 5-year time horizon

	Practice adoption pattern				Percentage changes for group in:				
Group	Practice	Emission reduction per cow, adopting farm (%)	Cost per cow increase, adopting farm (%)	Percent adoption per group	Costs per cwt milk (%)	Price of Milk	Quantity of milk	Methane Emission	Group's share of methane reduction
<500 Freestall	2a	-86.6	9.0	30.0	2.69	0.27	-4.84	-29.6	8.9
<500 Non-freestall	2a	-65.3	9.3	30.0	2.80		-5.05	-23.7	1.0
500-2000 Freestall	3a	-24.3	1.3	30.0	0.38		-0.21	-7.5	20.4
500-2000 Non-freestall	3a	-23.2	1.0	30.0	0.29		-0.04	-7.0	2.0
>2000 Freestall	4a	-59.1	0.7	30.0	0.22		0.10	-17.6	64.3
>2000 Non-freestall	3a	-23.2	0.8	30.0	0.25		0.04	-6.9	2.1
Organic	2a	-86.2	3.2	30.0	0.95	0.76	-0.38	-26.1	1.4
Total California								-13.6	100.0

Table 5.6 Effect of practices of Scenario 2 in 5-year time horizon

<table>
<tr><th colspan="5">Practice adoption pattern</th><th colspan="5">Percentage changes for group in:</th></tr>
<tr><th>Group</th><th>Practice</th><th>Emission reduction per cow, adopting farm (%)</th><th>Cost per cow increase, adopting farm (%)</th><th>Percent adoption per group</th><th>Costs per cwt milk (%)</th><th>Price of Milk</th><th>Quantity of milk</th><th>Methane Emission</th><th>Group’s share of methane reduction</th></tr>
<tr><td><500 Freestall</td><td>2a</td><td>-86.6</td><td>9.0</td><td>40.0</td><td>3.59</td><td rowspan="6">0.36</td><td>-6.45</td><td>-38.9</td><td>8.8</td></tr>
<tr><td><500 Non-freestall</td><td>2a</td><td>-65.3</td><td>9.3</td><td>40.0</td><td>3.73</td><td>-6.74</td><td>-31.1</td><td>1.0</td></tr>
<tr><td>500-2000 Freestall</td><td>3a</td><td>-24.3</td><td>1.3</td><td>40.0</td><td>0.50</td><td>-0.28</td><td>-10.0</td><td>20.4</td></tr>
<tr><td>500-2000 Non-freestall</td><td>3a</td><td>-23.2</td><td>1.0</td><td>40.0</td><td>0.39</td><td>-0.06</td><td>-9.3</td><td>2.0</td></tr>
<tr><td>>2000 Freestall</td><td>4a</td><td>-59.1</td><td>0.7</td><td>40.0</td><td>0.30</td><td>0.13</td><td>-23.5</td><td>64.4</td></tr>
<tr><td>>2000 Non-freestall</td><td>3a</td><td>-23.2</td><td>0.8</td><td>40.0</td><td>0.34</td><td>0.05</td><td>-9.2</td><td>2.1</td></tr>
<tr><td>Organic</td><td>2a</td><td>-86.2</td><td>3.2</td><td>40.0</td><td>1.27</td><td>1.01</td><td>-0.51</td><td>-34.8</td><td>1.4</td></tr>
<tr><td>Total California</td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td>-18.1</td><td>100.0</td></tr>
</table>

Table 5.7 Effect of practices of Scenario 3 in 5-year time horizon

		Practice adoption pattern			Percentage changes for group in:				
Group	Practice	Emission reduction per cow, adopting farm (%)	Cost per cow increase, adopting farm (%)	Percent adoption per group	Costs per cwt milk (%)	Price of Milk	Quantity of milk	Methane Emission	Group's share of methane reduction
<500 Freestall	2a	-86.6	9.0	30.0	2.69	0.15	-5.08	-29.7	5.0
<500 Non-freestall	2a	-65.3	9.3	30.0	2.80		-5.29	-23.9	0.6
500-2000 Freestall	Digester	-86.1	0.5	30.0	0.15		-0.01	-25.8	39.4
500-2000 Non-freestall	3a	-23.2	1.0	30.0	0.29		-0.28	-7.2	1.1
>2000 Freestall	Digester	-82.6	0.1	30.0	0.03		0.25	-24.6	50.2
>2000 Non-freestall	Digester	-57.8	0.1	30.0	0.04		0.22	-17.2	2.9
Organic	2a	-86.2	3.2	30.0	0.95	0.76	-0.38	-26.1	0.8
Total California								-24.3	100.0

Table 5.8 Effect of practices of Scenario 4 in 5-year time horizon

		Practice adoption pattern				Percentage changes for group in:			
Group	Practice	Emission reduction per cow, adopting farm (%)	Cost per cow increase, adopting farm (%)	Percent adoption per group	Costs per cwt milk (%)	Price of Milk	Quantity of milk	Methane Emission	Group's share of methane reduction
<500 Freestall	2a	-86.6	9.0	5.0	0.45		-0.76	-5.1	0.6
<500 Non-freestall	2a	-65.3	9.3	10.0	0.93		-1.73	-8.1	0.2
500-2000 Freestall	Digester	-86.1	0.5	20.0	0.10		-0.07	-17.3	19.9
500-2000 Non-freestall	3a	-23.2	1.0	15.0	0.15	0.07	-0.16	-3.6	0.4
>2000 Freestall	Digester	-82.6	0.1	60.0	0.05		0.03	-49.5	76.4
>2000 Non-freestall	Digester	-57.8	0.1	30.0	0.04		0.05	-17.3	2.2
Organic	2a	-86.2	3.2	10.0	0.32	0.25	-0.13	-8.7	0.2
Total California								-32.1	100.0

Table 5.9 Effect of practices of Scenario 5 in 5-year time horizon

		Practice adoption pattern				Percentage changes for group in:			
Group	Practice	Emission reduction per cow, adopting farm (%)	Cost per cow increase, adopting farm (%)	Percent adoption per group	Costs per cwt milk (%)	Price of Milk	Quantity of milk	Methane Emission	Group's share of methane reduction
<500 Freestall	3a	-24.2	1.6	5.0	0.08	0.05	-0.05	-1.3	0.1
<500 Non-freestall	3g	-23.4	1.9	10.0	0.19		-0.28	-2.6	0.0
500-2000 Freestall	Digester	-86.1	0.5	20.0	0.10		-0.10	-17.3	18.6
500-2000 Non-freestall	3a	-23.2	1.0	15.0	0.15		-0.18	-3.7	0.4
>2000 Freestall	Digester	-82.6	0.1	66.0	0.06		-0.01	-54.5	78.3
>2000 Non-freestall	Digester	-57.8	0.1	35.0	0.05		0.01	-20.2	2.4
Organic	3a	-22.0	0.7	10.0	0.07	0.06	-0.03	-2.2	0.0
Total California								-34.5	100.0

Discussion

One central observation of the detailed results presented in this chapter is that under all scenarios we find small changes on price of milk and quantity of milk production. Manure management costs change substantially in percentage terms in some scenarios for some categories of dairy farms. However, manure management continues to contribute a relatively small share of total dairy farm costs, which are still dominated by feed costs, herd replacement costs and labor costs, especially labor costs for milking.

The calibrated simulation model shows that with a more costly methane reduction practice for a category of farm, the implied reduction in milk production is larger indicate more potential impact on economic sustainability. This common-sense result indicates that the model has successfully captured some of the realistic economic forces facing dairy farms.

The practices that we included to reduce methane emissions in the simulations of Chapter 5, represent practices now being used on some California dairies. When applied more widely they contribute subst

antial reductions in overall methane from dairy manure management in California. Most of the reduction occurs on the midsize and larger freestall dairies where most of the milk in California is produced. The bulk of the most cost-effective methane reduction occurs in scenarios that impose higher digester adoption on the larger dairies.

Conclusion

This chapter focuses on applying our simulation model to adoption of manure management practices and develops the implications with a five-year horizon. The calibrated simulation model shows that with a more costly methane reduction practice for a category of farm, the implied reduction in milk production is larger indicate more potential impact on economic sustainability.

The model preformed as expected and the calibrations and parameter choices yield a pattern of results and implications that are consistent with broader observations about the California dairy economy. More scenarios with other time horizons a studied in detail in the next two chapters.

Recommendations

By themselves the results of this chapter do not yield recommendations. The results do indicate that the simulation approach can be an effective tool and the next two chapters also contain additional results of interest to the industry participants, policymakers and other researchers.

CHAPTER 6 COSTS, BENEFITS AND IMPLICATIONS OF ADOPTION OF METHANE REDUCTION PRACTICES ACROSS SMALLER AND LARGER DAIRIES FOR 1-YEAR, 5-YEAR, AND 10-YEAR TIME HORIZONS

Introduction

This chapter uses the economic model and simulation framework developed in Chapter 4 to examine three distinct time horizons. The scenarios are the same as those examined in Chapter 5 and in that sense this chapter builds directly on those results. For that reason, we avoid duplication of all the background already explained in Chapter 5.

The alternative time horizons considered here in Chapter 6 affect the supply and demand elasticities and the implications of fixed costs of adopting manure management practices. Generally large investments are not economic if the time horizon facing a farm or other business is short. Therefore, when horizons are longer, more larger investments in fixed costs become economically feasible.

The model includes components of scale of capital investment, management and location in the context of cost-benefit analysis. Our economic model incorporates both costs and benefits to dairy operations. Results generate implications for the price and quantity of milk produced and marketed in California.

Materials and Methods

The time horizons that we considered in this chapter have the following interpretation. Table 6.1 describes the demand and supply elasticities that apply to each horizon. We assumed that the manure management practice has been fully implemented and consider the time period after implementation. We did not consider effects while projects are being built. The practices affect costs and these costs affect the quantity of milk produced more when more time has passed. That is the major implication shown in the results.

Importantly, we note that, as shown in Table 6.1, the demand and supply elasticities both are larger for longer time horizons as producers and buyers have more time to adjust to the new cost situations. These are standard implication of economic modeling. Recall that supply and demand elasticities are defined as the proportional change in quantity for a one percent change in price. That is the elasticities are unitless ratios of percentage changes. Generally, when producers or consumers have a longer time horizon over which to consider adjustments, the costs of a change of a given magnitude is smaller and therefore the economically effective adjustment is larger. Another way to describing this result is simply to say some factors that are constraints in a very short time horizon are less binding when there is more time over which to consider adjustment.

We did not include any evaluation of the effects of California dairy methane emissions on the global or California economies. That broad and complex topic is beyond the scope of this study, which focused on economic implication for dairy farms of different herd size category and for the price and quantity of milk in California.

Moreover, as noted in Chapter 5, there are a range of environmental issues that affect the California dairy industry and dairy production regions. We have noted that those local environmental issues are only tangentially affected by the economics of methane emission strategies that we considered in this chapter.

Table 6.1 Values of supply and demand elasticities in 1, 5 and 10-year time horizon.

Group		Supply Elasticities	
	1 year	5 year	10 year
A	0.5	2.0	3.0
B	0.5	2.0	3.0
C	0.5	2.0	3.0
D	0.5	2.0	3.0
E	0.5	2.0	3.0
F	0.5	2.0	3.0
G	0.5	2.0	3.0
Market		Demand Elasticities	
	1 year	5 year	10 year
Conventional	1.0	1.0	2.0
Organic	0.5	0.5	1.0

Results

Effects of adoption of patterns of adoption across size groups over different horizons
This section is organized by scenarios just as was chapter 5. Results are similar to those presented there. We document that time horizons are not crucial in this context when trends in herd size patterns and consolidations are not yet incorporated. Those trends are discussed extensively in Chapter 7. Here we describe briefly the implication of scenarios 0 through scenario 5 for each of the three specified time horizons. Results are similar across scenarios and we provide more detail about results of scenario 0. We set out some key results of each scenario, but attempt to avoid undue repetition.

Scenario 0. Implemented projects scenario
Recall that this scenario includes representative practices for each group and adoption rates that are roughly consistent with CDFA-funded projects under the AMMP and digester programs. In the top panel of Table 6.2 a manure management practice was listed for each group along with the associated percentage emission reductions, cost increases per cow, and adoption rates. These are identical to what is shown in Chapter 5 for this scenario and each of the other scenarios.

The second part of Table 6.2 shows the impacts of the scenario, for each farm size and housing group, on costs per cwt of milk, price of milk, quantity of milk, methane emission reduction, and the contribution of that group to the overall impact on methane emissions. In each case, the definition of the horizon 1-year, 5-year, and 10-year is the period of time over which market adjustments take place. That is for the 1-year horizon after the practices are implemented only adjustments that are complete in a single year are included in the scenario results.

The impacts of time horizons are minor for methane emissions, but significant for milk quantity produced, particularly for the smaller dairies. Consider for example, the decline in quantities of milk for groups A and B, which are the conventional dairies with less than 500 cows. Table 6.2 shows that after a 1-year adjustment quantity of milk decreases by 0.17 percent for group A and by 0.41 percent for group B. But after 10 years, with more elastic supply and thus more implied quantity response, the decline in quantity of is 0.88 percent for group A and a significant 2.3 percent for group B, which is assumed to have a higher adoption rate for the practice.

Milk price does not rise much in any of the horizons and emissions are similar across the time horizons. Note that the total change in emissions for California is an average of changes for each group, weighted by the share of total emissions of each group.

Scenarios 1, 2 and 3.
Scenario 1 (Table 6.3) applies a 30 percent adoption rate for a set of non-digester practices for every group. As in Chapter 5, these scenarios have less emission reduction than Scenario 0, but also lower milk quantity produced, particularly for the smaller dairies. After one year the quantity of milk production is down by more than 1.3 percent for the two groups of conventional dairies that have less than 500 cows and down about 0.32 percent for organic dairies (which are all assumed to be small). Table 6.3 shows that for the smaller conventional dairies, after a 10-year adjustment period, loss of production rises to 7.34 percent for group A and 7.66 percent for group B. These are major losses over this longer-term horizon.

Scenario 2 is identical to scenario 1, except that it uses a 40 percent adoption rate for the practices. Table 6.4 shows, as found in Chapter 5, the impacts on costs, prices, production and emissions are about one-third larger than scenario 1 (Table 6.3). The losses in quantities produced for the smaller size groups of conventional dairies for the 10-year horizon is even more pronounced. That is, Table 6.4 shows that a 40 percent rate of adoption of these practices would result in a reduction in milk output of the smaller dairies of about 10 percent and almost no change in the milk output of the larger dairies.

Scenarios 3 (Table 6.5) adds digesters, with a standard 30 percent adoption rate, to the pattern of assumed methane reducing practices. Assuming digester adoption increases total emission reductions for all time horizons. Losses of production quantity for the smaller conventional dairies remains large—almost 8 percent for the 10-year time horizon. The impact production on the larger dairies remains very small. Generally, the cost of digesters for larger dairy farms is assumed to be small, given that non-farm companies have generally accepted the costs of building and operating digesters in return for access to the methane and the strong market price for the biogas, which is assumed to continue to qualify as a renewable fuel under federal regulations and a low carbon fuel under California regulation (Lee and Sumner, 2018).

Scenarios 4 and 5.
Recall scenario 4 assumed moderate adoption of practices for smaller dairies and larger adoption of digesters for larger dairies. These practices and adoption rates are spelled out in Table 6.6. The quantity losses in Scenario 4for the smaller dairies are moderate for all time horizons shown in Table 6.6. After a 10-year adjustment period the loss is -1.2 percent for group A and -2.6

percent for group B. Other impacts change little over time (Table 6.6). The emission reduction over each horizon about 32 percent.

As discussed in Chapter 5 and shown in Table 6.7, Scenario 5 implied lower costs of methane reducing practices for the smaller dairies by assuming the adoption of lower cost alternative practices for these farms. Scenario 5 also assumes higher rate of adoption of digesters on the larger dairies than does scenario 4. Time horizons matter little for this scenario. Table 6.7 shows that even in the 10-year horizon, because the assumed practices have relatively low-cost impacts, the effects on quantities produced are small over all horizons. As shown in Table 6.7 the loss of output from smaller dairies is less than one-half of one percent. The impact on the larger dairies is even less.

Table 6.2 Effect of practices of Scenario 0 in 1, 5 and 10-year time horizons.

	Practice adoption pattern				
	Group size and type	Practice	Emission reduction per cow, adopting farm (%)	Cost per cow increase, adopting farm (%)	Percent adoption per group
A	<500 Freestall	2a	-86.6	9.0	4.0
B	<500 Non-freestall	2a	-65.3	9.3	9.0
C	500-2000 Freestall	4a	-59.1	1.1	14.0
D	500-2000 Non-freestall	3a	-23.2	1.0	16.0
E	>2000 Freestall	Digester	-82.6	0.1	46.0
F	>2000 Non-freestall	Digester	-57.8	0.1	25.0
G	Organic	2a	-86.2	3.2	7.0

	Percentage changes for group in:				
1-Year	Costs per cwt milk	Price of Milk	Quantity of milk	Methane Emission	Group's share of methane reduction
A	0.36	0.02	-0.17	-3.6	0.6
B	0.84		-0.41	-6.3	0.2
C	0.15		-0.07	-8.3	13.5
D	0.16		-0.07	-3.8	0.6
E	0.04		-0.01	-38.0	82.3
F	0.03		-0.01	-14.4	2.6
G	0.22	0.07	-0.07	-6.1	0.2
		Total California		-22.9	100.0
5 -Year					
A	0.36	0.07	-0.57	-4.0	0.7
B	0.84		-1.53	-7.3	0.2
C	0.15		-0.16	-8.4	13.6
D	0.16		-0.17	-3.9	0.6
E	0.04		0.06	-37.9	82.1
F	0.03		0.08	-14.4	2.6
G	0.22	0.18	-0.09	-6.1	0.2
		Total California		-22.9	100.0
10-Year					
A	0.36	0.07	-0.88	-4.3	0.8
B	0.84		-2.32	-8.1	0.2
C	0.15		-0.26	-8.5	13.7
D	0.16		-0.27	-4.0	0.7
E	0.04		0.07	-37.9	81.9
F	0.03		0.09	-14.4	2.6
G	0.22	0.17	-0.17	-6.2	0.2
		Total California		-23.0	100.0

Table 6.3 Effect of practices of Scenario 1 in 1, 5 and 10-year time horizons.

	Practice adoption pattern				
	Group size and type	Practice	Emission reduction per cow, adopting farm (%)	Cost per cow increase, adopting farm (%)	Percent adoption per group
A	<500 Freestall	2a	-86.6	9.0	30.0
B	<500 Non-freestall	2a	-65.3	9.3	30.0
C	500-2000 Freestall	3a	-24.3	1.3	30.0
D	500-2000 Non-freestall	3a	-23.2	1.0	30.0
E	>2000 Freestall	4a	-59.1	0.7	30.0
F	>2000 Non-freestall	3a	-23.2	0.8	30.0
G	Organic	2a	-86.2	3.2	30.0
	Percentage changes for group in:				
1-Year	Costs per cwt milk	Price of Milk	Quantity of milk	Methane Emission	Group's share of methane reduction
A	2.69	0.08	-1.30	-26.9	8.2
B	2.80		-1.36	-20.7	0.9
C	0.38		-0.15	-7.4	20.3
D	0.29		-0.11	-7.0	2.0
E	0.22		-0.07	-17.8	65.1
F	0.25		-0.09	-7.0	2.1
G	0.95	0.32	-0.32	-26.1	1.4
		Total California		-13.5	100.0
5 -Year					
A	2.69	0.27	-4.84	-29.6	8.9
B	2.80		-5.05	-23.7	1.0
C	0.38		-0.21	-7.5	20.4
D	0.29		-0.04	-7.0	2.0
E	0.22		0.10	-17.6	64.3
F	0.25		0.04	-6.9	2.1
G	0.95	0.76	-0.38	-26.1	1.4
		Total California		-13.6	100.0
10-Year					
A	2.69	0.24	-7.34	-31.4	9.4
B	2.80		-7.66	-25.8	1.1
C	0.38		-0.40	-7.6	20.6
D	0.29		-0.14	-7.1	2.0
E	0.22		0.06	-17.7	63.6
F	0.25		-0.03	-7.0	2.1
G	0.95	0.71	-0.71	-26.4	1.4
		Total California		-13.8	100.0

Table 6.4 Effect of practices of Scenario 2 in 1, 5 and 10-year time horizon.

	Practice adoption pattern				
	Group size and type	Practice	Emission reduction per cow, adopting farm (%)	Cost per cow increase, adopting farm (%)	Percent adoption per group
A	<500 Freestall	2a	-86.6	9.0	40.0
B	<500 Non-freestall	2a	-65.3	9.3	40.0
C	500-2000 Freestall	3a	-24.3	1.3	40.0
D	500-2000 Non-freestall	3a	-23.2	1.0	40.0
E	>2000 Freestall	4a	-59.1	0.7	40.0
F	>2000 Non-freestall	3a	-23.2	0.8	40.0
G	Organic	2a	-86.2	3.2	40.0
	Percentage changes for group in:				
1-Year	Costs per cwt milk	Price of Milk	Quantity of milk	Methane Emission	Group's share of methane reduction
A	3.59	0.11	-1.74	-35.8	8.1
B	3.73		-1.81	-27.5	0.9
C	0.50		-0.20	-9.9	20.3
D	0.39		-0.14	-9.4	2.0
E	0.30		-0.09	-23.7	65.1
F	0.34		-0.11	-9.4	2.1
G	1.27	0.42	-0.42	-34.7	1.4
		Total California		-18.4	100.0
5-Year					
A	3.59	0.11	-6.45	-38.9	8.8
B	3.73		-6.74	-31.1	1.0
C	0.50		-0.28	-10.0	20.4
D	0.39		-0.06	-9.3	2.0
E	0.30		0.13	-23.5	64.4
F	0.34		0.05	-9.2	2.1
G	1.27	0.42	-0.51	-34.8	1.4
		Total California		-18.1	100.0
10-Year					
A	3.59	0.32	-9.79	-41.0	9.2
B	3.73		-10.21	-33.7	1.1
C	0.50		-0.53	-10.2	20.6
D	0.39		-0.19	-9.4	2.0
E	0.30		0.09	-23.6	63.7
F	0.34		-0.04	-9.3	2.1
G	1.27	0.95	-0.95	-35.1	1.4
		Total California		-18.3	100.0

Table 6.5 Effect of practices of Scenario 3 in 1, 5 and 10-year time horizon.

	Practice adoption pattern				
	Group size and type	Practice	Emission reduction per cow, adopting farm (%)	Cost per cow increase, adopting farm (%)	Percent adoption per group
A	<500 Freestall	2a	-86.6	9.0	30.0
B	<500 Non-freestall	2a	-65.3	9.3	30.0
C	500-2000 Freestall	Digest.	-86.1	0.5	30.0
D	500-2000 Non-freestall	3a	-23.2	1.0	30.0
E	>2000 Freestall	Digest.	-82.6	0.1	30.0
F	>2000 Non-freestall	Digest.	-57.8	0.1	30.0
G	Organic	2a	-86.2	3.2	30.0
	Percentage changes for group in:				
1-Year	Costs per cwt milk	Price of Milk	Quantity of milk	Methane Emission	Group's share of methane reduction
A	2.69	0.05	-1.32	-27.0	4.6
B	2.80		-1.38	-20.7	0.5
C	0.15		-0.05	-25.9	39.5
D	0.29		-0.12	-7.1	1.1
E	0.03		0.01	-24.8	50.6
F	0.04		0.00	-17.3	2.9
G	0.95	0.32	-0.32	-26.1	0.8
		Total California		-24.4	100.0
5-Year					
A	2.69	0.15	-5.08	-29.7	5.0
B	2.80		-5.29	-23.9	0.6
C	0.15		-0.01	-25.8	39.4
D	0.29		-0.28	-7.2	1.1
E	0.03		0.25	-24.6	50.2
F	0.04		0.22	-17.2	2.9
G	0.95	0.76	-0.38	-26.1	0.8
		Total California		-24.3	100.0
10-Year					
A	2.69	0.14	-7.66	-31.6	4.6
B	2.80		-7.98	-26.0	0.5
C	0.15		-0.05	-25.9	39.5
D	0.29		-0.47	-7.4	1.2
E	0.03		0.33	-24.5	49.9
F	0.04		0.28	-17.1	2.9
G	0.95	0.71	-0.71	-26.4	0.8
		Total California		-24.4	100.0

Table 6.6 Effect of practices of Scenario 4 in 1, 5 and 10-year time horizon.

	Practice adoption pattern				
	Group size and type	Practice	Emission reduction per cow, adopting farm (%)	Cost per cow increase, adopting farm (%)	Percent adoption per group
A	<500 Freestall	2a	-86.6	9.0	5.0
B	<500 Non-freestall	2a	-65.3	9.3	10.0
C	500-2000 Freestall	Digest.	-86.1	0.5	20.0
D	500-2000 Non-freestall	3a	-23.2	1.0	15.0
E	>2000 Freestall	Digest.	-82.6	0.1	60.0
F	>2000 Non-freestall	Digest.	-57.8	0.1	30.0
G	Organic	2a	-86.2	3.2	10.0

	Percentage changes for group in:				
1-Year	Costs per cwt milk	Price of Milk	Quantity of milk	Methane Emission	Group's share of methane reduction
A	0.45	0.07	-1.52	-5.8	0.7
B	0.93		-3.46	-9.8	0.2
C	0.10		-0.14	-17.3	20.0
D	0.15		-0.31	-3.8	0.4
E	0.05		0.06	-49.5	76.3
F	0.04		0.11	-17.2	2.2
G	0.32	0.25	-0.25	-8.8	0.2
		Total California		-32.2	100.0
5-Year					
A	0.45	0.07	-0.76	-5.1	0.6
B	0.93		-1.73	-8.1	0.2
C	0.10		-0.07	-17.3	19.9
D	0.15		-0.16	-3.6	0.4
E	0.05		0.03	-49.5	76.4
F	0.04		0.05	-17.3	2.2
G	0.32	0.25	-0.13	-8.7	0.2
		Total California		-32.1	100.0
10-Year					
A	0.45	0.06	-1.16	-5.4	0.7
B	0.93		-2.61	-9.0	0.2
C	0.10		-0.12	-17.3	20.0
D	0.15		-0.25	-3.7	0.4
E	0.05		0.03	-49.5	76.3
F	0.04		0.06	-17.3	2.2
G	0.32	0.24	-0.24	-8.8	0.2
		Total California		-32.2	100.0

Table 6.7 Effect of practices of Scenario 5 in 1, 5 and 10-year time horizon.

	Practice adoption pattern				
	Group size and type	Practice	Emission reduction per cow, adopting farm (%)	Cost per cow increase, adopting farm (%)	Percent adoption per group
A	<500 Freestall	3a	-24.2	1.6	5.0
B	<500 Non-freestall	3g	-23.4	1.9	10.0
C	500-2000 Freestall	Digest.	-86.1	0.5	20.0
D	500-2000 Non-freestall	3a	-23.2	1.0	15.0
E	>2000 Freestall	Digest.	-82.6	0.1	66.0
F	>2000 Non-freestall	Digest.	-57.8	0.1	35.0
G	Organic	3a	-22.0	0.7	10.0
	Percentage changes for group in:				
1-Year	Costs per cwt milk	Price of Milk	Quantity of milk	Methane Emission	Group's share of methane reduction
A	0.08	0.02	-0.03	-1.2	0.1
B	0.19		-0.09	-2.4	0.0
C	0.10		-0.04	-17.3	18.6
D	0.15		-0.06	-3.5	0.4
E	0.06		-0.02	-54.5	78.4
F	0.05		0.02	-20.2	2.4
G	0.07	0.03	-0.06	-2.2	0.0
		Total California		-34.5	100.0
5-Year					
A	0.08	0.05	-0.05	-1.3	0.1
B	0.19		-0.28	-2.6	0.0
C	0.10		-0.10	-17.3	18.6
D	0.15		-0.18	-3.7	0.4
E	0.06		-0.01	-54.5	78.3
F	0.05		0.01	-20.2	2.4
G	0.07	0.06	-0.03	-2.2	0.0
		Total California		-34.5	100.0
10-Year					
A	0.08	0.05	-0.09	-1.3	0.2
B	0.19		-0.43	-2.8	0.0
C	0.10		-0.16	-17.3	18.6
D	0.15		-0.29	-3.8	0.4
E	0.06		-0.03	-54.5	78.3
F	0.05		0.00	-20.2	2.4
G	0.07	0.05	-0.05	2.3	0.0
		Total California		34.5	100.0

Discussion

This chapter has investigated the effects of manure management practices that reduce methane emissions on economic and environmental outcomes over 1-year, 5-year and 10-year time horizons. The longer time horizons allow more adjustment to the cost increases caused by adopting the practices.

Our analysis does not explicitly incorporate the uncertainties about market outcomes, technologies or policies that surround all business or farm enterprises, dairy included. Such uncertainties apply in the immediate run, when sudden shocks in supply and demand can disrupt plans. Over a long-term horizon such shocks may average out. But, over a 10-year horizon or longer, uncertainty about longer term trends become more important. Chapter 7 considers some of those trend issues.

We note that our simulation model did not include an explicit mechanism to specify which individual farms within each group adopted the methane reducing practices. That is a 30 percent adoption rate for the group does not isolate which farms adopt and which do not. The model produces a step-wise (group-by-group) cost curve for methane abatement as adoption increases within a group and there are different costs for each practice within each group. An extension of the model would add explicit measurable heterogeneity in costs across individual dairies within each group. We do not now have the necessary cost data to calibrate the patterns of heterogeneity. This model limitation does not bias any aggregate results. We interpret the results as using an implicitly random adoption across farms within each group. Such a pattern of adoption is consistent with adoption patterns in which important factors other than simply measured marginal costs of a practice contribute to driving adoption.

We recognize that some of the manure management practices considered in the simulations may have complex and subtle benefits or costs beyond those incorporated in our data. However, we note that these manure management practices have not been broadly adopted by California dairy farms until there have been government programs providing cost-sharing or other incentives.

Local environmental outcomes are affected by impacts related to number of cows and milk output. Generally, more cows and more milk production in a region are associated with local environmental concerns and pressures. It may be the case that smaller or larger dairies have differential local environmental impacts per cow or per unit of milk production. If that is the case, those local environmental impacts might be affected by a shift in number of cows and production over time. More research is needed to investigate these questions.

Our modeling and simulation methodology were based on assessing costs and benefits. Therefore, the results presented here are consistent with cost-benefit analysis principles. However, measuring the broad societal benefits of reduced methane emissions is beyond the scope of this project.

Conclusion

This chapter is comprised mainly of a set of detailed tables of result of applying our simulation model to alternative time horizons for each scenario. These details are important for some very specific questions but the overall conclusions for smaller dairies may be quickly summarized.

Especially for the longer 10-year time horizon, the supply and demand elasticities are relatively large. That means that the milk quantity impacts of adoption of more costly manure management practices may become larger. Furthermore, the larger impacts on per unit costs are for the smaller dairies. Therefore, we find that for the scenarios that include adoption of the more costly practices by smaller farms adopt, the decline in the production of these smaller dairies is substantial. Output declines for smaller dairies reaches about 10 percent for the 10-year horizon. In scenarios that allow adoption of lower cost practices have output declines for smaller dairies of well less than 0.5 percent. In general, the output effects on larger dairies are small in all scenarios and in all time horizons. This result is because we found that the manure management practices adopted imposed small to moderate costs per unit of output for the larger dairies.

Recommendations

In this chapter, a pattern is beginning to emerge that adoption of the most costly manure management practices may have significant negative output implications for the smaller dairies, while contributing relatively little to aggregate methane reduction. This may suggest a strategy to focus efforts of adoption on larger dairies where more cost-effective methane reduction could be achieved.

CHAPTER 7 PROJECTED ECONOMIC SUSTAINABILITY OF SMALLER DAIRIES IN CALIFORNIA OVER 5-YEAR, 10-YEAR AND 20-YEAR TIME HORIZONS, INCLUDING CONSIDERATION OF ECONOMIC AND ENVIRONMENTAL CONCERNS SUCH AS METHANE EMISSIONS REDUCTIONS

Introduction

This chapter has two major parts. In part 7.1 we used a data intensive consideration of how the dairy industry in California is likely to evolve over the next few decades in light of changes in the past few decades. In the second part of the chapter we incorporated the findings of the first part into the economic modeling and simulation approach developed in Chapter 4 and used in Chapters 5 and 6.

The California dairy industry has faced many economic challenges related to state, national and global markets for milk, national and global markets for grain and oilseeds, local costs of forage and labor, among other challenges. At the same time period over which economic challenges have become stronger, the costs of dairy farming and dairy product manufacturing have risen in California. These California cost challenges relate to costs of land, water, electricity and labor (among others) that are due, in part, to California regulatory choices. It is impossible to quantify here all these factors that drive the sustainability of the California dairy industry. Instead we offer a few introductory assessments before turning to the consequences.

First, California has long had a strong a resilient dairy industry comprised of both farming and dairy product processing. The industry was an early adopter of large-scale milk production and processing that lowered costs and attracted top managers to the business. With rapid consolidation and strong economic incentives, only the best managers have remained in the business. These economic incentives and pressures continue and consolidation continues.

Second, only a small share of California milk is used locally consumed fluid milk products in markets that are insulated from competition. Most California milk is used to make processed products that enter national and international markets. The prices in these markets are determined globally rather than locally. As dairy production has become more efficient in other competitive regions the national and international prices are lower. This competitive pressure and growing efficiency among competitors mean that the inflation-adjusted prices of dairy products have declined. Some of the efficiency gains in other locations has been due to their adoption of scale and management for which California was long known.

Third, because California remains a large net exporter of dairy products and because the costs of dairy product manufacturing has risen in California, the price of raw milk is relatively low compared to places to which California dairy products are shipped.

None of these underlying conditions seem likely to change materially in the next few decades and thus a return to very rapid growth of California milk production is unlikely. However, the inherent strengths of the California dairy industry remain. Therefore, it seems unlikely that significant aggregate declines in California milk production are on the horizon. California milk output has been roughly constant, with many moderate ups and downs, for about 13 years. That aggregate pattern seems likely to continue.

Of course, unforeseeable events may be on the horizon. As this is written, in March 2020, expecting the unexpected seems more appropriate than ever. Any projections therefore must be handled with caution.

Materials and Methods

Two methodologies are used in this chapter. Section 7.1 of the results section develops projections of a likely path for California dairy over the next 20 years and explains implications for different sized dairies in this context. A myriad of factors drives the economic future and subsection 7.1 cannot review them all. Moreover, no projections can be correct in all particulars with such a complex set of drivers, including both local and global supply and demand conditions well into the future. Nonetheless, it is important to consider protected paths, especially for the size of the industry and for the numbers of farms and share of farms and production by size categories.

The second methodology is a simulation model developed in Chapter 4 and was applied also in Chapters 5 and 6. In Section 7.2 the simulation model incorporates features on the projections developed in section 7.1 and shows how the manure handling practices affect farms in different size categories differentially against the baseline that includes projected changes that are likely to underway already.

Results

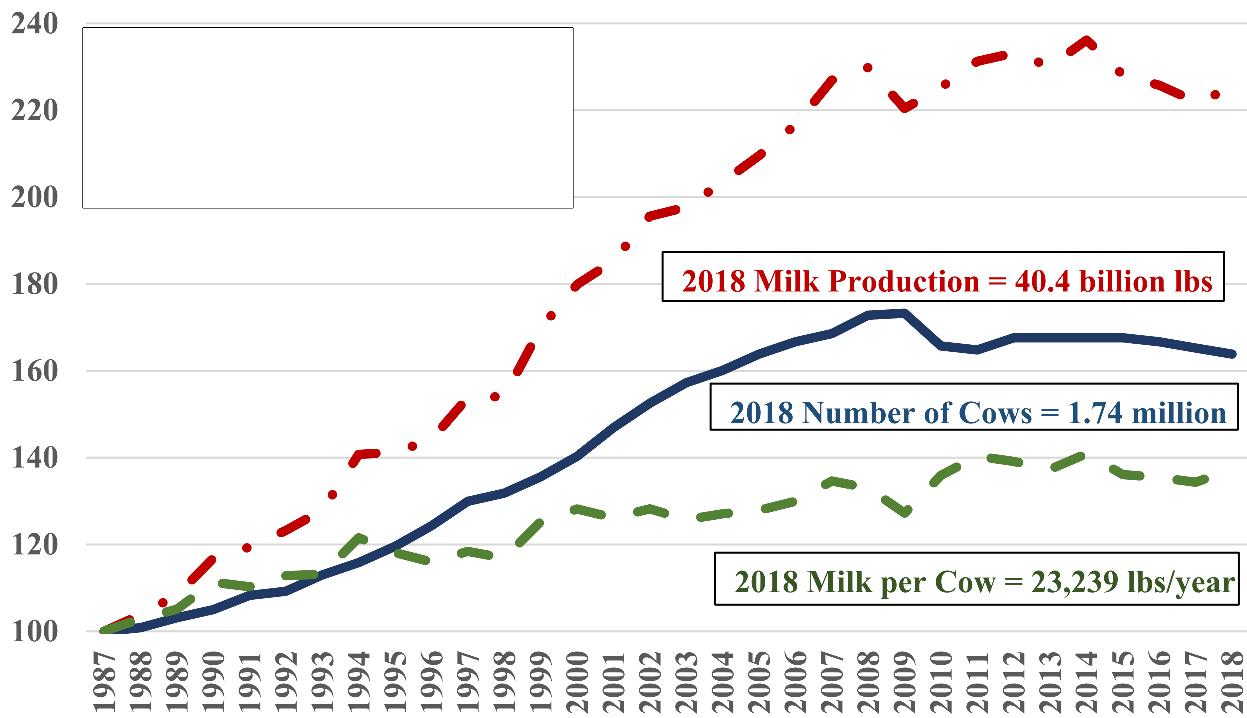
7.1 Economic Projections of the California Dairy Industry

The California dairy industry remains the single largest producer of milk and processed dairy products in the United States accounting for about 18 percent of all U.S. milk production. Almost all of the milk produced in California is also processed in California, and almost all of the milk processed in California is produced on dairy farms in the state. Much of California processed dairy product quantity and value is shipped out of California in the form of cheese, whey, lactose, milk powders, butter and other processed products that are used in the rest of the United States and globally.

7.1.1 California dairy overview and comparisons with the rest of the United States

Figure 7.1 shows a quick history of the evolution of the California dairy industry over the past three decades (See also Sumner, 2019 and Matthews and Sumner, 2019). All three lines, milk production, number of cows, and production per cow have been scaled to equal 100 in 1987. The data, based on USDA, NASS run through 2018. The beginning and ending values in pounds and cows are shown in the chart. We start in 1987 with 17.9 billion pounds of milk from a little over one million cows and therefore a little less than 17,000 pounds per cow.

The first 20 years, continuing from previous decades, was a period of remarkably steady growth that saw milk production rise by more than 120 percent with large increases in cow numbers and production per cow. That all came to an abrupt stop around 2008. Since then there has been essentially no growth in output as cow numbers have declined slightly and milk per cow has risen slowly.



Data Source: NASS, USDA

Figure 7.1 California Milk Production and Productivity Indexed to 1987

As decades of growth ended in California, in the rest of the United States milk production per cow has grown steadily, the number of cows has grown slightly, so that total milk production has risen, offsetting the reductions in California.

The lack of growth in the California milk cow herd over more than a decade has been in contrast with growth in other Western states such as Idaho and Texas and closer to the national average (Table 7.1). The decline in number of dairies in California has actually been slower than the national average and much slower than in states such as Texas and Wisconsin (Table 7.2). The implication is that cow numbers per farm have grown rapidly in California, and, as with other Western States, remain well above the national average. While the growth rate in cows per dairy farm has risen in California, it has done so much more quickly in Wisconsin, and even in Idaho and Texas. Herd size in Idaho and Texas are not quite similar to average herd size in California (Table 7.3).

Table 7.1 Number of Cows in Top Five Milk Producing States in the U.S. for 2004 and 2018.

	Number of Cows (1,000 cows)		Percentage change
	2004	2018	
California	1,700	1,740	5
Wisconsin	1,245	1,275	2
New York	658	625	-5
Idaho	412	600	46
Texas	317	515	62
U.S. Total	8,988	9,400	2

Data Source: NASS, USDA

Table 7.2 Number of Dairies in Top Five Milk Producing States in the U.S. for 2004 and 2017.

	Number of Dairies		Percentage Change
	2004	2017	
California	2,030	1,390	-32
Wisconsin	15,570	9,090	-42
New York	6,600	4,490	-32
Idaho	755	510	-32
Texas	810	400	-51
U.S. Total	66,825	40,219	-40

Data Source: NASS, USDA

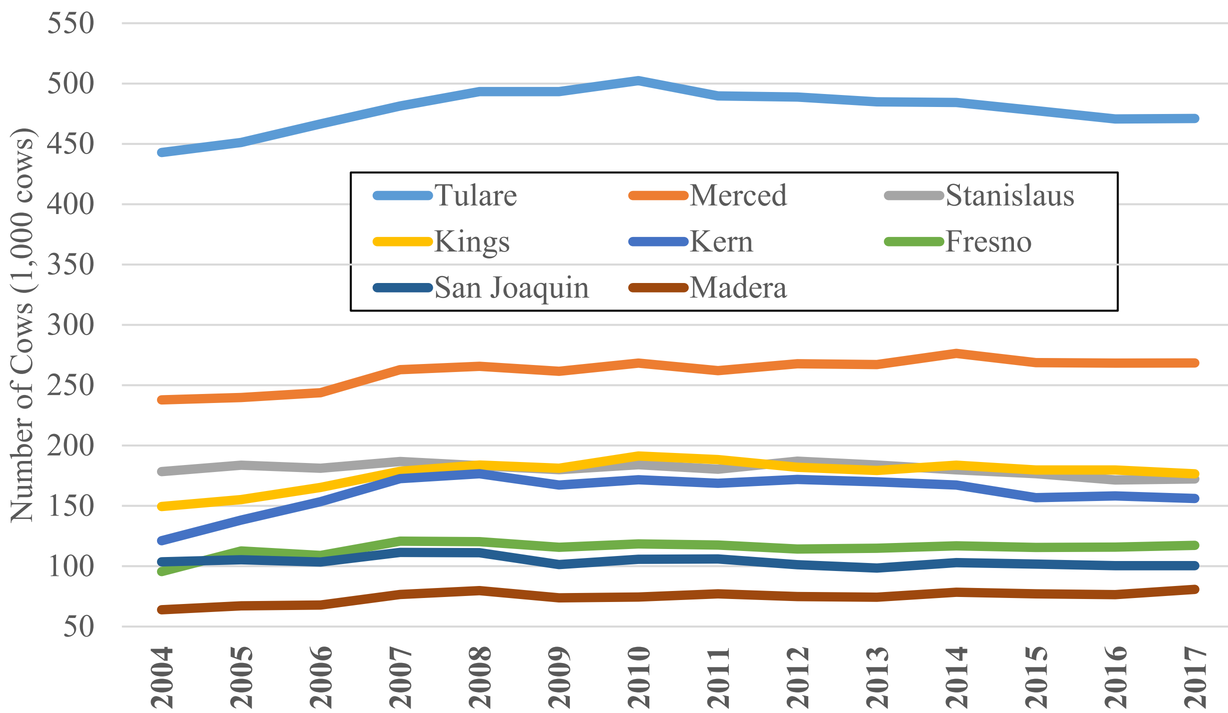
Table 7.3 Number of Cows per Dairy in Top Five Milk Producing States and U.S. Average for 2004 and 2017

	Number of Cows per Dairy		Percentage Change
	2004	2017	
California	837	1,263	51
Wisconsin	80	141	76
New York	100	138	38
Idaho	546	1,176	116
Texas	391	1,225	213
U.S. Average	134	232	73

Data Source: NASS, USDA

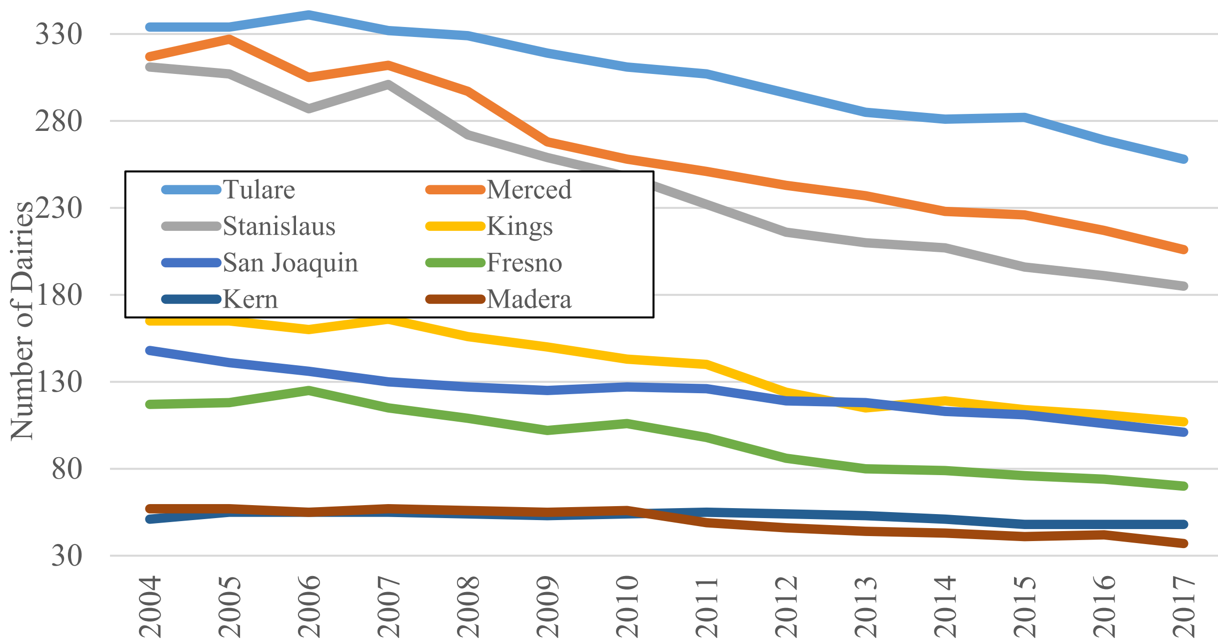
The comparison with other parts of the United States is useful to help us consider future trends and drivers as the competitive position of California dairy in the national and international market has changed in the most recent decade or two. The evolution of dairy processing plant capacity is consistent with little aggregate growth in milk production in California (McCully, 2018).

Within California the dairy industry has continued to be concentrated in eight counties of the San Joaquin Valley, led by Tulare County (Figure 7.2). The number of dairies has decreased rapidly in all these counties except Kern County (Figure 7.3). Kern County, which has relatively few dairy farms, has, by far, the largest average herd size in California at about 3,200 cows (Figure 7.4). But, herd size has grown rapidly for all these counties and for the California average (Figure 7.4). Overall, these data indicate that while much has changed for the California dairy industry, milk production remains large, and has not declined despite many challenges. At the same time, the trend is toward farm consolidation, a trend which California shares with the rest of the United States.



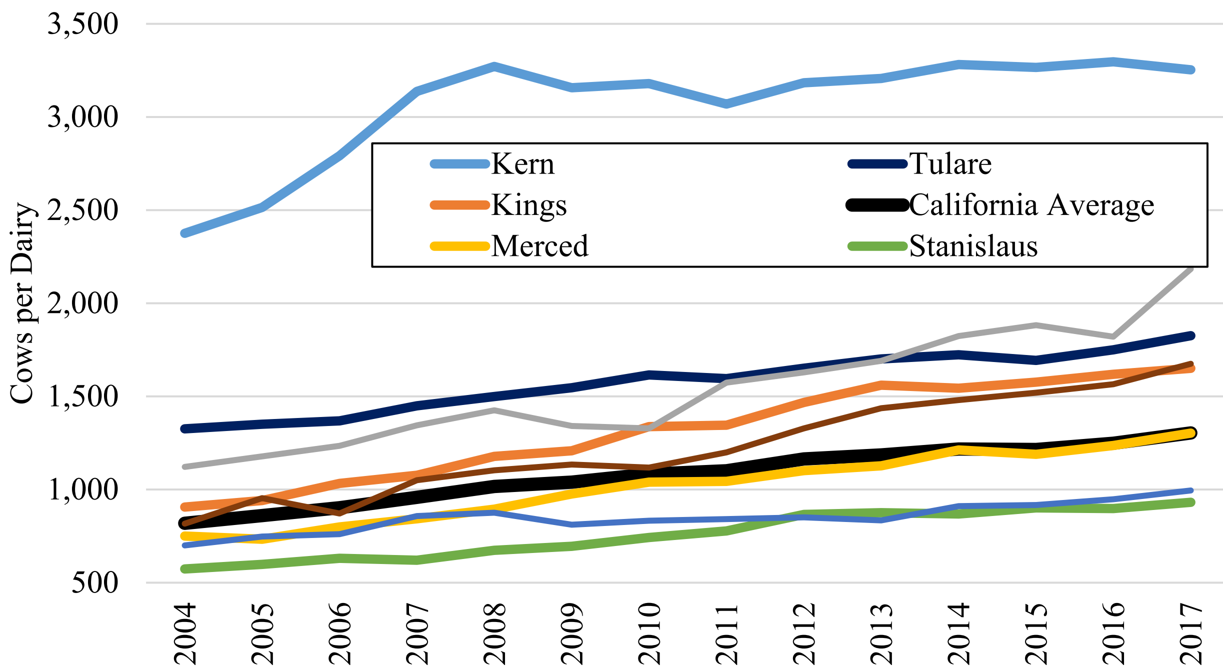
Source: CDFA California Dairy Statistics Annual, 2004 to 2017

Figure 7.2 Number of Cows in Top Milk Producing Counties in California, 2004 to 2017.



Source: CDFA California Dairy Statistics Annual, 2004 to 2017

Figure 7.3 Number of Dairies in Top Milk Producing Counties in California, 2004 to 2017.



Source: CDFA California Dairy Statistics Annual, 2004 to 2017

Figure 7.4 Average Number of Cows per Dairy in Top Milk Producing Counties in California, 2004 to 2017.

7.1.2 Dairy farm consolidation in California over three decades

Every five years for more than 150 years the U.S. Census of Agriculture provides consistently defined and statistically rigorous data on many characteristics of farms and agricultural markets. Despite some deficiencies, these data are useful in tracking herd size distributions for California dairy farms.

The biggest deficiency with the Census data for tracking the distribution of dairy herds by size category for California dairies is that the great detail about the smallest dairies (less than 100 cows) is irrelevant for California and information about distributions of herds by size categories of more than 1,000 cows has appeared only in the last decade or so. The other problem is that the Census provides great detail about dairy cow numbers on farms that market no milk. These farms may have a few milk cows for household use or to nurse calves, but they are irrelevant to our interest in the commercial dairy industry. In spite of these limitation, we can learn much by examining data from seven Census rounds that span three decades from 1987 through 2017.

Figures 7.5 through 7.10 show patterns of number of dairy farms that have milk sales by herd size category. The figures include trends and trend regressions for size categories from herds with less than 500 cows through herds with 2,500 cows or more.

Consider first the number of dairies with herd size 1-499 cows. There were 1908 herds in this category in 1987 and only 395 herds in 2017, a decline of about 80 percent in 30 years (Figure 7.5). The exponential regression trend line through these data explains 95 percent of the variation in the data. The trend shows a 26.7 percent decline in the number of herds every 5 years. This is substantially faster than 5 percent per year on a cumulative basis. We extend the trend line out one decade, to 2027 and note that the trend projection is for less than 250 herds remaining in this category (Figure 7.5).

Next, consider the number of dairies with 500 cows to 999 cows (Figure 7.6). This category is only available since 1992, so we have six census data points spanning 25 years. The number of herds in this category is also declining rapidly. The trend line does not fit quite so well, explaining 81 percent of the variation. The herd numbers were about constant for the first decade and rapid from 2012 through 2017. There were 558 herds in 2002 and only 300 herds in 2017 in this size category. Over the full 25 years, the rate of decline is about 14 percent every five years.

The exponential trend line explains about 81 percent of the variation in number of herds with 1,000 cows or more, but indicates continued rapid growth at about 12 percent every five years (Figure 7.7). This exponential trend projects almost 900 herds in 2027. However, a natural log trend fits these data much better (R^2 =0.93) and shows a flattening rate of growth. The logarithmic trend projects about 700 herds in 2027 (Figure 7.8).

We can break down the data for larger herds sizes only in the 2007, 2012 and 2017 Census rounds. The number of dairies from 1,000 to 2,499 cows (Figure 7.9) declined by about 9 percent over this 10-year period, but rose in the first five years before falling by 13 percent in the most recent 5 years. The number of dairies with more than 2,500 cows grew by 17 percent from 169 to 198 herds. We expect most of that growth was herds in the smaller category adding cows to their herds over this decade (Figure 7.10).

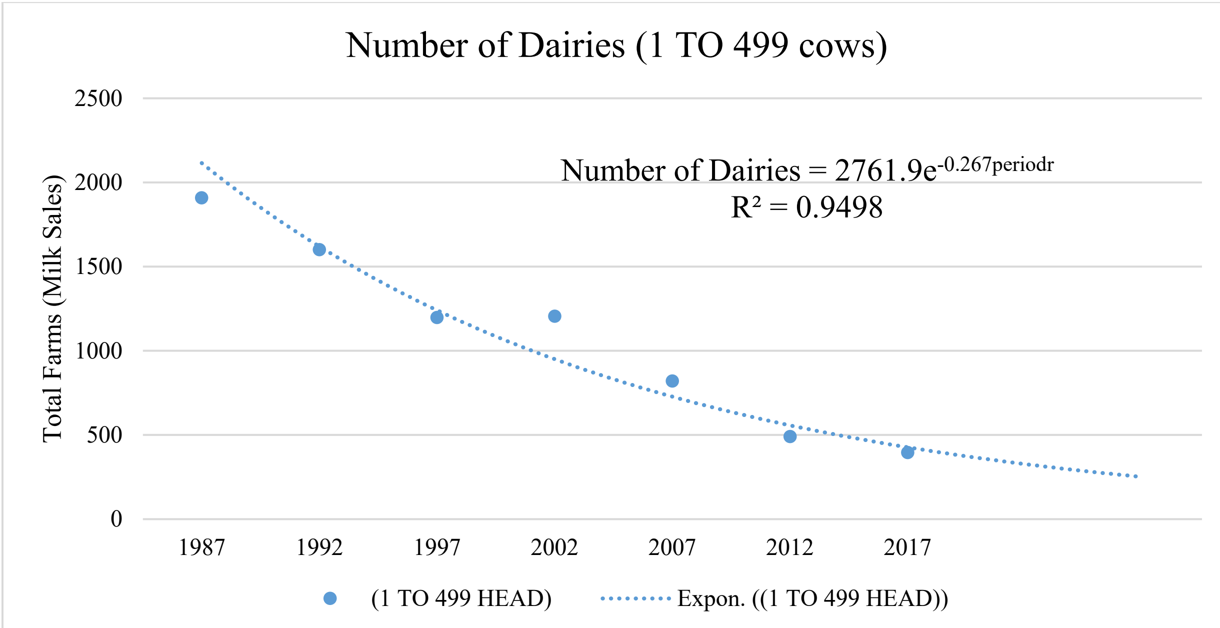


Figure 7.5 Trend in number of dairies by herd size categories in California for dairies of 1 to 499 cows.

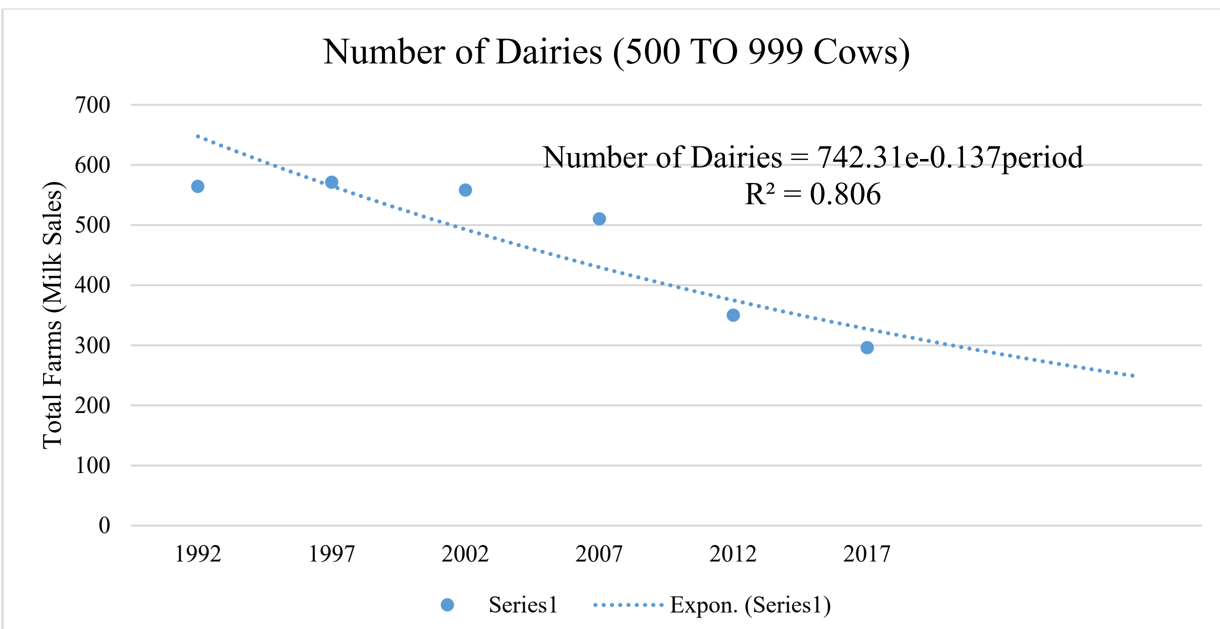


Figure 7.6 Trend in number of dairies by herd size categories in California for dairies of 500 to 999 cows.

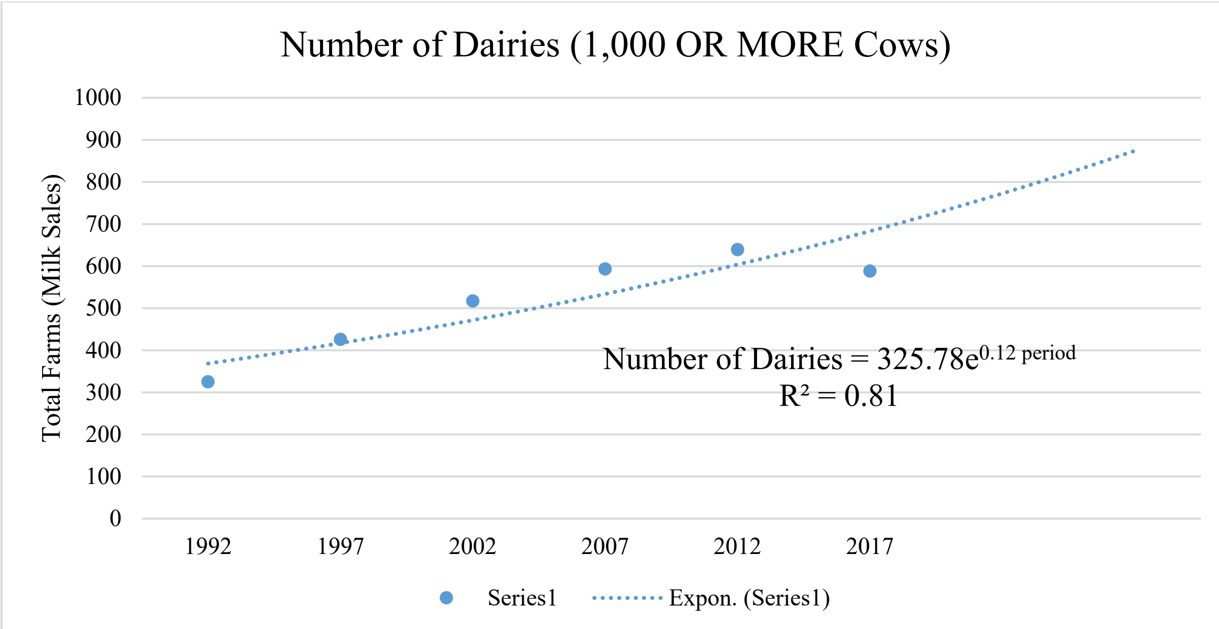


Figure 7.7 Exponential trend in number of dairies by herd size categories in California for dairies of 1,000 cows or more.

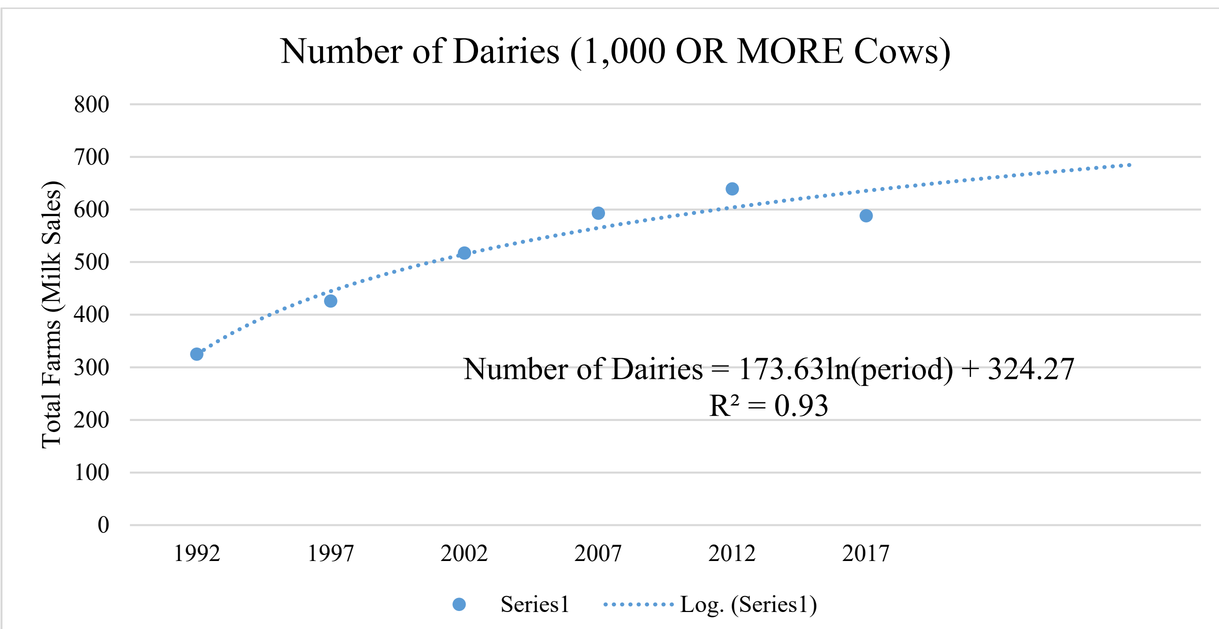


Figure 7.8 Logarithmic trend in number of dairies by herd size categories in California for dairies of 1,000 cows or more.

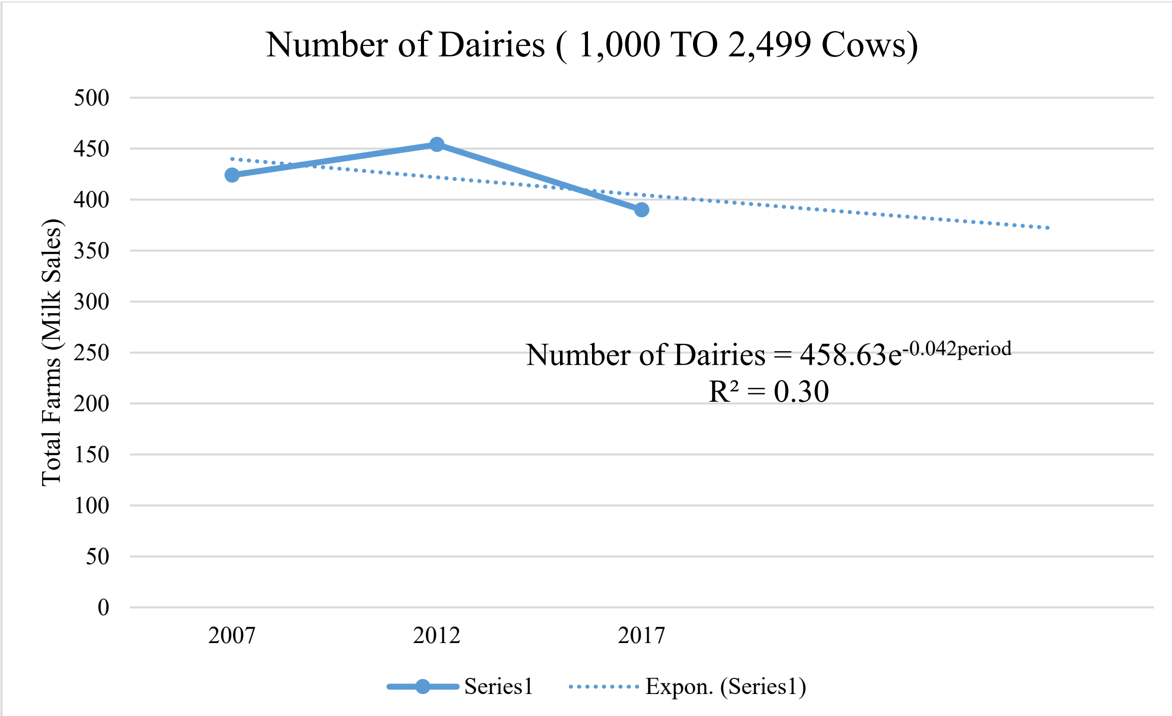
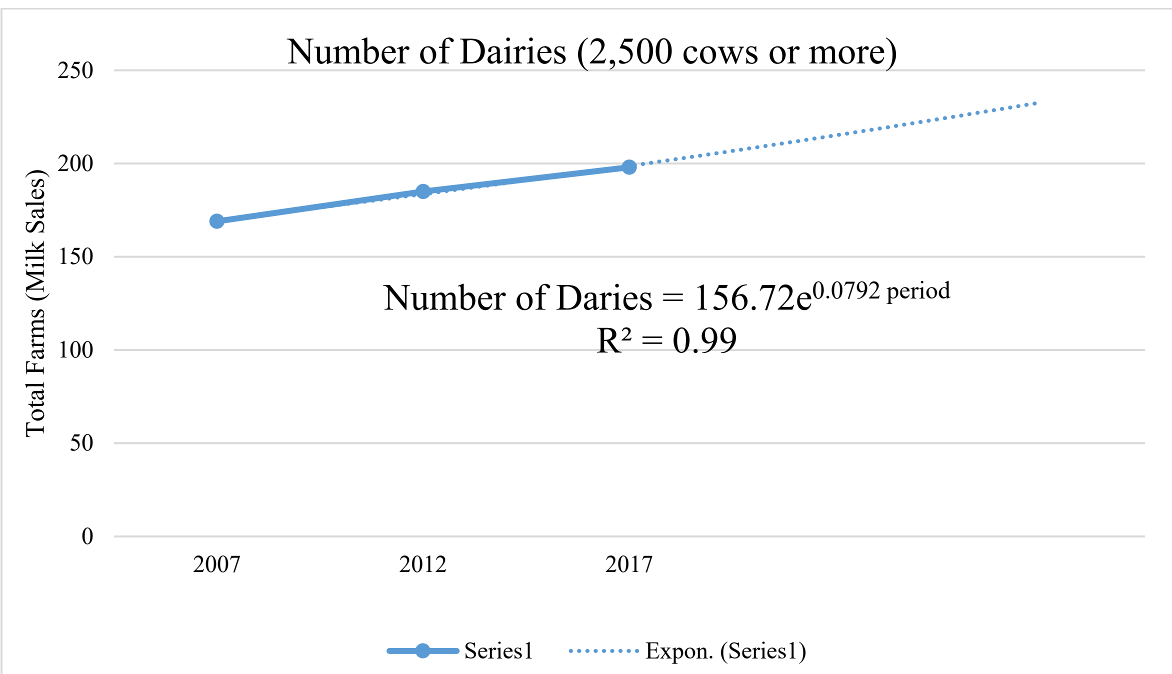


Figure 7.9 Trend in number of dairies by herd size categories in California for dairies of 1,000 to 2,499 cows.



Source: NASS, USDA. *U.S. Census of Agriculture.* Various years.

Figure 7.10 Trend in number of dairies by herd size categories in California for dairies of 2,500 or more cows.

The Census data of distributions across size categories in 2017 are shown in Table 7.4. The Census found 1,279 herds that sold milk that year, milk sales of about $6.5 billion and about 1.75 million cows. Other data show different aggregates due to different statistical procedures or differing administrative coverage.

Table 7.4 Distributions of Farms, Milk Revenue and Milk Cows by Herd Size Category in California, 2017.

Herd Size	Dairy Farms		Milk Revenue		Milk Cows	
Cows/Farm	Number	Percent	$ millions	Percent	Number	Percent
1 to 499	395	30.9	$364.4	5.6	94,120	5.4
500 to 999	296	23.1	$829.3	12.8	209,626	12.0
1,000 to 2,499	390	30.5	$2,385.2	36.8	638,080	36.5
2,500 to 4,999	163	12.7	$1,968.0	30.4	546,617	31.2
5,000 or more	35	2.7	$930.5	14.4	261,886	15.0
Total	1,279	100	$6,477.3	100	1,750,329	100

Source: NASS, USDA U.S. Census of Agriculture 2017.

About 31 percent of herds have fewer than 500 cows, but these herds account for about 5.6 percent of milk revenue and about 5.4 percent of cows. About 23 percent of farms have 500-999 cows and they account for about 12 percent of cows. About 30.5 percent of farms have 1,000-2,499 cows and they account for 36.5 percent of cows. About 12.7 percent of farms have 2,500-4,999 cows and they account for 31 percent of the total cows. Finally, the category with more than 5,000 cows per farm includes 2.7 percent of farms but 15 percent of the cows. These data, especially the percentages are consistent with other information about the size distribution of farms in the California dairy industry.

Based on these data, and underlying forces driving dairy economics in California, we expect a rough continuation of the trends of the past two or three decades to continue. We see no aggregate growth in cow numbers over the next 20 years. Very gradual growth in milk production may continue as milk per cow grows at its recent trend rates. The aggregate number of herds and share of cows in the size category of less than 500 cows will both decline by about 5 percent per year. The exception among this herd size category is that organic herds may maintain their farm numbers and cow numbers because they service a steady or growing niche demand. The reason this category does not grow more is that it serves primarily beverage and other liquid or soft product markets and this has been a declining share of California milk usage.

The number of herds and number of cows in the category of herd size between 500 and 2,000 cows will also decline. We project that decline to be about 1.5 percent per year consistent with recent trends. The most economically sustainable of these farms may join the larger herd size categories over time. The rate of growth in the larger herd size categories is about 1.6 percent per year initially. The number of cows in this category must grow to capture milk demand no longer supplied by smaller herd size categories and in order to be consistent with recent trends that the total cow numbers in California have not declined.

The percentage growth rate continues to be positive, but gradually declines to about 0.8 percent per year. This is an arithmetic requirement as fewer cows in the two smaller size categories, and more cows in the larger herd size categories, means that the constant rate of percentage decline implies gradually falling percentage increase in the larger herd size categories. These data and implications for shares of cows by herd size category over time are shown in table 7.5.

Table 7.5 Projected Trend Changes in Herds and Cow Numbers by Size Category, With Total Cow Numbers Constant.

	Organic	<500 cows	500-2000 cows	>2000 cows
Annual Percent Rate of Change	0	-5	-1.50	1.63 first period 0.084 last period
Initial Share of Cows in Year 1 (%)	1.3	4.9	41.1	52.7
Ending Share of Cows after 20 Years (%)	1.3	1.8	30.4	66.6
Cumulative % Change, 5 Years	0.0	-22.6	-7.3	7.8
Cumulative % Change, 10 Years	0.0	-40.1	-14.0	14.7
Cumulative % Change, 20 Years	0.0	-64.2	-26.1	26.3

Source: Calculations based on adjustments to historical trends outlined above.

The reductions in the herds with less than 500 cows is consistent with declines in numbers of herds that is likely to represent mainly exits. The reduction in the midsize herds is likely to be a combination of exits and shifting some herds into the larger size category. For the larger herds, the growth is likely to be a few more herds, but mostly larger herds. We assume that the organic share remains roughly constant as organic share of fluid milk demand grows but fluid milk of all demand declines.

Table 7.5 shows that at the end of 5 years there are about 22.6 percent fewer cows (and herds) in the category of farms with less than 500 cows due to these underlying trends. There are about 7.3 percent fewer cows and herds in the midsize groups (500 to 2,000 cows) and a growth of about 7.8 percent in the larger category of more than 2,000 cows (although consistent with past trends this is not primarily growth in numbers of herds, but rather more herds with many thousands of cows. At the end of 20 years about 64 percent of the smaller herds have exited. This rate of decline is fully consistent with trends of the past 20 or 30 years and is independent of changes in manure management practice. We note, however, policy risks as described by Lee and Sumner, (2018) may have implications for economic sustainability for some farms.

The rest of Chapter 7 explains how our simulations of the scenarios, combined with the underlying trends, have implications for changes in emissions, milk production and production of milk in each size group.

7.2 Incorporation of projections across groups on impacts of manure management practices to reduce methane emissions

In order to incorporate the trends in exits among dairy operations with smaller herd sizes and the parallel growth of cow numbers in herds in the larger herd sizes, we introduced exogenous trends for the number of cows over the 5, 10 and 20-year time horizons. For the four groups of operations with less than 2,000 cows in the model, we extended trends of observed reductions in number of herds rates as described in section 7.1. The bulk of this section consists in a set of tables that are similar in format to those displayed in Chapter 6.

7.2.1 Exogenous projections of cow numbers by group

Table 7.6 shows explicitly the exogenous annual trends in cow numbers by group. We assumed that rates of decline in numbers of cows observed over the last two decades will remain at about -5 percent per year for the operations of less than 500 cows, and about -1.5 percent for the dairies with 500 to 2,000 cows. These annual rates of change are visible in the column labeled "1 Year" and are assumed to be constant over the whole period of the simulations. However, since these rates are cumulative (5 percent every year for the smaller dairies), we also report the resulting rates for the 5, 10 and 20 year-horizons, which are the time horizons we consider in the simulations of this chapter. These rates correspond to the trends identified in the first part of this chapter and do not include the effect of GHG-mitigation costs.

Table 7.6 Projections of changes in cow numbers by dairy group over 5, 10 and 20-year time horizons used the scenarios.

		Projections in changes in numbers of cows by group (%)			
		1 year	5 year	10 year	20 year
A	<500 Freestall	-5.00	-22.62	-40.13	-64.15
B	<500 Non-freestall	-5.00	-22.62	-40.13	-64.15
C	500-2000 Freestall	-1.50	-7.28	-14.03	-26.09
D	500-2000 Non-freestall	-1.50	-7.28	-14.03	-26.09
E	>2000 Freestall	NA	7.78	14.66	26.30
F	>2000 Non-freestall	NA	7.78	14.66	26.30
G	Organic	0.00	0.00	0.00	0.00

Source: Author projections based on trends established in Section 7.1.

The 1-year rate of change in Table 7.6 is provided as reference for a yearly growth rate but is not included in the simulations in this chapter. (See Table 7.5 for further information.) We expect the negative changes proportional for smaller herd size groups to be mainly in farm exits with some farms to the next larger size category. Increase in average herd sizes is likely to represent most of the growth in cow numbers for the larger groups.

Table 7.6 also displays the rates of increase in cow numbers for the two groups with 2,000 or more cows per operation. These rates are consistent with the limited historical evidence on the growth of larger dairies and we project continued growth, much of which occurs through consolidation. There may be some growth in the number of dairies in the larger size category, but most of the growth will be in average number of cows per farm. Consistent with the projections of section 7.1, we held the total number of cows in the state constant over each of these horizons. That implies that the annual percentage rate of increase in the groups of larger dairies cannot be constant over time. Accordingly, we calculated the rate of increase among the two groups of larger operations that offsets the reduction in number of cows of the smaller dairies.

These exogenous rates of change are included in the simulation model as described in chapter 4 and result in significant shifts in methane emissions that occur simultaneously with the direct abatement effect of adoption of manure management practices that reduce methane emissions.

In addition, the supply and demand elasticities are different for each time horizon, as in chapter 6, in order to reflect adjustments in quantities supplied and demanded. As in Chapter 6, the share of manure management costs in total costs of production is relatively small (2.4 percent at most) across groups.

7.2.2 Economic effects of adoption of methane emission reduction practices with exogenous trends

Scenario 0.
The economic and emission effects of adoption of practices in the pattern of Scenario 0 are reported in Table 7.7. To facilitate interpretation and comparisons, the top section provides again the description of the impact of adoptions on production costs and emissions for each of the dairy groups as well as the proportion of farms adopting the practice. As before, the practices are fully implemented and we consider impacts after a 5-year adjustment horizon.

Let us consider first the 5-year time horizon. Relative to the case where no trend changes were simulated, additional changes in emissions abatement distribution occur though the reallocation of cows and milk production among groups. This reallocation is visible in the large decreases in milk production of 23 percent and 24 percent for the two groups with fewer than 500 cows. The endogenous quantity effects are small, of a few percentage points at most, since they are exclusively driven by cost changes which are 0.36 percent and 0.84 percent here and as before. The reallocation results also affects the middle groups that see a reduction in quantities of 7.44 percent, mostly due to exogenous trends. The two groups of dairies with more than 2,000 cows see their output increase by 7.84 percent and 7.85 percent, reflecting in large part the increase in herd sizes within these groups. The price effect linked to cost shifts derived from adoption of manure practices remain below 1 percent.

Table 7.7 Effect of practices of Scenario 0 in 5, 10 and 20-year time horizon, with projected changes in cow numbers across groups.

	Practice adoption pattern				
	Group size and type	Practice	Emission reduction per cow, adopting farm (%)	Cost per cow increase, adopting farm (%)	Percent adoption per group
A	<500 Freestall	2a	-86.6	9.0	4.0
B	<500 Non-freestall	2a	-65.3	9.3	9.0
C	500-2000 Freestall	4a	-59.1	1.1	14.0
D	500-2000 Non-freestall	3a	-23.2	1.0	16.0
E	>2000 Freestall	Digest.	-82.6	0.1	46.0
F	>2000 Non-freestall	Digest.	-57.8	0.1	25.0
G	Organic	2a	-86.2	3.2	7.0

	Percentage changes for group in:				
5-Year	Costs per cwt milk	Price of Milk	Quantity of milk	Methane Emission	Group's share of methane reduction
A	0.36		-23.19	-25.7	4.4
B	0.84		-24.15	-28.3	0.7
C	0.15	0.07	-7.44	-15.1	23.3
D	0.16		-7.44	-10.9	1.7
E	0.04		7.84	-33.1	68.4
F	0.03		7.85	-7.7	1.3
G	0.22	0.18	-0.09	-6.1	0.2
			Total California	-24.0	100.0
10 -Year					
A	0.36		-41.01	-42.7	7.0
B	0.84		-42.45	-45.0	1.1
C	0.15	0.07	-14.29	-21.3	31.7
D	0.16		-14.30	-17.4	2.7
E	0.04		14.74	-28.8	57.1
F	0.03		14.76	-1.8	0.3
G	0.22	0.17	-0.17	-6.2	0.2
			Total California	-25.0	100.0
20-Year					
A	0.36		-65.30	-65.8	10.1
B	0.84		-67.22	-67.3	1.5
C	0.15	0.07	-26.41	-32.4	45.1
D	0.16		-26.42	-29.1	4.2
E	0.04		26.43	-21.6	40.1
F	0.03		26.45	8.2	-1.3
G	0.22	0.18	-0.18	-6.2	0.2
			Total California	-26.6	100.0

The reallocation of quantity of output among groups has a large impact on emissions as well, since manure and methane emissions can be estimated as proportional to milk production. While the milk and emission quantities are not exactly proportional and many factors related to diet and other livestock management practices alter methane emissions for a given milk output, these effects are small relative to the very large exogenous effects of a reduction in cow numbers for smaller dairies and an increase in cow numbers on larger dairies. The relationship between milk production and methane emissions is reflected in the result that the changes in methane emissions for the dairies of less than 500 cows are only a few percent larger than their respective changes in quantity of milk. For instance, Table 7.7 shows that group A sees a milk output reduction of 23.2 percent and methane emission reduction of 25.7 percent. These are both close to the exogenous 22.6 percent reduction in cow numbers for the 5-year horizon. Actual methane reduction from adoption of pack barn by 4 percent of the dairies in the group contributes to the difference between milk production and methane emission changes. The situation of the dairies in the intermediate size groups is similar to the case of the groups of farms with fewer than 500 cows.

The two groups of dairies with more than 2,000 cows show the opposite trend. The quantity of milk in each group increases by 7.8 percent. This expansion in milk quantity for these groups offsets some of the emission reduction per cow due to adoption of practices that reduce emissions. The group of freestall dairies adopting digesters reduces emissions by 33 percent instead of 38 percent when no consolidations were projected (see table 6.2).

Organic dairies are again assumed to see no exogenous changes in cow numbers and are supplying a separate dairy product market from conventional dairies, therefore their results are the same as in Chapter 6 and will not be discussed further.

With trends in cow numbers across groups, the total methane emission reduction for the industry is 24 percent in the 5-year horizon. The reallocation of cows across size groups results in a slightly larger emission reduction than without trends because some of the cows that shift into the operations with digesters and high emission reduction rates come from operations with no adoption of manure practices that reduce methane or do little to reduce emissions.

These patterns are reinforced and stronger in the 10-year and 20-year time horizons. The reduced cow numbers on smaller dairies dominate any impacts from methane reducing practices. In contrast, the net reduction of methane for the groups with large herd sizes is progressively reduced because the addition of cows to the larger size groups tends to offset most of the methane emission reductions that are caused by adoption of practices that reduce methane emissions per cow.

When interpreting the results for the “contribution” of each group to total methane abatement, one must be careful to account for the changes in cow numbers across groups. For instance, the share of group E’s contribution to methane reductions decreases from 68.4 percent in the 5-year horizon to 40.1 percent in the 20-year horizon because of a growth in number of cows and milk production in the group. The reduction in methane emission per cow caused by adoption of digesters remains unchanged.

Scenarios 1, 2 and 3.
The results for Scenarios 1, 2 and 3 are dominated by changes in milk production related to changes in aggregate cow numbers in each group. As the length of the horizon increases, the dairy farms in groups with larger herd size groups increasingly have larger shares of the total milk production in California.

In Table 7.8 (Scenario 1, which has the 30 percent adoption rate), total emissions decline only about 14 percent over the 20-year horizon because, with about 26 percent more production from more total cows in the groups, the total emissions from dairies with more than 2,000 mature cows increase. The very large decline in milk production of the two conventional production groups with smaller herds sized are accompanied by growth in production in the larger herd size groups.

Table 7.9, which shows results for Scenario 2, which has a 40 percent adoption rate, simply increases the impacts of methane reducing practices by about one third. However, in Table 7.9 the impacts across groups is dominated by the exogenous trends that result in a shift of cows and milk quantity from dairies with less than 2,000 mature cows towards dairies with more than 2,000 mature cows. The dominant impacts revealed in this scenario as in others are the importance of underlying herd size trends more than the impacts of adoption of manure handling practices. Overall, methane emissions decrease by about 18.7 percent for the 20-year horizon.

Table 7.10 applies the 30 percent adoption rate to a set of practices that include digesters for the largest groups initially. The result is a reduction in emission by about 24 percent across all the time horizon. This is slightly smaller than the reduction with no trends in cows per group that were shown for a 10-year horizon in Chapter 6. The implication is that for this scenario the groups with slightly lower emissions per cow experience reduced cow numbers, so average emission per cow increases because of the different changes in total numbers of cows per group.

Scenarios 4 and 5.
Scenario 4, in Table 7.11, applies relatively low adoption rates for the smaller farms and high digester adoption rates for larger farms. Therefore, for this scenario, the trends to larger herd sizes over time tend to reinforce adoption of methane reducing practices by the larger dairies. Smaller herd size dairies that have relatively high emission per cow have progressively fewer cows mainly because of the underlying trends. Group E, which has a high rate of digester adoption continues to have a net emission reduction despite a 26 percent increase in milk quantity. Overall methane reduction increases from 33.4 percent for the 5-year horizon to 36.5 percent for the 20-year horizon.

Finally, scenario 5, which is shown in Table 7.12, has modest adoption of low cost and low methane-reduction practices for the smaller dairies. It has high adoption of digesters for the larger dairies. Aggregate cow numbers are declining on the smaller dairies that have higher emissions per cow in this scenario. This almost completely a consequence of the underlying trends not the result of adoption of manure practices. Table 7.12 shows that aggregate methane emission reductions are 39.7 percent over the 20-year horizon because the large emission reduction from digester adoption in group E offsets the 26 percent increase in milk quantity.

Table 7.8 Effect of practices of Scenario 1 in 5, 10 and 20-year time horizon, with projected changes in cow numbers across groups.

Practice adoption pattern

	Group size and type	Practice	Emission reduction per cow, adopting farm (%)	Cost per cow increase, adopting farm (%)	Percent adoption per group
A	<500 Freestall	2a	-86.6	9.0	30.0
B	<500 Non-freestall	2a	-65.3	9.3	30.0
C	500-2000 Freestall	3a	-24.3	1.3	30.0
D	500-2000 Non-freestall	3a	-23.2	1.0	30.0
E	>2000 Freestall	4a	-59.1	0.7	30.0
F	>2000 Non-freestall	3a	-23.2	0.8	30.0
G	Organic	2a	-86.2	3.2	30.0

Percentage changes for group in:

5-Year	Costs per cwt milk	Price of Milk	Quantity of milk	Methane Emission	Group's share of methane reduction
A	2.69		-27.46	-45.5	13.7
B	2.80		-27.67	-40.9	1.8
C	0.38	0.27	-7.49	-14.2	38.6
D	0.29		-7.32	-13.8	3.9
E	0.22		7.87	-11.2	40.8
F	0.25		7.81	0.3	-0.1
G	0.95	0.76	-0.38	-26.1	1.4
			Total California	-13.6	100.0%
10 -Year					
A	2.69		-47.47	-58.9	17.5
B	2.80		-47.79	-55.5	2.4
C	0.38	0.24	-14.43	-20.6	55.2
D	0.29		-14.17	-20.1	5.6
E	0.22		14.73	-5.6	20.0
F	0.25		14.64	6.7	-2.0
G	0.95	0.71	-0.71	-26.4	1.3
			Total California	-13.8	100.0
20-Year					
A	2.69		-73.83	-76.0	22.3
B	2.80		-74.25	-74.1	3.1
C	0.38	0.27	-26.51	-31.8	84.4
D	0.29		-26.17	-31.3	8.6
E	0.22		26.49	4.1	-14.6
F	0.25		26.37	17.6	-5.2
G	0.95	0.76	-0.76	-26.4	1.3
			Total California	-14.0	100.0

Table 7.9 Effect of practices of Scenario 2 in 5, 10 and 20-year time horizon, with projected changes in cow numbers across groups.

Practice adoption pattern

	Group size and type	Practice	Emission reduction per cow, adopting farm (%)	Cost per cow increase, adopting farm (%)	Percent adoption per group
A	<500 Freestall	2a	-86.6	9.0	40.0
B	<500 Non-freestall	2a	-65.3	9.3	40.0
C	500-2000 Freestall	3a	-24.3	1.3	40.0
D	500-2000 Non-freestall	3a	-23.2	1.0	40.0
E	>2000 Freestall	4a	-59.1	0.7	40.0
F	>2000 Non-freestall	3a	-23.2	0.8	40.0
G	Organic	2a	-86.2	3.2	40.0

Percentage changes for group in:

5-Year	Costs per cwt milk	Price of Milk	Quantity of milk	Methane Emission	Group's share of methane reduction
A	3.59	0.36	-29.07	-52.7	11.9
B	3.73		-29.36	-46.7	1.5
C	0.50		-7.56	-16.5	33.6
D	0.39		-7.33	-15.9	3.3
E	0.30		7.91	-17.6	47.8
F	0.34		7.82	-2.2	0.5
G	1.27	1.01	-0.51	-34.8	1.4
			Total California	-18.2	100.0
10 -Year					
A	3.59	0.32	-49.91	-64.7	14.3
B	3.73		-50.34	-60.3	1.9
C	0.50		-14.56	-22.8	45.6
D	0.39		-14.22	-22.1	4.6
E	0.30		14.75	-12.4	33.1
F	0.34		14.63	4.0	-0.9
G	1.27	0.95	-0.95	-35.1	1.3
			Total California	-18.5	100.0
20-Year					
A	3.59	0.36	-77.06	-79.6	17.4
B	3.73		-77.62	-77.1	2.4
C	0.50		-26.65	-33.6	66.6
D	0.39		-26.20	-33.0	6.7
E	0.30		26.56	-3.3	8.7
F	0.34		26.39	14.7	-3.2
G	1.27	1.01	-1.01	-35.1	1.3
			Total California	-18.7	100.0

Table 7.10 Effect of practices of Scenario 3 in 5, 10 and 20-year time horizon, with projected changes in cow numbers across groups.

Practice adoption pattern

	Group size and type	Practice	Emission reduction per cow, adopting farm (%)	Cost per cow increase, adopting farm (%)	Percent adoption per group
A	<500 Freestall	2a	-86.6	9.0	30.0
B	<500 Non-freestall	2a	-65.3	9.3	30.0
C	500-2000 Freestall	Digest.	-86.1	0.5	30.0
D	500-2000 Non-freestall	3a	-23.2	1.0	30.0
E	>2000 Freestall	Digest.	-82.6	0.1	30.0
F	>2000 Non-freestall	Digest.	-57.8	0.1	30.0
G	Organic	2a	-86.2	3.2	30.0

Percentage changes for group in:

5-Year	Costs per cwt milk	Price of Milk	Quantity of milk	Methane Emission	Group's share of methane reduction
A	2.69	0.15	-27.70	-45.6	7.8
B	2.80		-27.91	-41.1	1.0
C	0.15		-7.28	-31.2	48.0
D	0.29		-7.56	-14.0	2.2
E	0.03		8.02	-18.7	38.4
F	0.04		7.99	-10.7	1.8
G	0.95	0.76	-0.38	-26.1	0.8
			Total California	-24.1	100.0
10 -Year					
A	2.69	0.14	-47.79	-59.1	10.1
B	2.80		-48.11	-55.7	1.4
C	0.15		-14.08	-36.3	55.9
D	0.29		-14.49	-20.4	3.2
E	0.03		14.99	-13.5	27.7
F	0.04		14.95	-4.9	0.8
G	0.95	0.71	-0.71	-26.4	0.8
			Total California	-24.0	100.0
20-Year					
A	2.69	0.15	-74.31	-76.2	13.1
B	2.80		-74.74	-74.2	1.9
C	0.15		-26.10	-45.2	70.5
D	0.29		-26.65	-31.6	5.1
E	0.03		26.79	-4.5	9.4
F	0.04		26.73	4.9	-0.8
G	0.95	0.76	-0.76	-26.4	0.8
			Total California	-23.8	100.0

Table 7.11 Effect of practices of Scenario 4 in 5, 10 and 20-year time horizon, with projected changes in cow numbers across groups.

Practice adoption pattern

	Group size and type	Practice	Emission reduction per cow, adopting farm (%)	Cost per cow increase, adopting farm (%)	Percent adoption per group
A	<500 Freestall	2a	-86.6	9.0	5.0
B	<500 Non-freestall	2a	-65.3	9.3	10.0
C	500-2000 Freestall	Digest.	-86.1	0.5	20.0
D	500-2000 Non-freestall	3a	-23.2	1.0	15.0
E	>2000 Freestall	Digest.	-82.6	0.1	60.0
F	>2000 Non-freestall	Digest.	-57.8	0.1	30.0
G	Organic	2a	-86.2	3.2	10.0

Percentage changes for group in:

5-Year	Costs per cwt milk	Price of Milk	Quantity of milk	Methane Emission	Group's share of methane reduction
A	0.45	0.07	-23.38	-26.5	3.3
B	0.93		-24.35	-28.9	0.5
C	0.10		-7.35	-23.3	25.9
D	0.15		-7.43	-10.6	1.2
E	0.05		7.81	-45.6	67.6
F	0.04		7.83	-10.9	1.3
G	0.32	0.25	-0.13	-8.7	0.2
			Total California	-33.4	100.0
10-Year					
A	0.45	0.06	-41.29	-43.4	5.1
B	0.93		-42.74	-45.5	0.8
C	0.10		-14.15	-28.9	31.0
D	0.15		-14.28	-17.2	1.9
E	0.05		14.69	-42.1	60.4
F	0.04		14.72	-5.2	0.6
G	0.32	0.24	-0.24	-8.8	0.2
			Total California	-34.6	100.0
20-Year					
A	0.45	0.07	-65.67	-66.2	7.4
B	0.93		-67.61	-67.7	1.1
C	0.10		-26.22	-38.9	39.5
D	0.15		-26.40	-28.9	3.0
E	0.05		26.36	-36.2	49.2
F	0.04		26.40	4.5	-0.5
G	0.32	0.25	-0.25	-8.8	0.2
			Total California	-36.5	100.0

Table 7.12 Effect of practices of Scenario 5 in 5, 10 and 20-year time horizon, with projected changes in cow numbers across groups.

Practice adoption pattern

	Group size and type	Practice	Emission reduction per cow, adopting farm (%)	Cost per cow increase, adopting farm (%)	Percent adoption per group
A	<500 Freestall	3a	-24.2	1.6	5.0
B	<500 Non-freestall	3g	-23.4	1.9	10.0
C	500-2000 Freestall	Digest.	-86.1	0.5	20.0
D	500-2000 Non-freestall	3a	-23.2	1.0	15.0
E	>2000 Freestall	Digest.	-82.6	0.1	66.0
F	>2000 Non-freestall	Digest.	-57.8	0.1	35.0
G	Organic	3a	-22.0	0.7	10.0

Percentage changes for group in:

5-Year	Costs per cwt milk	Price of Milk	Quantity of milk	Methane Emission	Group's share of methane reduction
A	0.08		-22.67	-23.6	2.7
B	0.19		-22.90	-24.6	0.4
C	0.10	0.05	-7.37	-23.3	24.0
D	0.15		-7.46	-10.7	1.1
E	0.06		7.77	-51.0	70.1
F	0.05		7.79	-14.0	1.6
G	0.07	0.06	-0.03	-2.2	0.0
			Total California	-36.0	100.0
10 -Year					
A	0.08		-40.22	-40.9	4.5
B	0.19		-40.56	-41.8	0.7
C	0.10	0.05	-14.19	-28.9	28.7
D	0.15		-14.32	-17.3	1.8
E	0.06		14.64	-47.8	63.4
F	0.05		14.67	-8.5	0.9
G	0.07	0.05	-0.05	-2.3	0.0
			Total California	-37.4	100.0
20-Year					
A	0.08		-64.25	-64.6	6.7
B	0.19		-64.71	-65.2	1.0
C	0.10	0.05	-26.28	-38.9	36.4
D	0.15		-26.45	-28.9	2.8
E	0.06		26.28	-42.5	53.2
F	0.05		26.32	0.8	-0.1
G	0.07	0.06	-0.06	-2.3	0.0
			Total California	-39.7	100.0

Discussion

Adoption of manure management practices that reduce methane emissions per cow can be costly and if dairy farms bear those costs, the implication is likely to be some acceleration of the trend toward consolidation of the milk cow herd on fewer and larger herds. This is true in part because current regulations and earnings from using manure-generated methane as renewable natural gas mean digesters are a low-cost methane reducing option, especially on larger dairies. Indeed, in California digesters have been adopted most by the larger dairies and that has been especially true in the past few years in which the CDFA programs have stimulated more rapid adoption of digesters as a manure management strategy. Many smaller dairies find manure management strategies to reduce methane emissions reduction not cost effective and therefore are less economically sustainable.

This chapter began with an explanation of drivers of the future of the California dairy industry. Based on these forces, and the three-decade long trends in herd size patterns, we derived a set of projections for the next two decades. We project that the aggregate number of cows remains unchanged into the future, but the number of cows in the smaller herd size categories decline rapidly. The number of cows in the larger herd size rise, but not so rapidly in percentage terms because their herd size categories already account for most of the milk cows in California.

We next examine the impacts of our different scenarios of methane-reducing manure management practices in the context of our projections, including the underlying trends in number of cows in the different herd size categories.

We have discussed above the impacts of manure management scenarios, which each has a different pattern of adoption across groups of dairy farms with different housing and herd sizes. We find the impacts of the manure management practices remain, but in the longer time horizons manure management practices have small impacts, especially for the smaller dairies where they are dominated by the declining aggregate numbers of cows on the smaller farms.

Conclusions

Chapter 7 has placed our simulation modeling of Chapter 4 and the results introduced in Chapters 5 and 6 in the context of the steady long-term trend of reduced cow numbers on farms with smaller herd sizes and more cows on farms with larger herd sizes. We document that these trends have being on-going for at least three decades and, in fact, they have continued for much longer than that.

The most salient results of this chapter are exemplified by the implications of Scenario 5. This scenario illustrated a pattern of manure management practices in which smaller dairies have a relatively low adoption rate of practices that reduce emission by relatively small percentage amounts. There may be a set of digester-related practices that are suitable and cost-effective for smaller herd sizes, but we did not explore those in this study. In scenario 5, a high share of larger dairies adopt digester practices that, while relatively low cost to the dairies, have large methane reduction impacts. With a 5-year horizon aggregate reduction of methane emission reaches 36 percent. The groups with smaller dairies reduce emissions mainly because the number of cows in these have declined. The groups with larger dairies have more cows, but emission per cow declines enough that aggregate emissions also decline for these groups.

With longer time horizons, this pattern of results is reinforced and stronger. Especially over the 20-year horizon low-cost digester adoption among large dairies, together with little methane reduction among the smaller dairies, leads to an aggregate methane emission reduction of almost 40 percent. A part of the reduction in methane emissions is reinforced by a continuation of the trend toward consolidation that has been underway for decades.

Recommendations

The conclusions of this chapter suggest that trends to fewer dairies in the smaller herd size categories and more average cows per herd in larger herd size categories. In addition, with the adoption of digesters by a high share of dairies in the larger herd size categories their methane emissions per cow decline and are well below those of the smaller herds.

One implication is that it is unlikely to be effective to target methane reduction strategies on alternative manure handling practices of smaller dairies if the goal is to achieve low-cost reductions in methane emissions. Of course, there may be other social objectives for targeting methane reductions on smaller dairies, so this implication is not the only consideration.

REFERENCES

Arndt, C., A.B. Leytem, A.N. Hristov, D. Zavala-Araiza, J.P. Cativiela, S. Conley, C. Daube, I. Faloona, S.C. Herndon. 2018. Short-term methane emissions from 2 dairy farms in California estimated by different measurement techniques and US Environmental Protection Agency inventory methodology: A case study. *Journal of Dairy Science,* 101 (12):11461-11479. DOI: https://doi.org/10.3168/jds.2017-13881 .

ASAE (American Society of Biological and Agricultural Engineers). 2004. Uniform terminology for rural waste management. Standard 292.5, February. ASABE St. Joseph, MI.

Assembly Bill 32. 2006. California global warming solutions Act of 2006. September 27. Available http://www.leginfo.ca.gov/pub/05-06/bill/asm/ab_0001-0050/ab_32_bill_20060927_chaptered.pdf.

Bouchard, D. D. 2016. *An Analysis of Farm Profitability, Exit Decision, and Price Supports in the Maine Dairy Industry.*

Bragg, L. A., & Dalton, T. J. 2004. Factors affecting the decision to exit dairy farming: a two-stage regression analysis. *Journal of Dairy Science*, 87(9), 3092-3098.

California Air Resources Board. 2017. Short lived climate pollution reduction strategy. March. https://ww2.arb.ca.gov/sites/default/files/2018-12/final_slcp_report%20Final%202017.pdf .

California Air Resources Board. 2018a. Findings and Recommendations. Subgroup 1: Fostering markets for non-digester projects, Senate Bill 1383 Dairy and Livestock Working Group. November 26. https://ww3.arb.ca.gov/cc/dairy/dairy_subgroup_recommendations_to_wg_11-26-18.pdf. Accessed in January, 2020.

California Air Resources Board. 2018b. Dairy research prospectus to achieve California's SB 1383 climate goals. November 26. https://ww3.arb.ca.gov/cc/dairy/dsg3/dsg3_final_dairy_air_research_prospectus_11-26-18.pdf Accessed in January, 2020.

California Air Resources Board. 2019. Benefits calculator tool for the Alternative Manure Management Program. California climate Investments. Version 2. February 8. Available at https://ww2.arb.ca.gov/resources/documents/cci-quantification-benefits-and-reporting-materials .

California Air Resources Board. 2020. Sector GHG Emissions. https://www.arb.ca.gov/app/ghg/2000_2017/ghg_sector.php downloaded January 2020. Accessed in January 2020.

California Department of Food and Agriculture. 2018. California dairy statistics annual 2017 data. Division of Marketing Services, Dairy marketing Branch in collaboration with the United States Department of Agriculture. Also prior years of the same publications. No longer accessible online.

California Department of Food and Agriculture. 2020a. List of Award Recipients. https://www.cdfa.ca.gov/oefi/ddrdp/ . Accessed in January 2020

California Department of Food and Agriculture. 2020b. List of Award Recipients. https://www.cdfa.ca.gov/oefi/AMMP/. Accessed in January 2020

Cohen-Davidyan, T. D. Meyer, and P.H. Robinson. 2020. Development of an on-farm model to predict flow of fecal volatile solids to the liquid and solid handling systems of commercial California Dairy Farms. Waste Management 109: 127-135. https://doi.org/10.1016/j.wasman.2020.04.018 .

Foltz, J. D. (2004). Entry, exit, and farm size: assessing an experiment in dairy price policy. *American Journal of Agricultural Economics*, 86(3), 594-604.

Frick, F., & Sauer, J. (2018). Deregulation and Productivity: Empirical Evidence on Dairy Production. *American Journal of Agricultural Economics,* 100(1), 354-378.

IPCC (Intergovernmental Panel on Climate Change. 2006. Chapter 10: Emissions from livestock and manure management. https://www.ipcc-nggip.iges.or.jp/public/2006gl/pdf/4_Volume4/V4_10_Ch10_Livestock.pdf. Accessed January 15, 2020.

Kaffka, S., Barzee, T., El-Mashad, H., Williams, R., Zicari, S., & Zhang, R. 2016. Evaluation of Dairy Manure Management Practices for Greenhouse Gas Emissions Mitigation in California. Contract, 14.

Kaffka, S., Barzee, T., El-Mashad, H., Williams, R., Zicari, S. & Zhang, R. 2016. Evaluation of Dairy Manure Management Practices for Greenhouse Gas Emissions Mitigation in California. *Final Technical Report to the State of California Air Resources Board.*

Lee, Hyunok and Sumner, Daniel A. 2018. Dependence on policy revenue poses risks for investments in dairy digesters. *California Agriculture* (December)72(4):226-235. https://doi.org/10.3733/ca.2018a0037.

Lee, Hyunok, Sumner, Daniel A. and Champetier. Antoine. 2019. “Pollination Markets and the Coupled Futures of Almonds and Honey Bees: Simulating Impacts of Shifts in Demands and Costs.” American Journal of Agricultural Economics. 101(1): 230-249.

MacDonald, J. M., Cessna, J., & Mosheim, R. 2016. Changing structure, financial risks, and government policy for the US dairy industry (No. 1477-2017-3966).

MacDonald, J. M., McBride, W. D., O'Donoghue, E., Nehring, R. F., Sandretto, C., & Mosheim, R. 2007. Profits, costs, and the changing structure of dairy farming. *USDA-ERS Economic Research Report, (47).*

Matthews, W.A. and Sumner, Daniel A. 2019. Contributions of the California Dairy Industry to the California Economy in 2018 A Report for the California Milk Advisory Board. University of California Agricultural Issues Center. https://aic.ucdavis.edu/wp-content/uploads/2019/07/CMAB-Economic-Impact-Report_final.pdf

McCully, M. 2018. What's next for U.S. dairy plant capacity*? Cheese Market News* (August) https://cheesemarketnews.com/guestcolumn/2018/24aug18.html

Meyer, D., B. Reed, C. Batchelder, I. Zallo, P.L. Ristow, G. Higginbotham, M. Arana, T. Shultz, D.D. Mullinax, J. Merriam. 2006. Water use and winter liquid storage needs at central valley dairy farms in California. Applied Eng. Ag. 22: 121-126.

Meyer, D., I. Garnett & J.C. Guthrie. 1997. A survey of dairy manure management practices in California. J. Dairy Science, 80, 1841-1845. https://doi.org/10.3168/jds.S0022-0302(97)76119-8

Meyer, D., Price, P. L., Rossow, H. A., Silva-del-Rio, N., Karle, B. M., Robinson, P. H., DePeters, E.J. & Fadel, J. G. 2011. Survey of dairy housing and manure management practices in California. Journal of Dairy Science, 94, 4744–4750. https://doi.org/10.3168/jds.2010-3761.

Meyer, D., J. Heguy, B. Karle and P Robinson. 2019. Characterize physical and chemical properties of manure in California dairy sytems to improve greenhouse gas (GHG) emission estimates. Final Report Contract No. 16RD002.

Meyer, D., personal conversation, March 2020a. Conversation referenced information from a dairy farmer with freestall housing. Farmer provided herd size and invoices for the contractor service, itemized by date and number of loads excavated.

Meyer, D., personal conversation, March 2020b. Conversation referenced information provided by a dairy farmer with an open lot facility. Farmer provided herd size and a times per activity commensurate with the manure management on the open lot facility.

Mosheim, R., & Lovell, C. K. 2009. Scale economies and inefficiency of US dairy farms. American Journal of Agricultural Economics, 91(3), 777-794.

Newtrient. https://newtrient.com .

Perrin, Richard K. 1980. "The Impact of Component Pricing of Soybeans and Milk." American Journal of Agricultural Economics 62 (3): 445–55.

Rickard, Bradley J. and Sumner, Daniel A. 2008. Domestic Support and Border Measures for Processed Horticultural Products: Analysis of EU Tomato Protection and Subsidies. American Journal of Agricultural Economics, 90(1): 55-68.

San Joaquin Valley Dairy Manure Technology Feasibility Assessment Panel. 2005. An assessment of technologies for management and treatment of dairy manure in California's San Joaquin Valley. December. Available https://ww3.arb.ca.gov/ag/caf/dairypnl/dmtfaprprt.pdf

San Joaquin Air Pollution Control District. 2004. Rule 4550. Conservation Management Practices. Re-adopted August 19, 2004. https://www.valleyair.org/rules/currntrules/r4550.pdf .

San Joaquin Air Pollution Control District. 2010. Rule 4570. Confined Animal Facilities. Re-adopted June 18, 2009. Amended October 21, 2010. https://www.valleyair.org/rules/currntrules/R4570_1010.pdf .

Senate Bill 32. 2016. California Global Warming Solutions Act of 2006: emissions limit. September 8. Available:https://leginfo.legislature.ca.gov/faces/billTextClient.xhtml?bill_id=201520160SB32 .

Senate Bill 1383. 2016. Chapter 395. September 19. Available: https://leginfo.legislature.ca.gov/faces/billNavClient.xhtml?bill_id=201520160SB1383

South Coast Air Quality Management District. 2004. Rule 1127. Emission reductions from livestock waste. Adopted August 6. http://www.aqmd.gov/docs/default-source/rule-book/reg-xi/rule-1127.pdf.

Stokes, J. R. 2006. Entry, exit, and structural change in Pennsylvania's dairy sector. *Agricultural and Resource Economics Review*, 35(2), 357-373.

Sumner, D.A., and N.L.W. Wilson. 2000. Creation and Distribution of Economic Rents by Regulation: Development and Evolution of Milk Marketing Orders in California. *Agricultural History* 74(2):198–210.

Sumner, D. A. (2014). American farms keep growing: Size, productivity, and policy. *Journal of Economic Perspectives*, 28(1), 147-66.

Sumner, Daniel A. 2018. New California Milk Marketing Regulations Will Not Change Economic Fundamentals *Choices.* 4th Quarter 2018. 33(4).

Susanto, D., Rosson, C. P., Anderson, D. P., & Adcock, F. J. (2010). Immigration policy, foreign agricultural labor, and exit intentions in the United States dairy industry. *Journal of Dairy Science*, 93(4), 1774-1781.

Tauer, L. W. (2006). When to get in and out of dairy farming: a real option analysis. *Agricultural and Resource Economics Review*, 35(2), 339-347.

United State Department of Agriculture. 2019 State agriculture overview, Livestock inventory January 1, 2020. https://www.nass.usda.gov/Quick_Stats/Ag_Overview/stateOverview.php?state=CALIFORNIA

University of California Agriculture and Natural Resources Dairy Advisor, personal conversation, (March 2020). Conversation between author and dairy adviser with expertise in compost bedded pack barns.

United States Department of Agriculture, National Agricultural Statistics Service. 1974. Table 21.Cattle and Calves—Inventory and sales: 1074 and 1069. http://usda.mannlib.cornell.edu/usda/AgCensusImages/1974/01/51/305/Table-21.pdf .

United States Department of Agriculture, National Agricultural Statistics Service. 2017. Table 17. Milk cow herd size by inventory and sales: 2017. http://usda.mannlib.cornell.edu/usda/AgCensusImages/1974/01/51/305/Table-21.pdf

United States Department of Agriculture, National Agricultural Statistics Service, Agricultural Census, (2017). Available at https://www.nass.usda.gov/AgCensus/ accessed February 2020.

United States Department of Agriculture, National Agricultural Statistics Service, 2018. *Milk Production, Disposition and Income, 2017 Summary*. Washington, DC: U.S. Department of Agriculture, April.
http://usda.mannlib.cornell.edu/MannUsda/viewDocumentInfo.do?documentID=1105

United States Environmental Protection Agency. 2012. Part 122. EPA Administration Programs: the National Pollutant Discharge Elimination System. Clean Water Act, 33 U.S.C. 1251 *et seq.* Compiled CAFO Final Rule. July 30. https://www.epa.gov/sites/production/files/2015-08/documents/cafo_final_rule2008_comp.pdf . Accessed March, 2020.

Vacuum scraper manufacturer engineer, personal conversation, (March 2020). Telephone conversation between author and engineer for vacuum scraper manufacture.

Weiss, W. P., St-Pierre, N. R., & Willett, L. B. (2007). Factors affecting manure output on dairy farms. *Tri-State Dairy Nutrition Conf*erence, Ft. Wayne, (pp. 55-62).

APPENDIX 1 OUTREACH ACTIVITIES

Outreach activities for this project were conducted through a presentation at the Golden State Dairy Management Conference, the California Dairy Newsletter (information about the AMMP program as well as specific information from the grant products), and handouts prepared for the California Dairy Sustainability Summit originally to be held in March, 2020 and now postponed. An abstract for a poster for the California Dairy Sustainability Summit was accepted.

Meyer, D., Z. Joaquin-Morales, J. Heguy, B. Karle, P. L. Price, C. Miller, D. Mullinax. 2020. Manure management practices on California dairies. Presented at the Golden State Dairy Management Conference. March 4, 2020. Modesto. Available online.

Meyer, D., J. Heguy, B. Karle, Z. Joaquin Morales. 2020. What do California dairies look like? California Dairy Newsletter. Vol 11 Issue 4. November. Available online (pdf download).

Meyer, D. 2018. Buyer beware: homework is important when reducing methane emissions. California Dairy Newsletter. Volume 10 Issue 3. September. Available online (pdf download).

Meyer, D. 2018. Funding available to reduce manure methane emissions. California Dairy Newsletter. Vol 10 Issue 4. December. Available online (pdf download).

Meyer, D. 2020. Funds available for dairies to reach 40% reduction in greenhouse gases. California Dairy Newsletter. Vol 12 Issue 1. February. Available online (pdf download).

Handouts for the California Dairy Sustainability Summit.

- Price, P.L., D. Meyer. 2020. Scrape/Vacuum conversion with windrow composting.
- Price, P.L., D. Meyer. 2020. Scrape/Vacuum conversion with open solar drying.
- Price, P.L., D. Meyer. 2020. Solids separation with windrow composting.
- Price, P.L., D. Meyer. 2020. Solids separation with open solar drying.