The Low Carbon Fuel Standard and Dairy Practices in the San Joaquin Valley

Manure, Biomethane, and Air Quality

Jill Nicholls PhD
May 22, 2023

Disclaimer
This report was prepared for the Center for Law, Energy & the Environment (CLEE), a climate policy research group based at UC Berkeley School of Law, to support CLEE's ongoing work on methane policy. The study was conducted as part of the program of professional education at the Goldman School of Public Policy, University of California, Berkeley. This paper is submitted in partial fulfillment of the course requirements for the Master of Public Affairs degree. The conclusions are solely those of the author and are not necessarily endorsed by the Goldman School of Public Policy, by the University of California, or by any other agency, entity, or individual.

About the author
The study provided an opportunity to analyze a complex policy problem that included issues of environmental justice, climate change, air quality, and agricultural practices in the San Joaquin Valley. My Doctorate in nutrition science at UC Davis led to employment at the National Dairy Council for 16 years in public health nutrition policy and regulatory affairs. After leaving NDC in 2020, my goal was to learn more about food systems, energy, and climate, which this project helped me to accomplish. I do not represent or claim to speak for the environmental justice community, dairy producers, or California's Air Resources Board.

Table of Contents

I. EXECUTIVE SUMMARY

California has a history of implementing ambitious environmental policies, including an early emphasis on greenhouse gas (GHG) reduction. As part of this strategy, SB 1383, passed in 2016, mandated a 40% reduction from 2013 levels in methane emissions from dairy cows—the leading source of methane emissions in the state—by 2030. The California Air Resources Board (CARB) employed the Low Carbon Fuel Standard (LCFS), a market-based program designed to decrease the carbon intensity of the state's transportation fuels, to incentivize biomethane production from dairy manure. To participate, dairies employ an anaerobic digester to capture manure biogas that can be purified into biomethane for transportation fuel. These dairies are largely located in the San Joaquin Valley, which is home to about 90% of California's 1.7 million dairy cows, as well as some of the worst air quality in the nation.

The research question:

- **What are the impacts of dairy LCFS credits on methane emissions, dairy farm consolidation, and Valley air pollution?**

This project started with an analysis of perspectives of three key stakeholder groups and finished with a policy analysis and recommendations to improve the LCFS. The author chose the groups based on their different views about the impacts of LCFS dairy credits. Please note that summaries of stakeholder views are the author's own, based on research, and the author is not intending to resolve or align the different viewpoints of the stakeholders:

- **Environmental Justice (EJ) advocates and the communities they represent**
- **Dairy producers**
- **CARB**

The most notable differences across stakeholder perspectives were about the effectiveness and equity (accounting for financial benefits and local environmental impacts) of LCFS dairy credits. EJ advocates oppose the credits, dairy producers would prefer they continue, and CARB is in the process of LCFS rulemaking to be finalized in 2024. CARB has indicated changes may include modifying how biomethane carbon intensity is determined and developing policies to support biomethane demand in the future. Though stakeholders do not disagree that the LCFS reduces methane, disagreements emerge about other outcomes.

Report Conclusions:

1. LCFS dairy credits are significantly larger than those for other alternative fuels; the LCFS has increased dairy producer participation and dairy methane reductions. The LCFS rewards a dairy for (1) preventing manure methane from escaping into the atmosphere, and (2) producing biofuel that contributes to California's low-carbon fuel pool. The avoided methane emissions provide most of the value to dairy biomethane credits, a benefit available to dairies but not to other alternative fuel producers. More than 200 anaerobic digester projects have been constructed since SB 1383 passed, using both public and private funding. Expert reports from CARB and UC Davis disagree about the projected biomethane reductions that will be reached by 2030, but both recognize the significant contributions of dairy to livestock reductions. Though the LCFS reduces manure methane, it's role in air quality is contentious, especially since it was not designed to directly reduce dairy air pollutants.

2. Because LCFS dairy credits are large, dairy farms may change their practices to grow biogas revenues, such as by increasing herd consolidation. If consolidation rates increase, increased dairy air pollution and exposure of disadvantaged communities may increase environmental harm for Valley residents. Disadvantaged communities living near high concentrations of dairies report odors and air pollution, and EJ advocates contend that LCFS incentivizes consolidation and its consequences, especially by dairy operations associated with digesters and biomethane production facilities. The LCFS was implemented without simultaneous efforts to address local dairy air pollution and other community priorities, leading to resistance to the program by the EJ community. Consolidation—fewer but larger farms—is a longstanding trend for dairies in California. The state's average herd size has been increasing for decades, while the total cow population has been stable since 2007 and is expected to gradually decline in coming years. The average dairy herd size has not increased since SB 1383 passed, but consolidation plus additional dairy/biomethane industry characteristics would provide a more complete picture of LCFS impacts looking ahead.

***3. Larger dairies can better afford to build and manage digesters, and therefore generate more revenue from the LCFS than smaller dairies without digesters*.** Digester subsidies, biogas revenue, and cost savings from economies of scale give larger dairy farms advantages compared to small farms. Smaller dairies without digesters manage their manure using non-digester or "alternative" management practices that do not yield revenue from the LCFS. Smaller dairies without digesters may be at a disadvantage and would benefit from having revenue-generating opportunities from manure management. California supports research and development to improve alternative practices; strengthening evidence on best manure management practices aids all dairies and should continue. Larger dairies have more cows and produce most of the state's dairy methane, while smaller dairy farms represent more dairy farmers but produce less methane. Smaller dairy farm operations should have opportunities to implement environmental policies without disadvantage.

4. Novel approaches that reduce GHG emissions and air pollution equitably and simultaneously would provide a more durable solution. Air pollution and climate change occur together, but they are managed by different agencies and policy frameworks. It is well-recognized that co-benefits from GHG emission reduction programs can improve air quality and public health, and these benefits can offset costs of GHG mitigation, but more can be done. Increasingly, climate change and air pollution are recognized as problems that can be more effectively addressed simultaneously. In the context of the LCFS, methane reduction, and air quality, dairies may be good candidates for a combined approach. Proposing policy alternatives to address this combined approach in depth is beyond the scope of this analysis, yet this conclusion represents an important outcome.

Policy recommendations to limit LCFS' negative impacts:

- Develop and implement policies to co-reduce dairy methane *and* ammonia using lessons learned from the LCFS to reduce Valley air pollution and GHG emissions
- Implement alternative financial mechanisms to manage risk for dairies and stabilize the LCFS biomethane market consistent with California's 2045 goals
- Continue research and development to improve dairy manure methane reduction, including digester and non-digester approaches and technologies
- Increase accuracy of dairy emission measures, with and without digesters, to improve air quality models: increase dairy emission monitoring and establish dairy contributions to emission inventories

Dairy producers are part of a food and agricultural system with environmental, social, economic, and health impacts in the Valley as well as national—and broader—implications. Dairies produce milk and dairy products, and they contribute to methane, ozone, particulate matter, ammonia, VOCs, and odor levels in different ways, including interactions between GHGs and air pollutants:

- Ozone is a criteria air pollutant and a GHG, and methane reduction can help reduce local ozone over the short-term and global ozone over the long-term
- Dairy manure methane reduction with anaerobic digestion may come at the expense of increased ammonia emissions from digestate; ammonia is an important agricultural air pollutant and a particulate matter precursor

Dairy emission reduction efforts highlight a specific example of a broader need for better integration across climate change and local air quality policies. California methane emissions are managed in California by CARB yet have global consequences. Valley air pollution is primarily a local issue managed by the San Joaquin Valley Air Pollution Control District together with US EPA and CARB. Given the multiple impacts dairies have on the Valley environment, mitigating dairy GHG and air pollutant emissions together may be a more effective way to reduce emissions. Because disadvantaged communities disproportionately experience climate change and air pollution impacts, improved mitigation can lead to benefits for these communities.

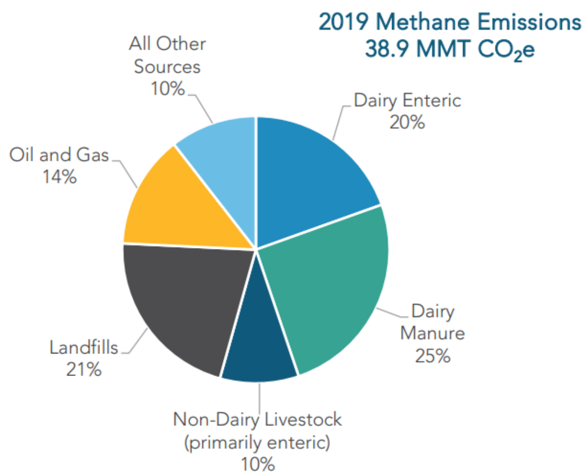
II. INTRODUCTION

The Problem

California has been a leader in creating policy solutions to address climate change, air quality, and environmental protection for decades and, in the process, influencing climate leaders across the U.S. and globally. The state's 2022 Scoping Plan for Achieving Carbon Neutrality sets a goal for cutting carbon emissions by 48% by 2030 and reaching carbon neutrality by 2045 (CARB, November 16, 2022; AB 1279).

California is second in the nation, after Texas, for total GHG emissions. Emissions from transportation, industry, and electricity make up about 75% of the total, while commercial and residential, agriculture, and forestry emissions make up the remaining 25%. Agriculture contributes 9% of California's GHG emissions, most of which is methane. Methane is a colorless, odorless GHG that accounts for up to 30% of Earth's warming (UNEP & CCAC, 2021). Methane forms during bacterial decomposition of organic material in the absence of oxygen.

Figure 1: California's Methane Emissions by Source (2019)



Source: Carb, 2022 Scoping Plan to Achieve Carbon Neutrality

Dairy cows produce methane in their rumen and emit it as burps, known as enteric emissions. Dairies also emit methane from pooled manure as it decomposes during storage. From these sources, dairy emissions contribute about half of California's methane (see Figure 1). California is home to 1.7 million dairy cows and is the most productive dairy state in the U.S. California dairies are largely located in the San Joaquin Valley (Valley) (Sumner, 2020).

The Low Carbon Fuel Standard (LCFS) is one of a suite of California programs designed to reduce GHG emissions. It aims to reduce the carbon intensity (CI) of transportation fuels in California. The California Air Resources Board (CARB) oversees the LCFS and uses a system of fuel deficits and credits to reward producers of alternative, low-carbon fuels. In 2016, California's SB 1383 mandated livestock methane reductions of 40% of 2013 levels by 2030. CARB employed the LCFS to help dairies meet manure methane reduction goals.

This report aims to describe and assess the evidence supporting the perspectives about LCFS dairy credits of three main stakeholder groups:

- Environmental Justice advocates and the communities they support
- Dairy Producers
- California's Air Resources Board

The report will analyze impacts of LCFS dairy credits on dairy methane reduction, dairy consolidation, dairy air pollution, and exposure of disadvantaged communities (DAC) to air pollution in the Valley. Please note the author is not intending to resolve or align the different viewpoints of stakeholders. Instead, the author will describe each stakeholder group's perspective and offer insight into policy recommendations that may be of interest for all three groups. Background on all groups is provided below.

The Stakeholders

Environmental Justice advocates (**EJ advocates)** work to empower underserved communities and improve their environment and quality of life. In the Valley, many groups have been active representing the DAC perspective about the LCFS, including but not limited to Leadership Counsel for Justice and Accountability, Central California Environmental Justice Network, and the Central Valley Air Quality Coalition. The Valley is home to a higher proportion of DACs than the rest of the state, and the Valley's unique social, economic, and environmental landscape contributes to the disproportionate burdens they experience. Valley EJ advocates have opposed CARB's market-based approach to meeting the state's 2030 dairy methane reduction goals because generous dairy subsidies may lead to larger farms that increase air pollution and harm Valley communities. CARB's efforts to incentivize biomethane production without also directly addressing dairy contributions to Valley ozone and fine particulate matter ($PM_{2.5}$), have led some EJ advocates to request California to exclude dairies from the LCFS and to replace avoided emissions accounting with direct regulations to meet 2030 methane reduction goals (Lazenby et al., October 27, 2021; Seaton et al., March 15, 2023).

Dairy is the top agricultural commodity in California, and dairies in the eight Valley counties produce 20% of milk in the U.S. Methane reduction is a top global priority to reduce climate change. U.S. dairies have been growing and increasing production efficiency (milk per cow) for decades, and California has led the trend. Standard practice for dairies is to flush manure from free-stall barns and store it in open lagoons, which allows biogas—about 70% methane—to escape into the air. The LCFS rewards dairies for capturing biogas with an aerobic digester and turning it into pipeline-injectable biomethane. CARB's LCFS supports California dairies to achieve the state's 2030 methane reduction goals and national dairy industry goals to achieve GHG neutrality by 2050 (U.S. Dairy Net Zero Initiative). California dairies support the continuation of the LCFS program to reduce methane emissions at dairies (Dairy Cares, March 15, 2023).

CARB has responsibility for programs and policies to reduce air pollution and fight climate change. The LCFS originated from the Global Warming Solutions Act of 2006, AB 32, and was designed to decrease the CI of California's transportation fuels. British Columbia, California, and Oregon were the first to pass legislation to increase low CI fuels, and Washington recently passed a Clean Fuel Standard. New Mexico, Minnesota, Illinois, and Massachusetts are considering similar legislation. CARB employed the LCFS to incentivize dairies, the leading methane source in California, to reduce manure methane and meet the 2030 statutory goal in SB 1383. In addition to reducing dairy methane, the LCFS aimed to limit dairies from moving out of California to other states. While this approach has been effective to reduce methane during early stages of the LCFS, rulemaking to modify the LCFS is underway, and CARB is expected to vote on proposed changes in 2024.

III. STAKEHOLDER PERSPECTIVES

This section summarizes publicly expressed perspectives by the three stakeholders about the LCFS program based on the author's research analyzing public comments, websites, and publicly available reports. These points were chosen to highlight different interpretations of LCFS dairy credits and their implications.

EJ Advocates

- LCFS dairy credits are overvalued
- LCFS dairy credits can create perverse incentives that lead to dairy herd growth to maximize biogas profit
- Dairy consolidation will result in increased dairy air pollution exposure by EJ communities

Dairy Producers

- External market forces determine dairy consolidation rates
- Large dairy herds are more efficient at milk production and methane reduction
- Anaerobic digesters will improve overall air and water quality

California Air Resources Board

- LCFS dairy biomethane CI scores reflect the difference between current manure management practices and captured methane emissions; they have been effective to reduce dairy methane during the voluntary phase of LCFS
- In the near-term, LCFS dairy biomethane will be used less for transportation fuel, and in the long-term, complementary policies will support future dairy biomethane demand
- 2024 rulemaking will include LCFS modifications for dairy biomethane

IV. CRITERIA FOR POLICY EVALUATION

The author chose the criteria below to evaluate the LCFS policy alternatives proposed in this report. These criteria prioritize values that minimize air pollution and climate change, while minimizing disproportionate environmental harm to California communities. The criteria will be used to determine to what extent policy alternatives represent these values.

Criteria:

- LCFS incentives are effective to reduce methane
- LCFS incentives minimize harm to the environment or local communities
- LCFS incentives minimize harm to smaller dairies without digesters
- LCFS incentives are acceptable to key political actors in California

> *"In the context of EJ, fairness means that the benefits of a healthy environment should be available to everyone, and the burdens of pollution should not be borne by sensitive populations or communities that already experience its adverse effects."*
>
> *California Attorney General Bonta*

V. METHODS

Literature Review

This analysis reviewed publicly available peer-reviewed literature and grey literature such as government, technical, and research reports; press releases; and policy briefs. Reference inclusion criteria comprised:

- References published or released after AB 32 (2006); Google Scholar was the main search engine used to locate peer-reviewed literature
- Newer, directly-relevant studies, e.g., studies conducted in California, when available
- Peer-reviewed research studies and reviews
- Publicly-available agency publications, e.g., from CARB, US Environmental Protection Agency (EPA), and California Department of Food and Agriculture (CDFA)

Interviews

Select expert interviews were conducted to provide background about topics new to the author. Experts included a Clean Air Act lawyer at the UC Berkeley Goldman School of Public Policy, an Associate Professor of Environmental Science and Management at Cal Poly Humboldt, and an environmental justice research and policy expert who lives and works in the Valley.

Analytical Framework

The primary purpose of this report is to describe and assess the perspectives of the key stakeholder groups. As a student of policy analysis, the author deployed some of the tools described in the *Eightfold Path for Policy Analysis* (Bardach). The author developed criteria to evaluate, compare, and make recommendations among policy alternatives (see Section VIII).

Scope

This report focuses on the LCFS and dairy impacts regarding methane and air pollution emissions. Due to limited resources, it does not cover Valley water issues in depth, LCFS impacts on overall GHG reductions, and animal welfare, or sustainable farming or dietary practices.

Limitations

The publicly available literature available on topics covered, such as Valley air quality, Valley agricultural history, Valley environmental justice, California and U.S. dairy economic and environmental impacts, the Clean Air Act, and biogas production for fuel was extensive. A limitation of this report is that it was not possible to comprehensively review the literature on all topics in the time available. In addition, resources to conduct multiple primary interviews with members of the EJ community were not available, so narrative accounts were obtained from recordings of public comments delivered to CARB and in published literature.

VI. LITERATURE REVIEW: ANALYSIS AND FINDINGS

The literature review forms the basis for report conclusions and recommendations. It reviews the following six topics to provide context, clarification, and assess stakeholder perspectives:

- California's Policy Landscape
- Context: The San Joaquin Valley and Key Stakeholders
- Low Carbon Fuel Standard 101
- Financial Incentives and Dairy Practices
- The LCFS and California's 2030 Methane Reduction Goals
- Dairy Emissions and San Joaquin Valley Air Pollutants of Concern

California's Policy Landscape

California's Climate Change Policies

California's Climate Policy Framework			
GHG Targets & Goals	Scoping Plan	Regulations & Incentives	Projects
Legislation and Executive Orders: Total GHGs (AB 32/ SB 32/AB 1279) or sector targets (SB 1383)	Actionable plan across all sectors	Advanced Clean Cars, Low Carbon Fuel Standard, climate change incentives, etc.	Examples: Zero-emission trucks, energy infrastructure & renewables, compost facilities, digesters, etc.

Source: Adapted from CARB, 2022 Scoping Plan for Achieving Carbon Neutrality

AB 32 (2006)		
Decrease GHG 1990 levels by 2020	Maximize Air Quality Co-Benefits	Align with Environmental Justice Principles

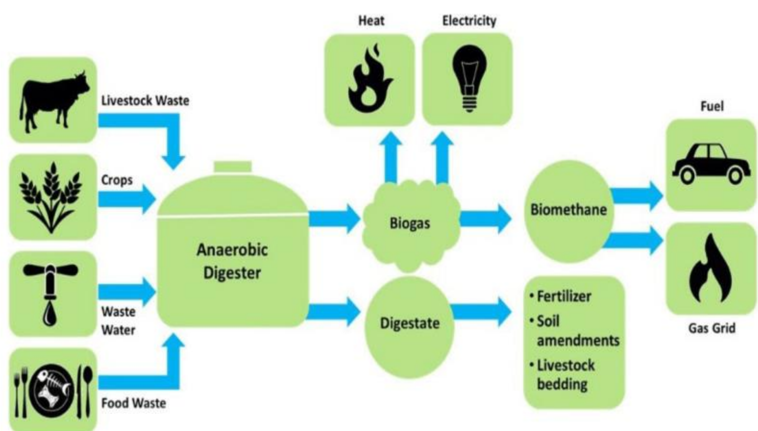
AB 32, the Global Warming Solutions Act, was landmark legislation signed into law in 2006 by Governor Schwarzenegger that was updated in 2016 (SB 32) and 2022 (AB 1279). Though focused primarily on GHG reductions, it also required CARB to address air quality and engage marginalized communities in policy-making in new ways. Achieving all three goals in a coordinated way remains a work in progress.

SB 1383 (2016)		
Decrease dairy methane 40% of 2013 levels by 2030 Dairy goal: 7.2 $MMTCO_2e$	**Use DDRDP & AMMP to manage manure methane**	**Divert 75% of organic waste from landfills**

SB 1383, the Short-Lived Climate Pollutant Strategy, was signed into law in September 2016 by Governor Brown. It included methane reduction goals for livestock of up to 40% of 2013 levels by 2030, an annual reduction of 7.2 million metric tons of carbon dioxide equivalents ($MMTCO_2e$) from dairy, and diversion of 75% of organic waste from landfills by 2025.

CARB worked with CDFA to develop the Dairy Digester Research and Development Program (DDRDP) to support anaerobic digester construction, which complements the LCFS because it is currently the most effective method to reduce manure methane. An anaerobic digester is a closed system that uses bacteria to break down organic matter to produce biogas (see Figure 2). Biogas and digestate are co-products, and biogas is purified to produce biomethane. The complementary Alternative Manure Management Program (AMMP) funds non-digester manure management projects to reduce methane.

Figure 2: Anaerobic Digester Inputs and Outputs



Adapted from: EESI Fact Sheet

Scoping Plan to Achieve Carbon Neutrality (2022)		
Decrease GHG 48% by 2030	**Decrease GHG 85% by 2045**	**Reach carbon neutrality by 2045**

The 2022 Scoping Plan outlines how California will reach carbon neutrality by 2045. The Proposed Scenario recommended by CARB includes methane reduction via biomethane production as a strategy.

- ***Federal Air Quality Policy: The Clean Air Act (1970s-1990)***

The EPA oversees the Clean Air Act and establishes federal standards for six common or "criteria" air pollutants (EPA, 2002). Federal, state, and local agencies work together to develop plans to reduce air pollution in California. Criteria pollutants can be emitted from mobile source e.g., cars, trucks, and trains; stationary sources e.g., oil refineries, power plants, and agriculture; and area-wide sources e.g., dust and burning. The three agencies are responsible for managing different air pollution sources.

The Valley has some of the worst air quality in the country. CARB and the San Joaquin Valley Air Pollution District are responsible for developing the Valley's State Implementation Plans to attain federal air quality standards for criteria pollutants. The Plans are approved by EPA and implemented by state and local agencies. Ozone and $PM_{2.5}$ are the two criteria pollutants of most concern in the Valley.

Ozone. Ground-level ozone, also known as smog, is created by photochemical reactions between oxides of nitrogen (NOx) and Volatile Organic Compounds (VOC).

$PM_{2.5}$. Fine particulate matter is a complex mixture of components that occur in tiny particles that enter the body through the lungs and bloodstream. In addition to direct emissions of $PM_{2.5}$ from fuel combustion, the leading source according to CARB, fine particle components are formed from various precursors, for example, airborne ammonia and nitric acid can react to form ammonium nitrate.

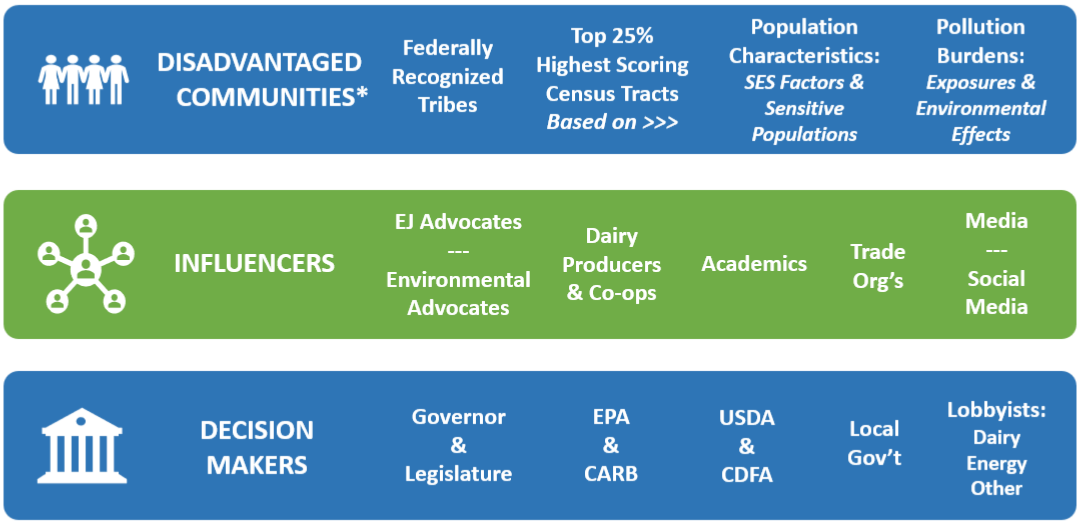
Context: The San Joaquin Valley and Key Stakeholders

- ***Stakeholder Location: The Valley***

The San Joaquin Valley is an agriculturally-rich region in Central California that encompasses eight counties. It is 400 miles from north to south and includes more than 17 million acres, 5 million of which are farmland. Agriculture is its main economic driver, producing $51 billion in cash receipts in 2021 (CDFA, 2021). The Valley's 4.3 million population is diverse and growing. The Valley is facing social, economic, and environmental challenges that inform stakeholder perspectives about the LCFS.

Of the 400 agricultural commodities produced in the Valley, milk is the top commodity (CDFA, 2021). In addition to agriculture, oil and gas extraction, and transportation are other major employers (Westerling et al., 2018). The surrounding mountain ranges exacerbate air pollution. The Sustainable Groundwater Management Act (SGMA) implementation plan is underway and set to conclude in 2042, including groundwater cut-backs and approximately 500,000 acres of fallowed land (Escriva-Bou et al., 2023). Residents of rural Valley communities often depend on agricultural employment, though labor shortages have become more common following COVID. Agriculture also contributes to air and water pollution. Dairies, for example, have contributed to depleted groundwater tables and groundwater contamination with manure nitrogen, a grave issue for rural communities who rely on wells for drinking water.

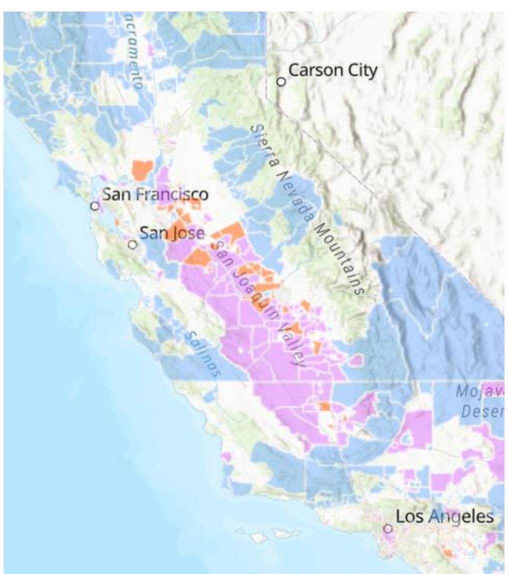
Figure 4: LCFS Biogas Stakeholders in the San Joaquin Valley



*Disadvantaged Communities as defined according to CalEnviroScreen 4.0, CalEPA (2021)

- ***Context: EJ Advocates & the Communities They Serve***

Figure 5: California's Disadvantaged and Low-Income Communities



Source: https://webmaps.arb.ca.gov/PriorityPopulations/

Disadvantaged Communities (DAC)

DAC and Low-Income Communities

Low-Income Communities

The Valley has low socioeconomic conditions compared to the rest of the state (see Figure 5). DACs experience disproportionate amounts of pollution, environmental degradation, and socioeconomic and public health conditions, as defined by CalEnviroScreen (August et al., 2021). Six of the top 10 DACs in California are in the Valley, and Latinos are over-represented in the 10% most impacted census tracts. Rural DACs often do not have basic services such as safe, dependable, and affordable drinking water, sewage systems, and health care, and limited communication and transportation infrastructure leaves them isolated (Westerling et al., 2018).

California defines Environmental Justice as “the fair treatment and meaningful involvement of people of all races, cultures, income, and national origins with respect to the development, adoption, implementation, and enforcement of environmental laws, regulations, and policies” (AB 1628). Air pollution is top-of-mind for Valley DAC members. Valley DACs identified air quality as the “most threatening” issue in recent interviews (Flores-Landeros et al., 2022). Burdens that DACs experience can be exacerbated by climate change, including water quality and availability, air quality, pesticide drift, flooding, and access to healthy foods (Fernandez-Bou et al., 2021).

In 2003, Valley advocates formed the Central Valley Air Quality Coalition (CVAQ) to address environmental, environmental justice, and public health topics (Lighthall & Capitman, 2007). The same groups remain active today and collaborate with new organizations. The CVAQ and 14 additional organizations, for example, co-signed public comments about the LCFS and EJ submitted to CARB in March 2023 (Seaton et al., March 15, 2023).

Some of these groups were engaged in EJ issues during early AB 32 implementation, when disagreements arose about how to reduce air pollution and GHG emissions equitably (London et al., 2013; Fowlie et al., 2020).

> *“It is market-based decisions, within a framework of structural racism in planning and zoning decisions, which has created the disparate impact of pollution that exists today; relying on that same mechanism as the ‘solution’ will only deepen the disparate impact” (In: London et al., 2013).*
>
> *‘‘Some environmental justice advocates are concerned that some market-based strategies, such as cap-and-trade, may lead to a situation where low-SES and minority communities would bear a continued – or potentially exacerbated – disproportionate burden of co-pollutant hotspots at the local community level’’ (Shonkoff et al., 2009).*

Similar themes persist regarding the LCFS among EJ advocates and DACs. The experience of the community of Pixley helps to illustrate this point. Pixley is an unincorporated community of about 4,400 residents in Tulare County. The community is 89% Hispanic, and the census tract is in the 97th percentile for poverty, meaning the percent of people living below twice the poverty level is more than 97% (OEHHA).

Pixley dairies are part of a digester cluster connected to a biogas purification center run by Calgren Dairy Fuels. The Calgren project collects biogas from anaerobic digesters at 12 dairies housing 75,000 cows. In 2019, the facility was the largest dairy biogas project in the nation. Pipeline-injectable biomethane produced from manure biogas is injected into SoCalGas’ natural gas network and delivered to refueling stations in California. The project was primarily funded privately, but it received incentives from California’s DDRDP and the California Public Utility Commission’s Biomethane Incentive Program (SoCalGas, 2019).

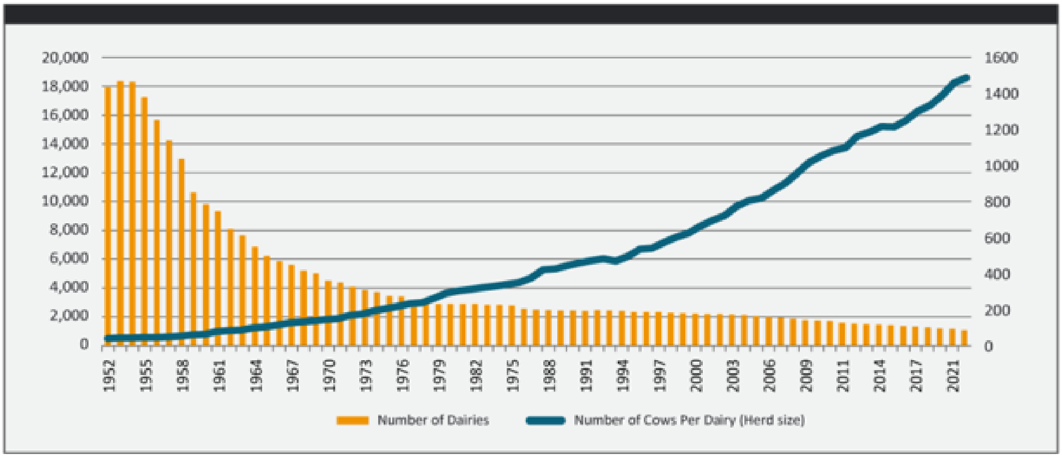
> *"There is a constant smell of manure that only worsens during hot weather and in the rain. We need to stop incentives for dairy expansion. The state needs to stop giving money to this industry that is hurting us. Our community is in need, and we receive nothing."*
>
> J. Gonzales, Pixley resident, in Oral Comment delivered during CARB Public Workshop to Discuss Potential Changes to the Low Carbon Fuel Standard; February 22, 2023

- ***Stakeholder Context: Dairy Producers***

Milk is the top agricultural commodity in California based on revenue, and the eight Valley counties, combined, produce about 20% of milk in the U.S. Direct sales from California's milk production yielded $6.3 billion and created about 22,700 on-farm jobs in 2018. When production, processing, and related businesses are included, dairy's impact is close to $60 billion and includes 180,000 jobs (Matthews & Sumner, 2019).

Dairy consolidation in California has occurred since the 1950s, at least (see Figure 6), and it is expected to continue (Sumner, 2020). Dairy consolidation occurs in all states in the U.S., and it happens faster than in most other areas of agriculture (MacDonald et al., 2020). As a result, the way dairy farms are managed is changing. California dairies led the trend for farm growth for years and are now among the largest, but California dairies are also facing challenges such as climate change, labor shortages, high resource costs, and environmental regulations that may limit growth for some. For example, feed costs account for about half of total dairy farm costs in California (Sumner, 2020), and local forage sources are preferred to manage transport costs. In 2022, forage costs in California were high due to drought. As SGMA is implemented, high-value crops will predominate in the Valley and alfalfa growth will shift to being grown farther away (Escriva-Bou et al., 2023). Variable weather patterns such as alternating drought and floods add more uncertainty regarding feed sources and costs.

Figure 6: California Dairy Herd Consolidation trend, 1950-2021



Source: Kebreab et al., 2022

California dairies, increasingly, belong to member-owned co-operatives. Eighty-five percent of milk produced in the U.S. is managed by co-operatives, which provide services such as negotiating prices and other terms of sale on behalf of their farmer-members. Some have diversified to processing and marketing dairy products (GAO, 2019). Co-ops may provide protection from volatile markets, improve economic opportunities for dairies, and provide guidance about state and national industry priorities. The largest three co-ops in California are California Dairies, Inc., Land O'Lakes and Dairy Farmers of America (Agri-View, May 2018).

U.S. demand for dairy products is increasing, with per capita consumption in 2021 at 667 pounds, an increase of about 10% since 2011 (IDFA). Dairy demand is made up primarily of cheese, butter, and ingredients. The decrease in fluid milk consumption in California may lead to more re-location of dairy farms away from urban areas (Sumner, 2020).

Low Carbon Fuel Standard 101

This section provides background about the LCFS market, the value of dairy biomethane, the role of avoided methane accounting, methane's global warming potential, and how the LCFS may change in the future. The CI of dairy biomethane determines its credit price, the high value of which has generated much disagreement about the LCFS and dairy.

- ***What is the Low Carbon Fuel Standard?***

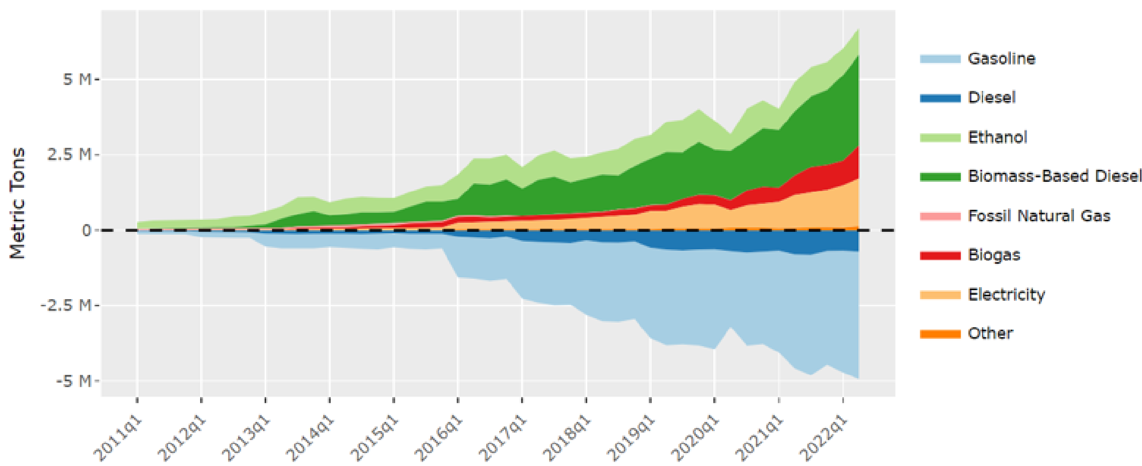
The LCFS is a market-based regulatory program created by CARB under its AB 32 authority (17 Cal Code Regs 95480 et seq.). It is designed to reduce California's reliance on fossil fuels by decreasing the CI of transportation fuels sold in California. CI refers to the GHGs emitted, as $MTCO_2e$, during fuel production, distribution, and use. Conventional, high-carbon fuels like diesel or gasoline have higher CIs than alternative, low-carbon fuels.

The LCFS rewards the production and use of alternative fuels using a system of credits and deficits. Each year, CARB sets a CI target for all transportation fuels, combined, known as the

annual benchmark or standard CI. Conventional fuels with a CI above the benchmark generate deficits; alternative fuels with a CI below the benchmark generate credits. Dairy biogas is just one alternative fuel eligible for LCFS credits.

Figure 7 shows LCFS deficits produced by diesel and gasoline (in blue, below zero) and credits produced by alternative fuels since 2011, with biomass-based diesel contributing the biggest proportion (in dark green). Note that biogas production has increased since SB 1383 passed in 2016, but it is not a major contributor to California's transportation fuel pool.

Figure 7: Quarterly LCFS Credits and Debits

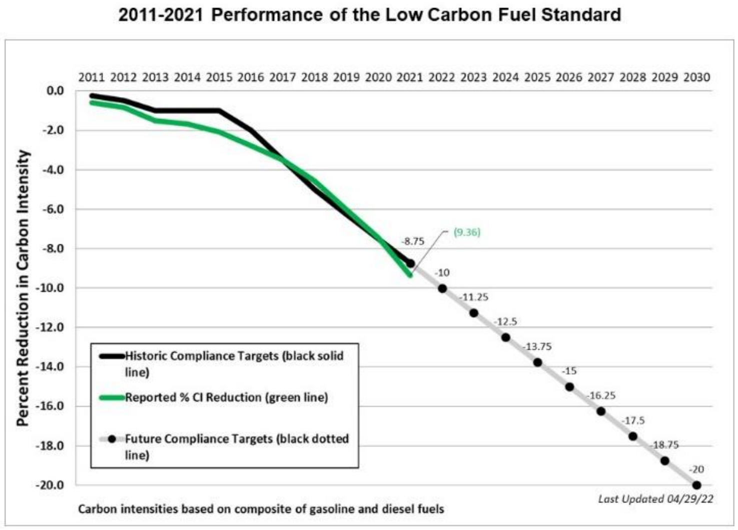


Source: Smith A, February 3, 2021

- ***How does the LCFS market function?***

LCFS performance is based on CARB's annual benchmark CI. Annual reductions to achieve a 20% reduction in average CI by 2030, compared to 2020, are illustrated in Figure 8. Each credit or deficit represents one $MTCO_2e$. Suppliers of conventional fuels must obtain credits from suppliers of alternative fuels to help meet the benchmark CI each year. Ethanol and biomass-based diesel generated the most LCFS credits while production of other alternative fuels increased.

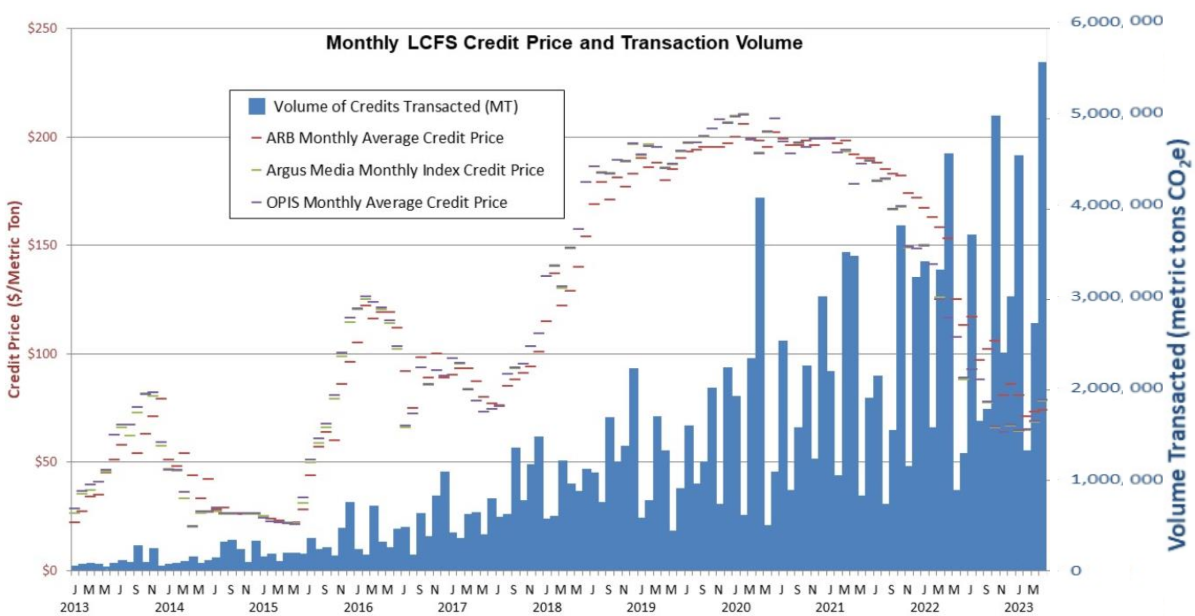
Figure 8: 2011-2021 Performance of the Low Carbon Fuel Standard



Source: CARB, LCFS Dashboard

A higher demand for credits will result from an increased production of conventional fuels and an increase in the benchmark CI, e.g., from 20% to 30%, known as increased stringency. An increase in the credit supply results from an increased supply of alternative fuels. When credit prices are low, there is less incentive to invest in new alternative fuel projects. LCFS credits can be bought, transferred, banked, and traded; they are retired when used to cover annual deficits.

Figure 9: Monthly LCFS Credit Price and Transaction Volume



Source: CARB, LCFS Dashboard

Volumes of alternative fuel traded have increased overall, but fuel volumes per credit are not the same for all fuels, and LCFS credit prices can fluctuate. In 2019, the average LCFS credit price was $200, while in early 2023, credits prices were in the $70-80 range (see Figure 9). To increase credit prices, CARB is looking at ways to increase demand and limit the credit supply.

How are LCFS CI scores and credits determined?

A fuel's CI is based on a lifecycle analysis of direct GHGs emitted during feedstock and fuel production, distribution, and use. A fuel's CI is calculated using a California-specific version of a lifecycle analysis model called the Greenhouse Gases, Regulated Emissions, and Energy Use in Transportation model or GREET. CIs are adjusted to account for differences in performance efficiency between an alternative fuel and the conventional fuel it is replacing. CARB provides adjustment values, or Energy Economy Ratio (EER) values, for fuel-vehicle pairs such as light duty trucks using electricity. The EER-adjusted CI value is used to calculate credits and debits for alternative fuels. The biggest differences result when vehicles use electricity to replace conventional fuels.

Tradeable credits are determined by

- The CI score of the alternative fuel (EER-adjusted)
- The CI score of the conventional fuel replaced (usually gasoline or diesel)
- The price of carbon

Credits are generated when

- The alternative fuel replaces the conventional transportation fuel
- The CI score of the alternative is lower (more negative) than the replaced fuel

The bigger the difference between the CIs, the bigger the LCFS carbon credits. Alternative fuels can receive credits from California's Cap-and-Trade *or* the LCFS, but not both. They can earn credits from both the LCFS and the national Renewable Fuel Standards (RFS) program. Some research indicates the LCFS and RFS can have complementary outcomes (Whistance et al., 2017), but research is limited regarding biomethane. In addition, stacking credits from two programs may violate the concept of additionality.

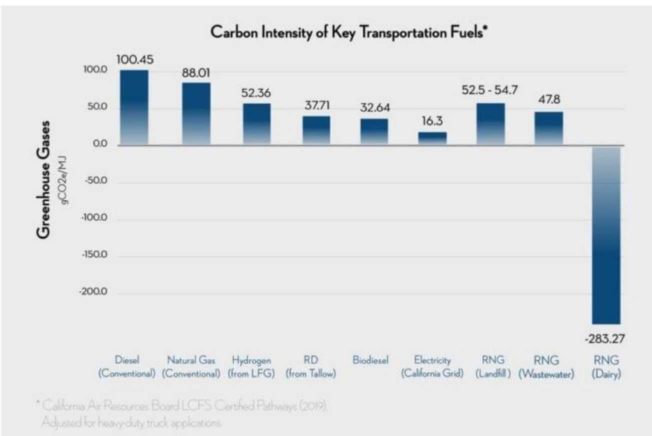
How does avoided methane accounting impact dairy biomethane CI scores?

At the same time SB 1383 passed, CARB started to approve LCFS pathway applications using an "avoided methane" baseline scenario to reflect existing dairy practices in California of flushing manure into lagoons for storage (CARB, April 13, 2017). This led to the large, negative CIs that characterize dairy biomethane, also known as renewable natural gas (RNG).

Emitted methane is considered avoided when it is captured by a digester. Because methane is avoided, not emitted, the emissions have a negative value in the CI calculation. GHG emissions from the remainder of the digester project, such as production of pipeline-injectable RNG, will have a positive value. An overall negative CI score results when baseline emissions are larger than project emissions. See an example here:

1.	Avoided methane emissions from lagoon storage	-345
2.	Emissions from energy consumption to upgrade to biomethane fuel	+50
3.	Project GHGs associated with biogas-to-RNG system, transport & use	+85
	CI Score (gCO_2e/MJ)	**-210**

Figure 10: LCFS Carbon Intensity Scores



Source: CARB

A chart of CI scores produced by CARB (Figure 10) can be used to determine the GHG reduction when RNG replaces diesel. It also illustrates the CI differences between dairy RNG and other alternative fuels. The absolute difference between the CI scores of conventional and alternative fuels represents the GHG reduction:

$$\begin{array}{rl} & 100 \text{ g } CO_2e/MJ \text{ (diesel)} \\ + & \underline{283 \text{ g } CO_2/MJ \text{ (RNG)}} \\ & 383 \text{ g } CO_2e/MJ \end{array}$$

The GHG reduction is converted to MTCO_2e to yield credits. Eligible digester projects generate LCFS credits for 10 years using these CI scores, though total credit revenue could change during that time, for example, if the benchmark CI became more stringent.

- ***Is biomethane a negative-CI fuel?***

In critiques of the LCFS, advocates and media have expressed surprise that dairy biomethane receives credits as if it is carbon-negative or it can "suck carbon from the air" (Fu, May 2022). To be carbon-negative, a fuel would need to remove or sequester more CO_2 than it emits.

This is how CARB explains the avoided emissions accounting:

> *"Renewable natural gas is rich in methane that is produced from organic materials or waste streams and can be processed so that it meets existing fossil natural gas pipeline and vehicle specifications. When burned in vehicles, RNG emits similar levels of greenhouse gases as fossil fuels, but different upstream processes result in an overall reduction of lifecycle GHG emissions due to methane capture and avoided upstream emissions"* (Jaffe & Dominguez-Faus, 2016).

Methane lasts about a decade in the atmosphere while CO_2 lasts for centuries, but methane absorbs more energy during its lifetime. Methane's Global Warming Potential is 27-30 times higher than CO_2 over 100 years (GWP-100) (EPAa). If manure methane is captured, transformed into biomethane, and used to replace conventional fuels, CARB's model asserts that methane's warming will be avoided for its lifetime. In addition, the GHGs that would have been emitted during the lifecycle of the replaced conventional fuel are also avoided. In other words, on a CO_2e basis, the GHGs removed by a fuel's production are more than the GHGs generated by its use.

- ***The role of the LCFS will change in 2030 and beyond***

California's 2022 Scoping Plan includes methane reduction via biomethane production to achieve SB 1383 methane targets. During the Public Workshop to Discuss Potential Changes to the Low Carbon Fuel Standard held in February (CARB, February 22, 2023), CARB presented proposals for changes anticipated in 2024, including:

- No new dairy pathways using avoided methane accounting would be approved after 2030, and credits could be generated until 2040
- Biomethane supplies would grow rapidly in the short-term but be used less as a transportation fuel moving ahead
- Complementary policies would support future biomethane demand, such as biomethane as a hydrogen production feedstock

It is unclear how proposed changes would incentivize farmers in coming years. Strong and stable LCFS market signals encourage investment, but eliminating current dairy credits introduces uncertainty without a clear goal for biomethane post-2030. Because the LCFS market depends on government policies, the risk of major policy changes may limit investment without clear next steps (Lee & Sumner, 2018). Dairy farms will continue to be required to manage manure methane emissions, and digesters completed or under construction will provide needed infrastructure.

Key Findings

- Dairy biogas CI scores are larger and more negative than other alternative fuels due to avoided methane accounting
- Biogas credits treat manure as waste and take advantage of the different GWPs of conventional fuels and biomethane
- Current credits are lower than 2018-2021, but if CARB increases the benchmark CI stringency, credit prices will be expected to increase
- CARB is in the rulemaking process to prepare for possible changes to the LCFS, including dairy biomethane, in 2024

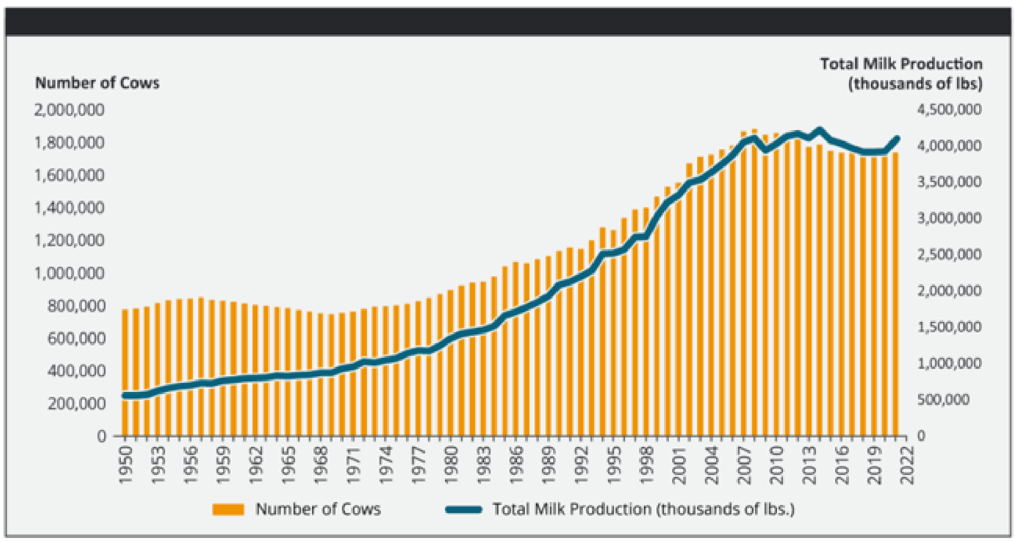
The LCFS, Costs, and Dairy Practices

California dairy practices, including responses to climate change, depend on multiple inputs. This section reviews how LCFS costs and incentives affect dairy producer choices.

- ***California dairy consolidation trends are driven by economies of scale***

The Valley is home to 90% of California's dairy cows and some of the largest dairy farms in the country (Sumner, 2020). Economies of scale drive consolidation and, in general, larger dairy operations demonstrate "substantial cost advantages" compared to smaller farms (MacDonald et al., 2020). California also has smaller organic farms in the North Coast region, which make up about 3% of the state's herd. In that area, grazing and pasture-based management are common (CDFA, 2018).

Figure 11: California Cow Population, 1950-2021



Source: Kebreab et al., 2022

Figure 12: Growth of Dairies in Western Dairy States

Table 6.1. Cow Numbers in California and Major Dairy States

	Number of Cows (Thousands)		Change
	2004	2018	Percent
California	1,700	1,740	2
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

Source: USDA NASS Quickstats. Available at: https://bit.ly/36FAhoV

Table 6.2. Milk per Cow in California and Major Dairy States

	Milk per Cow (in pounds)	
	2004	2018
California	21,450	23,239
Wisconsin	17,739	23,974
New York	17,705	23,842
Idaho	22,070	25,077
Texas	18,956	24,955
U.S. Average	19,008	23,137

Source: USDA NASS Quickstats. Available at: https://bit.ly/36FAhoV

Table 6.3. Average Number of Cows per Dairy in California and Major Dairy States

	Number of Cows per Dairy		Change
	2004	2017	Percent
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

Source: USDA/NASS Quickstats
Available at: https://www.nass.usda.gov/Quick_Stats/

Source: Sumner, 2020

California's cow population grew rapidly until 2007, but it has since stabilized (Figure 11) (Kebreab et al., 2022). Though consolidation is likely to continue, California's cow population is expected to gradually decline. Other Western states are growing at rates faster than California (Sumner, 2020). Figure 12 illustrates dairy trends in 2004 compared to 2017-2018:

- State dairy cow populations were growing in Western states in 2018, and in Texas and Idaho, the cow populations were growing approximately 25% faster than California
- Production efficiency continues to increase, and more states have production rates on par with California in 2018 than in 2004
- California had the largest herds in 2017, but Texas and Idaho farm sizes were growing 2-4 times faster than California

Applying advances in animal husbandry, feeding and housing practices, animal breeding, crop genetics, and crop management can increase production efficiency. These dairy practices can improve land and water use as well as GHG emissions per cow. Milk produced in California in 2014, compared to 1965, was produced with 50% fewer GHG emissions, and using less water and land (Naranjo et al., 2020).

Efficiency is a useful metric for GHG emissions, and it is consistent with "doing more with less." It is not the only way, however, to assess a sustainable farm model. Smaller farms may emit more GHGs per cow, but their total emissions are less per farm. Farm practices can prioritize soil health, animal welfare, biodiversity and/or water quality in diverse ways.

When cost pressures are high, farmers may choose to consolidate, sell, or relocate. Farm costs include feed, environmental regulations, labor costs, and resource costs such as land and water (Sumner, 2020). Aging farmer populations play a role in the consolidation trend when a retiring farmer sells to a local dairy. California's dairy farms are expected to face increasing challenges that can increase costs, such as:

- Drought and aridification
- Water scarcity, limits on groundwater pumping, more fallowed land due to SGMA
- Continued wage increases and labor shortages
- Rising energy, fuel, and feed costs
- Increasing regulations such as waste discharge requirements

These challenges will lead to an estimated decline in California's cow population of 1% per year (Kebreab et al., 2022). Implications for the viability of individual farms will vary.

When dairies relocate to another state, the reasons can be multi-faceted. If a California dairy moves to a state with less stringent regulations, the state's methane emissions may decrease, but because emissions are not geographically-bound, they increase nationally and globally. California limits dairy relocation by building a beneficial business environment for agriculture.

Key Findings

- Dairy consolidation has been happening since the 1950s and the trend is expected to continue due to economies of scale
- California dairy cow populations have been stable since 2007 and are expected to gradually decline in coming years due to cost pressures
- Larger, well-run dairy farms produce milk more efficiently per cow with respect to GHG emitted, and land and water used, compared to smaller farms

Farm Sizes: USDA defines small dairies as those with 100 cows or less, mid-sized with 300-400 cows, and large farms can reach many thousands of cows (ERS 2020). In California in 2017, most cows lived on farms with 1,000 to 2,499 cows (see Table 1).

Table 1: California Dairy Farm Distribution

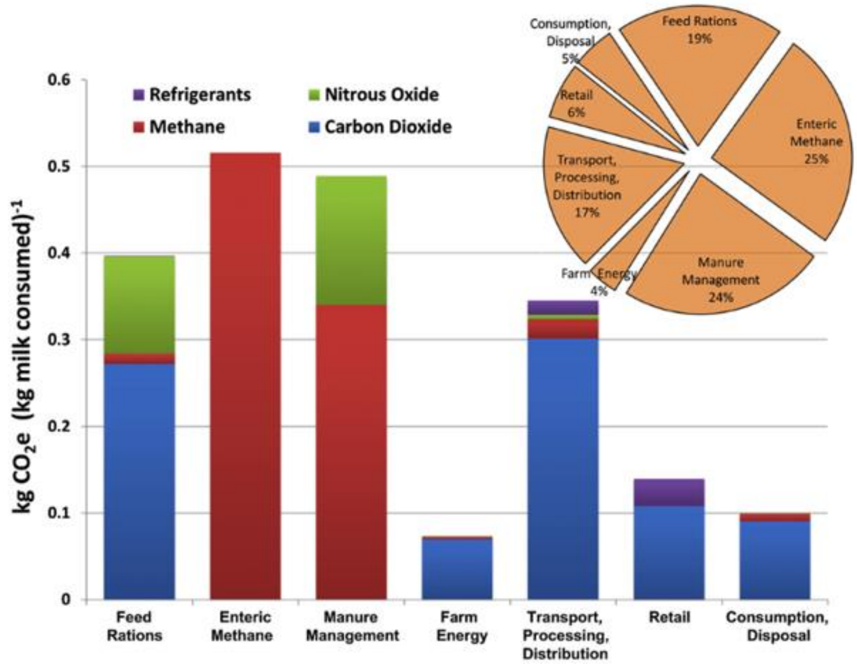
Total	Dairy Farms		Milk Cows	
Cows per Farm	Number	Percent	Thousands	Percent
1-499	395	30.9	94	5.4
500-999	296	23.1	210	12.0
1,000-2,499	390	30.5	638	36.5
2,500-4,999	163	12.7	547	31.2
5,000 or more	35	2.7	262	15.0
Total	1,279	100	1,750	100

Source: Adapted from Sumner Ch. 6, 2017; NASS/USDA U.S. Census of Agriculture 2017

- ***Are there better ways to determine LCFS dairy credits?***

CARB's CI scores for manure biogas treat manure as a waste product, i.e., the lifecycle analysis for manure biogas starts with manure as a feedstock and excludes the upstream emissions from raising dairy cows and producing milk. This approach is common when conducting a lifecycle analysis of waste feedstock (Martin et al., 2015), but it is not the only way to allocate methane emissions from a dairy. As mentioned above, a fuel's CI score is based on a lifecycle analysis of GHG emissions. Figure 13 summarizes the results of the first comprehensive lifecycle analysis of U.S. milk production, with a scope from farm to fork, published in 2013 (Thoma et al., 2013). Avoided methane accounting starting with manure has created large, negative CI scores for dairy biogas, but alternative crediting can create values more similar to other alternative fuels.

Figure 13: U.S. Dairy Lifecycle Analysis



Source: Thoma et al., 2013

Co-allocation to milk and manure production. If milk production is included in the lifecycle analysis, milk and manure can be considered co-products. When calculating the CI, some biogas can be allocated to milk and some to manure. This approach to examining CIs was illustrated in comments to CARB using a model 2,000-cow dairy farm producing biogas for electricity (Younes & Fingerman, 2021). The analysis confirmed that larger CI scores result when manure is treated as waste and when large farms have "methane-generating" manure management practices, i.e., uncovered lagoon storage. LCFS offered a "significant advantage" of 1.5-1.8 times more revenue to large 10,000-cow farms, compared to smaller 500-cow farms. With co-product allocation, CIs of manure and biogas revenues decreased for large farms, and the LCFS program became more affordable for small and medium dairy farms. This may provide an alternative mechanism to price dairy credits.

Dairy farms with 1,000 cows or less account for more than 50% of California dairy farms, but only 17% of the state's cows. These farms are likely to be the ones without a digester that rely on alternative manure management practices. CDFA does not discourage smaller farms from participating in the DDRDP, but it considers the AMMP a better fit for smaller farms because DDRDP projects require 50% matching funds. Thus, high digester costs limit participation by smaller dairies that use alternative manure management practices. Because LCFS rewards large methane-generating farms, that pay less than their fair share of the costs to reduce methane emissions, LCFS also creates a free-rider problem.

Allocation to milk. There is a growing interest in incorporating externalities like GHG emissions into food prices. The United Nations Environmental Program oversees The Economics of Ecosystems and Biodiversity (TEEB) for Agriculture & Food, a framework to evaluate “true costs” of food. If the LCFS allocated methane emissions to milk, the cost of milk would increase, and some or all of the cost for GHG emissions would shift from users of fuels to consumers of dairy foods. TEEB’s analysis of milk production in the Netherlands found that milk is underpriced by $5.40 per kg of milk protein, or $0.69 per gallon (TEEB, 2017). This example is included for illustration only, because the dairy industries and prices in the Netherlands and U.S. differ in important ways. Higher milk prices, however, introduce trade-offs for low-income consumers and food security in California. Food affordability underpins access to nutritious, sustainable dietary patterns (Drewnowski et al., 2021).

More information about CARB’s plans for LCFS dairy pathways in 2030 is needed to understand implications and alternatives. If avoided methane accounting is stopped in 2030, replacing it with an alternative financial mechanism may be a reasonable path for CARB to follow. In 2016, SB 1383 authorized CARB to develop a pilot financial mechanism to reduce risk to project developers due to price uncertainty of LCFS credits. CARB developed two alternatives, Contracts for Difference and a Put Option. Contracts for Difference ensures that dairies obtain a certain predetermined price for credits, regardless of the market price, while a Put Option ensures that the credit value will not fall below a minimum predetermined price (CARB, November 2018). CARB concluded that both mechanisms could help reduce risk and leverage capital, though they would also change the role that the state plays in the LCFS market.

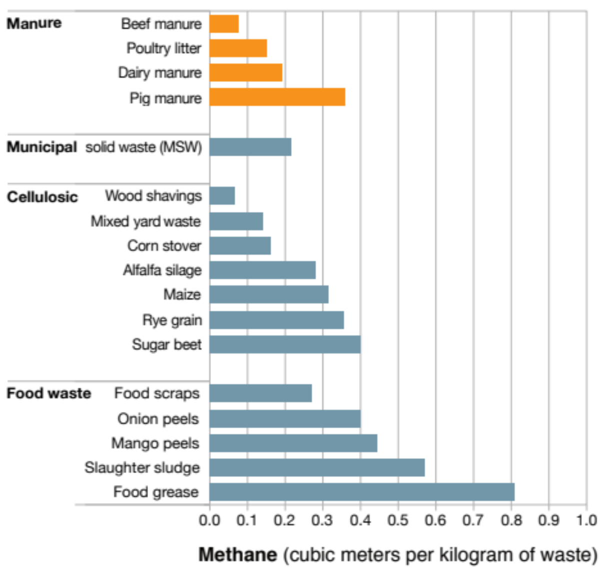
Key Findings

- LCFS avoided methane accounting yields generous credits for larger, methane-generating farms; the higher prices are paid by fuel purchasers
- Using co-product allocation lowers the price of LCFS dairy credits, and can even the playing field for smaller farms
- Assigning GHG emissions to milk production would increase milk and dairy food prices, creating a hardship for low-income groups
- CARB may revisit proposed alternative financial mechanisms to reduce risk and stabilize the LCFS market for dairy biomethane

- ***Manure is cheap; biogas is expensive***

SB 1383 was designed to modify manure management practices to reduce methane emissions in California. Standard practice in the Valley for a farm without a digester is to flush manure from free-stall barns and store it in open lagoons. Dairy cows produce an estimated 120 pounds of waste per cow every day, so manure is plentiful. In 2012, the area covered by manure lagoons in just five of the eight Valley counties was equivalent to 3,126 acres or about 2,400 football stadiums (Viers et al., 2012).

Figure 14: Methane Yield per Kilogram of Common Dry Materials from Anaerobic Digestion



Source: Aguirre-Villegas et al., 2021

Dairy manure is not an energy-rich feedstock; more dairy manure is required to yield a given amount of biogas per weight of dry material than many other feedstocks. See Figure 14 for the yield of various organic feedstocks used to produce biogas.

To produce biogas and pipeline-injectable biomethane, extensive infrastructure is required, which is an expensive proposition. Dairy digesters can cost several million dollars, and full project costs will be higher when vehicles for transportation, systems to purify biogas to biomethane, and pipelines are included. Anaerobic digesters are expensive, but they are valuable because they capture manure biogas, the step required before transforming it into biomethane for fuel.

Results from simplified cost and revenue estimates for milk and biogas revenue on dairy farms with digesters help compare contributions to farm income from milk and biogas (see Table 2). These projects were modeled after an analysis by Dr. Aaron Smith using data from CARB (Smith, February 3, 2021; CARB, 2017). Table 2 includes costs to build, operate, and maintain a digester on a 2,000-cow farm. Biomethane revenue comes from three sources, LCFS credits, RFS credits, and biomethane sales. It is worth noting that the credits received from the LCFS and RFS programs exceed the revenue from direct sales of natural gas, emphasizing the high production cost of biomethane. Revenue from milk production is based on an average milk production per cow of 230 CWT (hundredweight or 100 pounds of milk) per year. In these examples, milk represents 64%-74% of farm revenue, with the remainder from biomethane. Based on this analysis, biomethane increases farm revenue, but milk is the primary revenue source for dairy farms. Because the prices of milk and biomethane fluctuate, these proportions can also vary.

Table 2: Dairy Farm Costs and Revenue for 2,000 Cow Farm with an Anaerobic Digester

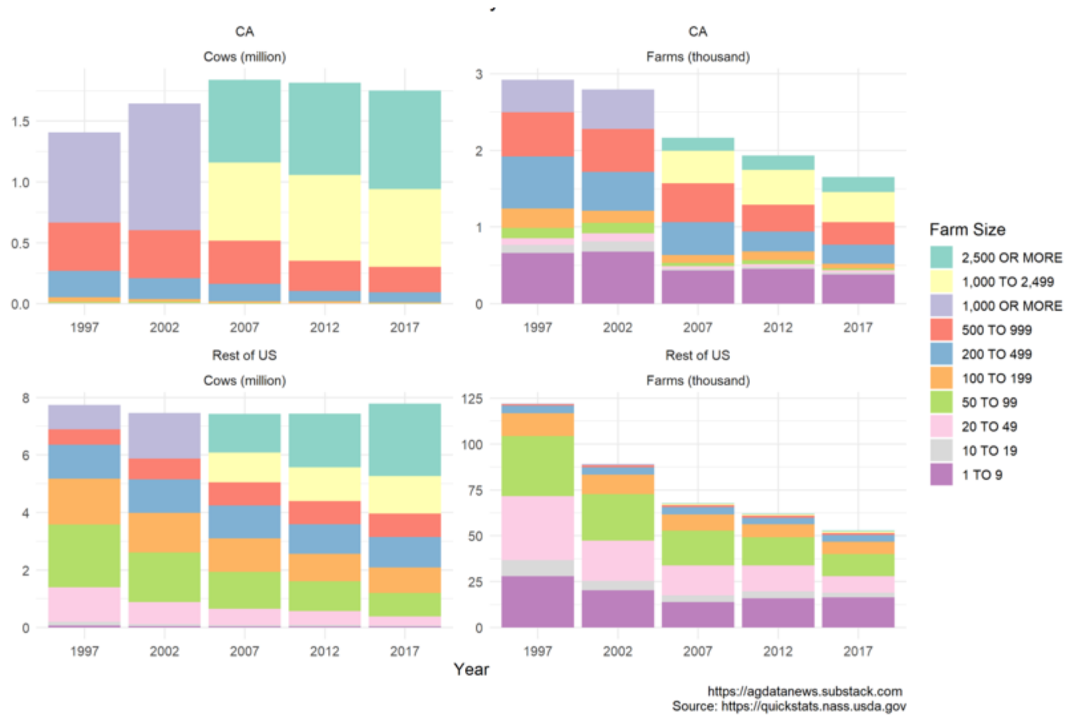
Source and Farm Model	Digester Capital Cost*	Digester Operation & Maintenance Cost**	Digester (gas) Revenue	Milk Revenue	Gas Revenue/ Total Revenue
Biomethane production; 2,000-cow farm in digester cluster (2018)[1]	**$2.9M**	**$174K**	**Total $2.7 million** LCFS $865K $432/cow-y RFS $1.1M $550/cow-y NG $149K $75/cow-y	**Total $7.6M** $16.50/cwt $3795/cow-y	**2.7/10.3 = 26%**
Biomethane production; 2,000-cow farm in digester cluster Smith (2022)[2]	**$2.9M**	**$174K**	**Total $5.8 million** LCFS $3.67M $1834/cow-y RIN $1.99M $993/cow-y NG $225K $113/cow-y	**Total $10M** $21.64/cwt $4977/cow-y	**5.8/15.8 = 36%**

1. Lee & Sumner (2018) ; 2. Smith (2022)
*$342/cow/year to install, 10-year amortization, farmer paid 100% of capital cost to build digester (Smith, 2022)
**$294/cow/year to operate and maintain digester, 10-year amortization (Smith, 2022)
LCFS credits: Low Carbon Fuel Standard carbon credits for dairy biomethane
RFS credits: Renewable Fuel Standard credits, also known as D3 Renewable Identification Numbers (RINs)
NG: Revenue if sold at natural gas spot price
CWT: Hundredweight or 100 pounds of milk

- ### Has the LCFS led to more dairy farm consolidation?

A 2023 analysis found that the number of dairy cows per farm grew slightly faster in 2019 than before the digester boom (Smith, April 7, 2023). Since 2019, however, the growth in farm size has been faster outside California than inside, thus LCFS and digester subsidies have not led to consolidation yet (see Figure 15). Limited information about this is available, but USDA will release updated information on dairy farm size in 2024 that will shed more light on this question.

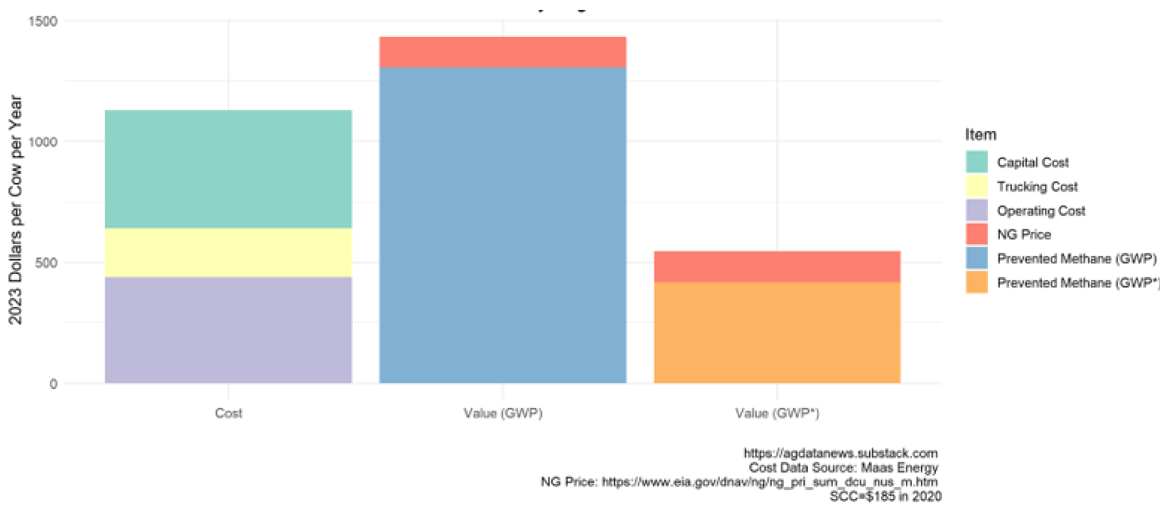
Figure 15: Dairy Sector Methane Reductions



Source: Smith, April 7, 2023

A recent economic analysis examined whether LCFS dairy credits were overvalued at a time of low LCFS credit prices (Smith April 14, 2023). The analysis compared outcomes using GWP-100 and GWP* (GWP "star"), a metric that accounts for methane as a short-lived GHG in a new way (Liu et al., 2021). Using GWP-100, biomethane revenues were higher than production costs, and with GWP* revenues were lower than costs. With GWP,* the value of biomethane was also higher than the social cost of carbon, meaning the value of the damage anticipated by the prevented methane emissions (see Figure 16). Thus, dairy credits were overvalued compared to the social cost of carbon according to this analysis. Please note that GWP-100 is used by CARB, and GWP* is not broadly used by policy-makers, though it is preferred by the author of the analysis. Because LCFS credit prices fluctuate, and CARB has plans to modify the LCFS in ways that may alter dairy credit generation, this conclusion may change as the program changes.

Figure 16: Costs and Benefits of Dairy Digesters in 2023



Source: Smith, April 14, 2023

Key Findings

- Biogas is expensive to produce compared to the spot price of natural gas
- Milk will account for most of the revenue on a dairy farm with a digester
- Because prices for LCFS credits and milk fluctuate, revenue generated for a dairy farm with a digester may be unpredictable
- LCFS dairy subsidies have not increased average California dairy herd sizes after seven years of LCFS dairy credits, based on available data

The LCFS and California's 2030 Methane Reduction Goals

CARB and UC Davis recently analyzed the progress of the livestock and dairy sectors to meet 2030 methane reduction goals (see Figure 17). CARB estimated emissions from beef and dairy cattle, combine (CARB, March 2022). CARB assumed there would be no changes in available methane reduction technology, that construction of manure methane reduction projects funded by DDRDP through 2021 would be completed, and beef and dairy cattle populations would decrease at an attrition rate of 0.5% per year. Based on these assumptions, methane reduction fell short of the 2030 goal by 4.4 $MMTCO_2e$, or about half of the livestock requirement of 9 $MMTCO_2e$. Total methane reductions from all sources also have not met expectations (see Figure 18).

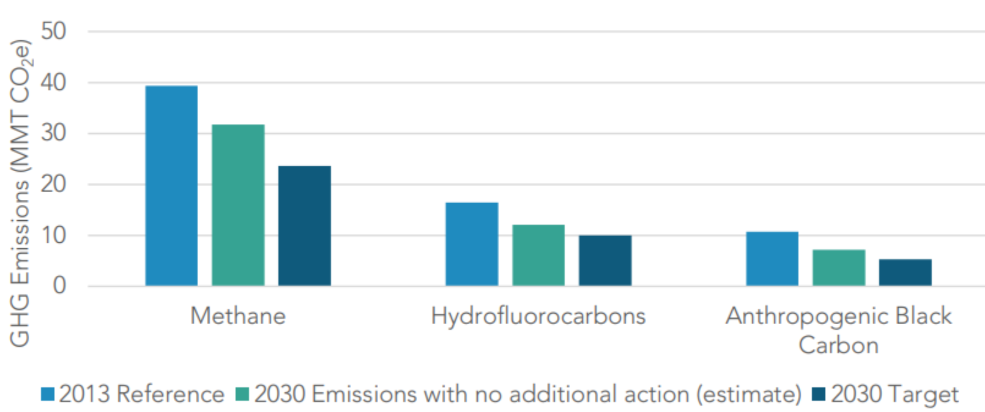
Figure 17: Projected 2030 Dairy Sector Methane Reductions From CARB and UC Davis

Reduction Type	CARB Identified Livestock Emission Reductions Through 2030 ($MMTCO_2e$)	Expected Dairy Emission Reductions Through 2030 ($MMTCO_2e$)
Herd Reduction	2.4	2.61-3.3
Anaerobic Digestion	1.9	4.15
Alternative Manure Management Practices	0.3	0.6-1.1
Enteric Emission Reduction Strategies	0	0.25-2.04
Total	**4.6**	**7.61-10.59**

Source: Adapted from Kebreab et al., 2022

Researchers at UC Davis conducted a similar assessment, but different assumptions informed their analysis. They analyzed only California dairy cows, which have higher attrition rates than beef cattle. Mandated methane reductions from dairy cows are 7.2 $MMTCO_2e$ of livestock's 9 $MMTCO_2e$. UC Davis researchers used attrition rates of 1% per year, and they included a more current inventory of California dairy digesters that included double the number used by CARB (Kebreab et al., 2022). They also assumed products would become commercially available to reduce enteric emissions, though these reductions were not a major contributor to total reductions. UC Davis researchers concluded the 2030 dairy methane reduction goals can be met with current projects, though the higher end of the UC Davis estimate for dairy emission reductions includes the full livestock requirement. Note that the UC Davis analysis more accurately addressed dairy methane reductions and it was used to support the policy analysis below.

Figure 18: Methane, Hydrofluorocarbon and Black Carbon Progress Toward SB 1383 2030 Goals



Adapted from: 2022 Scoping Plan for Achieving Carbon Neutrality; based on strategies currently in place

Key Findings

- The LCFS has been effective for reducing dairy manure methane emissions
- Dairy manure methane reductions will contribute the largest proportion of SB 1383 livestock methane reduction goals
- Commercially-available, affordable products are needed to reduce enteric emissions

Dairy Emissions and San Joaquin Valley Air Pollutants of Concern

- ***Anaerobic digestion improves select dairy emissions, but not all types***

The debate about the LCFS has been projected against the backdrop of some of the worst air quality in the nation and longstanding distrust among DACs about agricultural pollution. The Valley is an Extreme Nonattainment zone for ozone and a Serious Nonattainment zone for $PM_{2.5}$. Valley ozone is high in the summer, and $PM_{2.5}$ is high in the winter. VOCs and ammonia are not criteria air pollutants like ozone and $PM_{2.5}$, but they are precursors to these pollutants.

Dairy manure emits methane, ammonia, VOCs, and odors. In addition to reducing methane emissions, digesters can reduce odors and VOC emissions, and some evidence indicates ammonia emissions may increase from digestate (See Table 3). Anaerobic digestion does not change the amount of nitrogen in digestate, compared to manure, but it changes its forms, and the changes can lead to increased ammonia emissions. The resulting digestate quality also may be better than manure (Aguirre-Villegas et al., 2014). Multiple studies indicate that California's emission inventories of methane and ammonia are lower than actual levels (see Table 3), and methane measurements near dairies are "spatially sparse and lack temporal resolution." These problems may lead to difficulty accurately assessing dairy emissions.

Table 3: Dairy Emissions and Effects of Anaerobic Digestion

Emission	Dairy Contributions	Digester Impact
Methane	Dairies among largest sources in California[1,2] Current inventories underestimated[1,2] Dairy-related measurements sparse[3] Lagoons emit more than enteric[1]	Decreases manure methane emissions[4,5] No effect on enteric
Ammonia	Agriculture (manure & fertilizer) main source[8,9] Current inventories underestimated[6-10] $PM_{2.5}$ and ammonium nitrate precursor[6, 8]	Can increase ammonia emissions[5] Covering digestate can reduce emissions[5]
Volatile Organic Compounds VOC)	VOCs are emitted from cow respiration [11] manure,[11] and silage[12]	Decreases VOC emissions[13,14] No effect on enteric
Odor	Hydrogen sulfide, ammonia[15] Volatile Fatty Acids [13,14]	Decreases odor [13-15]

1. Owen & Silver, 2015; 2. Zhao et al., 2009; 3. CARB, November 26, 2018; 4. El Mashad et al., 2023; 5. Aguirre-Villegas et al., 2014; 6. Kelly et al., 2018; 7. Miller et al., 2015; 8. Schifler et al., 2014; 9. Walker et al., 2012; 10. Zhu et al., 2013; 11. Shaw et al., 2007; 12. Hafner et al., 2013; 13. Page et al., 2014; 14. Page et al., 2015; 15. Orzi et al., 2018.

Manure management practices before digestion can also affect methane and ammonia emissions. SB 1383 recommended dry scraping manure from free-stall barns as an alternative to flushing to reduce methane emissions. One recent study found that dry scraping stalls increased methane and ammonia emissions compared to standard practices (Ross et al., 2021). Another study found solid-liquid separation (SLS) can be a cost-effective way to decrease methane and ammonia emissions from manure, with or without an anaerobic digester (Aguirre-Villegas, 2014). Groundwater issues are beyond the scope of this report, but responsible digestate management can help reduce air and water pollution. Agricultural fertilizers and animal waste applied to cropland have been the main regional sources of nitrate in California groundwater in the Valley (Viers, et al., 2012).

Key Findings

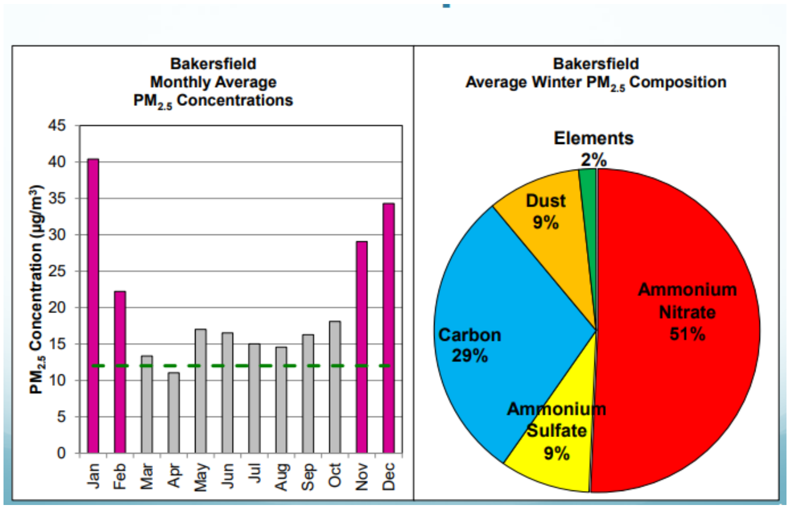
- Digesters decrease methane, odor and VOC emissions from manure
- Some research indicates there is a trade-off between methane emissions (decrease) and ammonia emissions (increase) after anaerobic digestion
- Further evaluation of pollution controls for dairies with digesters are needed

Dairy ammonia and $PM_{2.5}$: can new mechanisms provide solutions?

There are many contributors to the Valley's poor air quality, including multiple sources of pollution, including agriculture, rapid population growth, and low carrying capacity for the region. The Clean Air Act has been successful at improving air quality throughout the state and country, but it has failed in the Valley for ozone and $PM_{2.5}$. $PM_{2.5}$ particles can harm both lung and heart health (EPAb). $PM_{2.5}$ exposure is associated with reports in the Valley of asthma (Meng et al., 2010) and preterm birth (Ha, et al., 2022) and in California, of mortality from cardiovascular disease (Hayes et al., 2020).

$PM_{2.5}$. Ammonium nitrate is formed from NOx/nitric acid and ammonia, and it makes up about half of winter $PM_{2.5}$ when seasonal Valley $PM_{2.5}$ is high (see Figure 19). There is no disagreement about the negative health impacts of $PM_{2.5}$, but there is disagreement about the role of ammonia emissions in $PM_{2.5}$ formation and control in the Valley (Schiferl et al., 2014; Kelly et al., 2018; Chen et al., 2014) and globally (Gu et al., 2021). There is also disagreement on this point among the agencies in charge of the Valley's air quality.

Figure 19: Winter PM 2.5 Composition, Bakersfield, CA



Source: CARB, December 2016

CARB prioritizes NOx reduction to reduce ozone and $PM_{2.5}$ because NOx is a precursor to both. According to CARB, the leading source of NOx is traffic combustion, and NOx is a precursor to nitric acid, which can combine with ammonia to form secondary ammonium nitrate. CARB models indicate that "primary $PM_{2.5}$ and NOx controls are most effective" for reducing $PM_{2.5}$ in the Valley (Chen et al., 2014), which is supported by multiple studies. A CARB Staff Report summarized the finding indicating ammonia is not an important attainment precursor for secondary $PM_{2.5}$ formation (i.e., ammonium nitrate) (CARB, August 13, 2021):

> *"…because there is a far greater amount of ammonia in the Valley air than is necessary to participate in the chemistry that leads to ammonium nitrate…and actions to reduce ammonia will not provide significant $PM_{2.5}$ air quality improvements."*

Multiple studies have found that Valley ammonia inventories are underestimated (Schiferl et al., 2015; Kelly et al., 2018; Paulot et al., 2014), and soil NOx from agriculture may also be underestimated (Vechi et al., 2023). If inventories are incorrect, CARB's $PM_{2.5}$ models are, too.

> *"Accurate emission inventories are critical to the ability to effectively model reactive nitrogen and $PM_{2.5}$ formation in California" (Schiferl et al., 2014).*

> *"…additional work on NH_3 [ammonia] emission and air quality modeling is warranted based on underpredictions of NH_3 in emission source regions where very high mixing ratios were measured. …Improvements in the spatial allocation of NH_3 emissions are also warranted, especially near Hanford" (Kelly et al., 2018).*

EJ advocates contend that ammonia emissions from dairies contribute to $PM_{2.5}$ levels and disproportionately harm DACs (In: EPA October 5, 2022, Public Justice, 2022; Lazenby et al., October 27, 2021). Findings that anaerobic digestion may increase ammonia emissions from digestate despite lowering methane are of special concern. Valley neighborhoods with high proportions of Latinx residents already experience higher levels of $PM_{2.5}$ exposure (Lievanos, 2019). CARB's efforts to reduce dairy GHG emissions without reducing other dairy air pollutants have failed to meet the needs of the EJ community.

> *"Biogas is being falsely marketed as a renewable energy solution to solve the problems of an already polluting industry…"*
>
> D. Rodriguez, Written Comment #22, Public Workshop to Discuss Potential Changes to the Low Carbon Fuel Standard; submitted March 15, 2023

EPA, after initially approving the Valley's 2018 $PM_{2.5}$ Attainment Plan, disapproved parts of it in a proposed rule published in 2022 (EPA, October 5, 2022). EPA questioned CARB's conclusions about ammonia as a $PM_{2.5}$ precursor, among other things. CARB and the San Joaquin Valley Air Pollution District withdrew the Plan from EPA and asked for guidance about how to proceed. EPA will review CARB's revised Plan.

While air quality agencies determine the way forward regarding ammonia emissions and $PM_{2.5}$, DACs continue to be exposed to harmful air pollution. The role of dairy ammonia in $PM_{2.5}$ has been a key point of disagreement between CARB and EJ advocates that has yet to be resolved. Agriculture is the leading source of Valley ammonia, and ammonia control is recommended by some experts to reduce $PM_{2.5}$. If ammonia emissions are higher than Valley inventories indicate, and digesters increase ammonia emissions, the LCFS may have unintended impacts on Valley air quality that require better understanding before $PM_{2.5}$ mitigation plans are approved.

- ***Climate change and air quality benefit from co-management***

While Valley air quality has improved slowly over past decades, California's efforts to reduce methane have been accelerated to meet 2030 goals. Valley residents have argued that these efforts should move at the same pace. Air pollution and climate change occur together, but they are managed by different agencies and policy frameworks, which can hinder program coordination.

Air pollution and climate change are increasingly being recognized as problems that are more effectively addressed simultaneously (Melamed et al., 2016; Karlsson et al., 2020). Co-benefits from GHG emission reduction programs can offset costs of GHG mitigation via public health improvements (Melamed et al., 2016; Karlsson et al., 2020; Wang et al., 2020). Using a detailed, integrated technology model to illustrate health co-benefits of achieving net-zero GHG emissions in the Valley by 2050, for example, researchers found that reducing GHGs would reduce NOx, $PM_{2.5}$, ammonia, reactive organic gases, and sulfur oxides (dairy methane reductions were considered); these reductions would be associated with reduced mortality (Wang et al., 2020). This study found that avoided mortality and morbidity would yield $100 billion more than GHG abatement costs. In addition, health would be improved more in DACs, indicating additional benefits to the approach.

Some connections between dairy methane and ammonia emissions were discussed above; interactions also occur between methane and ozone. In addition to ground-level ozone being formed from NOx and VOCs, oxidation of methane can increase ozone levels (Abernethy et al., 2021). Methane reductions are more effective at reducing ground-level ozone when accompanied by efforts to reduce NOx and VOCs (Trousdell et al., 2019; West et al., 2006). Methane and ozone are both GHGs, so global methane reduction can improve climate change by reducing the warming associated with methane and ozone. Methane reduction to improve climate change is most effective when implemented nationally or internationally (West et al., 2006).

California can benefit from policy integration to maximize co-benefits for climate change, air quality, public health, and environmental justice. California's 2022 Scoping Plan recognizes the value of maximizing co-benefits, but the complexity of California's policy-making and implementation processes makes it difficult to develop a truly integrated approach linking local, state, federal, and global levels.

"Air pollution and climate change are two sides of the same coin, but they are typically addressed separately."

World Bank (2022)

VII. CONCLUSIONS ABOUT STAKEHOLDER PERSPECTIVES

Post-Review Analysis

This policy analysis started with the perspectives of three key stakeholders, and the literature review helped assess their statements. Key findings are summarized in Table 4.

Table 4: Post-Review Analysis Key Findings

Crediting Systems
• CARB built an effective, voluntary market to reduce methane from dairy manure, the largest methane source in California • CARB is conducting rulemaking to determine ways to amend the Low Carbon Fuel Standard to meet 2030 and 2045 goals • CARB is unlikely to replace avoided methane credits with regulations in 2024 because it would slow dairy methane reduction progress; continuing some dairy incentives until SB 1383 goals are achieved is more likely • New financial mechanisms could help achieve methane reduction goals cost-effectively
Effectiveness to reduce methane
• To meet SB 1383 livestock methane emissions goals, California will rely heavily on dairy manure methane reductions; AMMP projects cannot achieve the needed reductions during the same period • Though LCFS decreases methane emissions, experts disagree about 2030 projections • By 2030, CARB estimated ~2 $MMTCO_2e$ methane reductions from digesters funded through 2021, or 4.6 MMTCO2e methane from all dairy reduction technologies; CARB concluded more projects would be needed to meet 2030 goals (see Figure 17) • By 2030, Kebreab et al. estimated ~4 $MMTCO_2e$ reductions from digesters funded through mid-2022, or 7.6-10.6 $MMTCO_2e$ methane reduction from all dairy reduction technologies, including enteric. They concluded no additional projects would be needed to meet 2030 goals (see Figure 17) • Affordable, commercially-available products will help reduce enteric methane • Pasture-based systems are not feasible in the Valley
Consolidation
• Because dairy consolidation is a longstanding trend expected to continue, with or without the LCFS, it may be difficult to assign future farm size changes to the LCFS • LCFS has not led to more consolidation as defined by increased average farm size • Metrics that monitor growth of individual farms, growth of combined dairy and biogas operations, or changes in manure management practices may be better than average farm size to monitor LCFS outcomes

Air quality & DACs
• Anaerobic digestion reduces manure methane, odors, and VOC emissions, but may increase ammonia emissions from digestate; long-term, methane reduction may reduce ozone formation • Valley air quality impacts of LCFS dairy credits cannot be fully known until anaerobic digester infrastructure is in place • Replacing LCFS dairy credits with regulations for methane reduction would not significantly improve air quality • Basing Valley State Implementation Plans on updated, accurate monitoring—including of dairy digester projects—emission inventories, and air quality models will better serve needs of all Valley residents • California can benefit by exploring novel mechanisms to improve alignment among federal, state, and local air quality agencies to improve pollution mitigation • Integrated policy approaches and clear implementation mechanisms to improve climate change, air quality, and environmental justice are more likely to improve Valley air quality than stopping the LCFS

Post-Review Summary

The LCFS program will make significant contributions to reducing dairy methane and achieving dairy SB 1383 goals for 2030. It will also put infrastructure in place to support continued methane capture. Alternative manure management practices alone cannot achieve the same outcomes by 2030, though they can increase reductions compared to digesters alone.

Stakeholders disagree about the value of dairy credits depending on, in part, priorities and frames of reference. EJ advocates and DACs oppose credits in hopes of discouraging dairy growth and air pollution; dairy producers support credits and want to ensure LCFS market stability and continued investment; and CARB has indicated willingness to modify avoided methane accounting after 2030.

The LCFS program and digesters will reduce methane emissions, odor, and some VOCs. Consistent, long-term methane reduction may decrease ozone formation globally and improve air quality and climate change. Methane does not directly impact $PM_{2.5}$ formation, but trade-offs between reducing methane and increasing ammonia emissions with digesters are of concern if increased $PM_{2.5}$ results. Expectations from dairy producers that anaerobic digesters as currently used will improve air *and* water quality may be premature.

Dairy emission reduction efforts highlight a specific example of a broader need for better integration across climate change and local air quality policies. Climate change and air pollution challenges exist together, such as with methane and ammonia emissions from dairies, but different agencies and policy frameworks manage them. There is growing recognition that simultaneously addressing climate change and air quality problems is more beneficial than addressing them separately. Better integration among the multiple policies, agencies, and places involved in California's climate change and air quality management systems is a crucial step to advance progress toward environmental benefits for all Valley residents.

VIII. POLICY ANALYSIS

Policy Alternatives

1. **Let present trends continue**
   Aligned with CARB Perspective

Alternative One represents CARB's LCFS policy and evidence on LCFS impacts. CARB considered California's dairy production systems when designing the LCFS program and biomethane market. Dairy producers will make significant contributions toward achieving SB 1383 2030 livestock methane reduction goals by 2030.

Millions have been invested for digester infrastructure, from both public and private funds, and expected herd attrition rates contribute to methane reductions. CARB funded 131 digesters for $214 million from 2015-2021 and projected that only half of the mandated livestock reduction goals would be met. UC Davis researchers identified commitments for at least 225 digesters to be constructed by mid-2022 and concluded that dairies would reduce twice as much methane as CARB projected. UC Davis also more accurately evaluated dairy herd attrition rates. USDA's Partnerships for Climate-Smart Commodities program recently awarded $85 million to California Dairy Research Foundation, to be administered by CDFA, for collaborative dairy methane reduction and groundwater management projects. USDA, CDFA, and state and national dairy organizations continue to support anaerobic digester technologies to manage manure methane emissions. Continuing current trends will lead to methane reduction and related infrastructure growth in the short-term, but changes are coming.

Included as part of Alternative One is CARB's 2024 proposed rule to modify the LCFS announced in February 2023. More information is needed to understand its implications, especially regarding market priorities for biomethane. If CARB approves the proposal to stop avoided methane accounting in 2030, farms with digesters will continue to receive credits for ten years following pathway approval and dairy operations will have time to prepare for CARB's post-2030 plans. These may include new financial mechanisms, policies to address biomethane demand, a transition from methane reduction to maintenance of lowered emissions, and commercially-available products to reduce enteric emissions.

CARB's LCFS program, including dairy credits, has helped build an effective, voluntary market to reduce methane emissions from the leading methane source in California. The combination of California's environmental leadership, increased consumer awareness about sustainable agricultural practices, and dairy industry research and development have contributed to the current environment supporting anaerobic digestion for dairy methane reduction. Large farms or clusters of farms can better afford to build, operate, and maintain anaerobic digesters, which limits participation by smaller farms. LCFS credits have not led to bigger average dairy farm sizes, though continuing to monitor changes in consolidation rates and other dairy practices can inform impacts long-term.

2. Hold dairies accountable

Aligned with EJ advocate Perspective

Alternative Two entails the elimination of avoided methane crediting and the addition of regulatory mechanisms such as direct emissions reductions and exclusion of livestock-derived biogas for use as LCFS fuel by January 1, 2024, as recommended by EJ advocates in March 2023 comments to CARB (Seaton et al., March 15, 2023).

CARB chose a voluntary approach during early LCFS implementation to reduce manure methane and, initially, also included an option to impose regulations in 2024. In 2023, however, CARB proposed 2030 as the date to act via rulemaking, including to stop avoided methane accounting. Because current LCFS incentives are in place, Alternative Two would be an abrupt change compared to CARB's proposed 2030 implementation date. It would increase reliance on existing digesters and alternative manure management practices for farms without digesters.

Dairy digesters are the most effective method available for reducing methane for larger dairies, yet Alternative Two would limit investment and participation in dairy digester and biomethane projects. Alternative manure management practices cannot achieve the same reductions as anaerobic digestion by 2030, though combining some alternative practices with anaerobic digestion can improve methane reductions. Alternative practices will continue to improve with continued research and development.

Alternative Two would likely lead to more lawsuits and/or loss of dairies to other states than other alternatives, and Alternative Two may prevent the state from reaching its 2030 state and global methane reduction goals.

This report focused on LCFS impacts on Valley methane and air quality outcomes, including EJ advocate interests in limiting herd growth and dairy air pollution. Valley communities should expect federal, state, and local air quality agencies to improve air quality and attain public health standards despite the challenges that exist in the Valley. The LCFS has reduced methane, but it was not designed to reduce air pollution. Limiting the tools available to dairies to reduce methane is unlikely to significantly improve methane reduction or air quality by 2030.

3. Expand waste-to-energy solutions used with anaerobic digesters

Aligned with small-medium farm Perspective

Alternative Three involves policies to incent co-digestion of manure with biowaste e.g., agricultural, food, and yard waste, to increase biogas yield, improve digester affordability, and divert organic waste from landfills

One consequence of the LCFS is digesters are more affordable for large farms to build and run than small to medium dairy farms. This advantage could lead to market distortion for farms without digesters. Approximately 50% of California dairy farms have 1,000 cows or less, though they represent only 17% of California's cows. CARB modeled 2,000 cow farms to demonstrate costs of DDRDP-funded farm and digester clusters, and it recommends AAMP strategies for smaller farms because of the 50% match required in DDRDP. Not all AMMP strategies have been demonstrated to be effective, however, limiting options further.

Incenting co-digestion and waste-to-energy approaches, instead of producing biomethane to reduce manure methane emissions, could expand opportunities for digester operators of all sizes. Incenting co-digestion of manure with additional types of biowaste can:

- Increase energy yield per feedstock dry matter
- Help small farms reach the needed feedstock volume to use a digester
- Improve digestate properties, such as nutrient balance and flow properties
- Replace synthetic fertilizer with high-quality digestate fertilizer
- Divert biowaste from landfills or burning
- Save on-farm costs for waste disposal and treatment
- Generate income from tipping fees (waste disposal fees for the biowaste)

New incentives to promote cost-effective, efficient biogas production and high-quality digestate will be required to implement Alternative Three. Combining manure and other biowaste, including food waste, can significantly increase methane yields over manure alone. In addition to livestock methane reduction, SB 1383 aimed to divert 75% of organic waste from landfills to anaerobic digesters to reduce methane emissions. Diversion of food waste from landfills and manure methane reduction with anaerobic digesters are separate programs in SB 1383, but promoting co-digestion could connect them.

Some countries in the European Union have extensive experience compared to California using anaerobic digester systems. Existing models could be adapted to develop a state-of-the-art system in California to maximize waste-to-energy solutions. Alternative Three provides opportunities for smaller dairies, though because larger dairies emit most of California's methane, this approach will be more politically feasible once 2030 goals are met.

4. Develop policies to co-reduce dairy methane *and* ammonia emissions
Aligned with Valley Community Perspective

Alternative Four includes improving CARB's LCFS strategies for dairy methane reduction to support voluntary incentives to co-reduce methane and ammonia, the dairy emissions of biggest concern for climate change and air quality, from manure and digestate.

CARB has successfully targeted dairies to reduce methane with the LCFS. California can use a similar strategy tailored to reduce dairy ammonia emissions from farms that have received or applied to receive digester funding. Manure emits methane and ammonia; while digestion decreases methane emissions, it can increase ammonia emissions. Methane is colorless and odorless, but ammonia has a characteristic odor and is a precursor to $PM_{2.5}$. It is unacceptable to reduce methane with anaerobic digestion, while increasing ammonia emissions. Co-reducing methane and ammonia would achieve multiple goals:

- Simultaneously reduce GHG and local air pollutants from the same dairy source to address a specific Valley challenge
- Build on successful collaborations between CARB and CDFA, expand the current strategy to reduce manure methane, and pilot innovative strategies to produce co-benefits
- Demonstrate California's leadership on air quality at local, state and federal levels
- Engage EPA's participation and leadership
- Create economic opportunities for dairies with digestate by-products

Relevant recommendations are available in the recently released *Manure Recycling and Innovative Products Talk Force Report* (CDFA, 2022). The report includes recommendations to reduce surplus manure nitrogen using conventional manure recycling strategies, compost strategies, nitrogen capture, denitrification and treatment, and options to combine existing and emerging strategies. Common manure management practices like solid-liquid separation (SLS) are cost-effective and can be used by small, medium, and large farms, with or without digesters. Using SLS before anaerobic digestion can reduce more methane and ammonia from manure.

Alternative Four would require expanded relationships between state and local agencies, including CARB and CDFA, and partnerships to drive innovation and identify the most effective strategies to pilot. Experience gained from California projects funded by USDA's Partnerships for Climate-Smart Commodities program may yield valuable findings. The goal would be to develop policies and mechanisms that build on existing frameworks but improve and expand them.

Policy Recommendations

The LCFS has been effective for reducing methane, but the program is in transition and can be improved. CARB is developing a proposed rule to update the LCFS in 2024, including its approach to biomethane production and credit pricing. Their proposed amendments will inform 2030 GHG reduction goals while looking ahead to California's 2045 goals.

Table 5 summarizes the analysis of the four Policy Alternative based on the criteria for policy analysis (Section IV).

Table 5: Policy Analysis Criteria Applied to Policy Alternatives

Policy Alternatives	Reduces methane by 2030	Minimizes harm from air quality impacts	Minimizes harm for smaller farms w/o digesters	Politically feasible
1. Let present trends continue	✓✓✓	✓	✓	✓✓✓
2. Replace incentives with regulations	✓✓	✓	✓	✓✓
3. Co-digest manure and biowaste	✓✓	✓	✓✓✓	✓
4. Co-reduce methane and ammonia	✓✓✓	✓✓	✓	✓✓

More check marks indicate higher score for criterion

Alternatives One and Four scored highest for meeting criteria in the chart:

Alternative One—"let present trends continue"—reduces methane, is politically feasible, and has momentum. It is difficult to analyze until more is known about CARB's proposed rule to modify the LCFS to be finalized in 2024. Alternative One does not minimize air pollution or improve options for smaller farms. In addition, it does not improve integration across agencies to address major Valley issues.

Alternative Four—"co-reduce methane and ammonia"—builds on Alternative One by adding ammonia reduction to existing manure methane reduction efforts. It reduces methane, improves Valley air quality by reducing ammonia emissions, and it can be developed to give benefits to smaller farms. Alternative Four provides an opportunity for California to continue to demonstrate leadership and innovation in policy approaches for environmental improvements by demonstrating that simultaneous improvements to climate change, air quality, and environmental justice are priorities in the San Joaquin Valley. The combination of methane and ammonia reduction is likely to appeal to environmental and environmental justice advocates, though dairy producers may resist additional regulations.

Final policy recommendations to limit LCFS' negative impacts:

- Develop and implement policies to co-reduce dairy methane *and* ammonia using lessons learned from the LCFS (Alternative Four)
- Implement alternative financial mechanisms to manage risk for dairies and stabilize the LCFS biomethane market consistent with California's 2045 goals
- Continue research and development to improve dairy manure methane reduction, including digester and non-digester approaches and technologies
- Increase accuracy of dairy emission measures, with and without digesters, to improve air quality models: increase dairy emission monitoring and establish dairy contributions to emission inventories

IX. RECOMMENDATIONS FOR FUTURE RESEARCH

While conducting research for this report, topics emerged that were of interest but out of scope. A few of them are included here:

1. Use the LCFS to systematize a waste-to-energy system to convert biogas to electricity to fuel electric vehicles in low-income communities in the Valley.

   See: Younes A, Fingerman KR, Barrientos C, Carman J, Johnson K, Wallach EA (2022). How the U.S. Renewable Fuel Standard could use garbage to pay for electric vehicles. *Energy Policy,* 166*,* 112916. https://doi.org/10.1016/j.enpol.2022.112916

2. Develop policies to simultaneously mitigate climate change and air quality, such as the potential for methane and ammonia co-emissions from dairies

   See: Fowlie, M, Walker, R, & Wooley, D (2020). Climate policy, environmental justice, and local air pollution. *University of California, Berkeley*. https://www.brookings.edu/research/climate-policy-environmental-justice-and-local-air-pollution/

3. Analyze the full spectrum of GHG and air pollutant emissions before and after anaerobic digestion of dairy manure.

   See: Duren R, Thorpe A & McCubbin I (2020). Energy Research and Development Division. The California Methane Survey. https://www.energy.ca.gov/sites/default/files/2021-05/CEC-500-2020-047.pdf

   See: Arndt C, Leytem AB, Hristov AN, D. Zavala-Araiza D, Cativiela JP, Conley S, Daube C, Faloona I, Herndon SC (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. https://doi.org/10.3168/jds.2017-13881

4. Analyze the economic and environmental impacts of stacking or layering biomethane credits in LCFS and RFS.

X. REFERENCES

Abernethy S, O'Connor FM , Jones CD & Jackson RB (2021). Methane removal and the proportional reductions in surface temperature and ozone. Philosophical Transactions Royal Society A. 379, 20210104. https://doi.org/10.1098/rsta.2021.0104

Aguirre-Villegas HA, Larson R & Reinemann DJ (2014). From waste-to-worth: energy, emissions, and nutrient implications of manure processing pathways. *Biofuels, Bioproducts, Biorefining*, 8(6), 739-870. https://doi.org/10.1002/bbb.1496

Aguirre-Villegas HA, Larson RA, Sharara MA, Sanford J, Liu Z & Schott L (2021). Anaerobic Digestion from Animal Manure. UW Madison Learning Store. https://learningstore.extension.wisc.edu/products/anaerobic-digestion-from-animal-manure?_pos=1&_sid=a0e564174&_ss=r

Agri-View (May 22, 2018). Co-ops support California proposal. https://agupdate.com/agriview/news/business/co-ops-support-california-proposal/article_1b358ed5-e75e-5f10-9d74-319d1620b389.html#:~:text=California's%20three%20largest%20milk%2Dmarketing,and%20Land%20O'Lakes%20Inc.

Arndt C, Leytem AB, Hristov AN, D. Zavala-Araiza D, Cativiela JP, Conley S, Daube C, Faloona I & Herndon SC (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. https://doi.org/10.3168/jds.2017-13881

August L, Bangia KL, Plummer L, Prasad S, Ranjbar K, Slocombe A & Wieland W (October 2021). CalEnviroScreen 4.0. https://oehha.ca.gov/media/downloads/calenviroscreen/report/calenviroscreen40reportf2021.pdf

Bardach E & Patashnik EM (2020). *A practical guide for policy analysis: the eightfold path to more effective problem solving.* CQ Press.

CalEPA (October 2021). Preliminary Designation of Disadvantaged Communities Pursuant to Senate Bill 535. https://calepa.ca.gov/wp-content/uploads/sites/6/2021/10/2021_CalEPA_Prelim_DAC_1018_English_a.pdf

CARB. LCFS Dashboard. https://ww2.arb.ca.gov/resources/documents/lcfs-data-dashboard

CARB. Air Quality Agencies. https://ww2.arb.ca.gov/our-work/programs/resource-center/introduction-community-air-quality/government-roles-and-contacts

CARB (December 2016). Meeting PM2.5 Standards in the San Joaquin Valley Public Workshop Fresno, California December 1, 2016. https://ww2.arb.ca.gov/sites/default/files/classic/planning/sip/sjvpm25/workshopslides.pdf

CARB (2017). Appendix F: Supporting Documentation for the Economic Assessment of Measures in the SLCP Strategy. https://ww2.arb.ca.gov/sites/default/files/2021-01/appendixF-SLCP-Final-2017.pdf

CARB (April 13, 2017). Staff Discussion Paper Renewable Natural Gas from Dairy and Livestock Manure. https://ww2.arb.ca.gov/sites/default/files/classic/fuels/lcfs/lcfs_meetings/041717discussionpaper_livestock.pdf

CARB (November 2018). California Air Resources Board Staff White Paper: SB 1383 Pilot Financial Mechanism Paper. https://ww2.arb.ca.gov/sites/default/files/2020-07/sb1383_financial_pilot_mechanism_whitepaper.pdf

CARB (November 26, 2018). Dairy Research Prospectus to Achieve California's SB 1383 Climate Goals. A document from the Dairy and Livestock Subgroup #3. Comprehensive outline of dairy research concepts and needs to effectively achieve California's SB 1383 climate goals. https://ww2.arb.ca.gov/sites/default/files/2020-11/dsg3-dairy-research-prospectus.pdf

CARB (August 13, 2021). Staff Report Proposed SIP Revision for the 15 µg/m^3 Annual PM2.5 Standard for the San Joaquin Valley. https://ww2.arb.ca.gov/sites/default/files/2021-08/SJV%2015%20ug%20SIP%20Revision%20Staff%20Report%20FINAL.pdf

CARB (March 2022). Analysis of Progress toward Achieving the 2030 Dairy and Livestock Sector Methane Emissions Target. https://ww2.arb.ca.gov/sites/default/files/2022-03/final-dairy-livestock-SB1383-analysis.pdf

CARB (December 2022). Scoping Plan for Achieving Carbon Neutrality. https://ww2.arb.ca.gov/sites/default/files/2022-12/2022-sp.pdf

CARB (February 22, 2023). Low Carbon Fuel Standard Public Workshop: Potential Regulation Amendment Concepts. Presentation. https://ww2.arb.ca.gov/sites/default/files/classic/fuels/lcfs/lcfs_meetings/LCFSpresentation_02222023.pdf

CDFA (2015-2022). Report of Funded Projects (2015–2022). https://www.cdfa.ca.gov/oefi/ddrdp/docs/2022_DDRDP_Legislative_Report.pdf

CDFA (2021). California Agricultural Production Statistics. https://www.cdfa.ca.gov/Statistics/.

CDFA (2018). Small Dairy Climate Action Plan: A Report to the Joint Legislative Budget Committee. A California Department of Food and Agriculture Report to Comply with Item 8570-101-3228 (1)(B) of the 2017 Budget Act. https://www.cdfa.ca.gov/oefi/ammp/docs/SmallDairyClimateActionPlan_July2018.pdf

CDFA (December 14, 2022). Manure Recycling and Innovative Products Talk Force Report. https://www.cdfa.ca.gov/oefi/research/docs/MRIP_FinalReport.pdf

Chen J, Jin Lu J, Avise JC, DaMassa JA, Kleeman MJ & Kaduwela AP (2014). Seasonal modeling of PM2.5 in California's San Joaquin Valley *Atmospheric Environment*, 92, 182-190. https://doi.org/10.1016/j.atmosenv.2014.04.030

Dairy Cares (March 15, 2023). Comments re: the Workshop to Discuss Potential Changes to the Low Carbon Fuel Standard held February 22, 2023. https://www.arb.ca.gov/lists/com-attach/103-lcfs-wkshp-feb23-ws-W2kBNFdmUzMGMVNm.pdf

Drewnowski A, Darmon, N, Monsivais P (2021). Affordable nutrient density: Toward economic indicators of sustainable healthy diets. *Sustainability*, 13, 9300. https://doi.org/10.3390/su13169300

Duren R, Thorpe A & McCubbin I (2020). Energy Research and Development Division Final Project Report. The California Methane Survey. https://www.energy.ca.gov/sites/default/files/2021-05/CEC-500-2020-047.pdf

EESI. Fact Sheet. Biogas: Converting Waste to Energy. https://www.eesi.org/papers/view/fact-sheet-biogasconverting-waste-to-energy

El Mashad HM, Barzee TJ, Franco RB, Zhang R, Kaffka S & Mitloehner FM (2023). Anaerobic digestion and alternative manure management technologies for methane emissions mitigation on Californian dairies. *Atmosphere*, 14(1), 120. https://doi.org/10.3390/atmos14010120

EPAa. Understanding Global Warming Potentials. https://www.epa.gov/ghgemissions/understanding-global-warming-potentials#:~:text=Methane%20(CH4)%20is%20estimated,more%20energy%20than%20CO2

EPAb. Health and Environmental Effects of Particulate Matter (PM). https://www.epa.gov/pm-pollution/health-and-environmental-effects-particulate-matter-pm

EPA (2002). Latest Findings on National Air Quality. https://www.epa.gov/sites/default/files/2017-11/documents/trends_brochure_2002.pdf

EPA (October 5, 2022). A Proposed Rule: Clean Air Plans; 2012 Fine Particulate Matter Serious Nonattainment Area Requirements; San Joaquin Valley, California. 40 CFR 52, Docket Number EPA-R09-OAR-2021-0884, pages 60494-60531. https://www.federalregister.gov/documents/2022/10/05/2022-21492/clean-air-plans-2012-fine-particulate-matter-serious-nonattainment-area-requirements-san-joaquin

ERS (2020). Scale Economies Provide Advantages to Large Dairy Farms. https://www.ers.usda.gov/amber-waves/2020/august/scale-economies-provide-advantages-to-large-dairy-farms/#:~:text=American%20dairy%20farms%20cover%20a,operations%20with%20several%20thousand%20cows

Escriva-Bou A, Hanak E, Cole S & Medellin-Azuara J (2023). Policy Brief: The Future of Agriculture in the San Joaquin Valley. https://www.ppic.org/publication/policy-brief-the-future-of-agriculture-in-the-san-joaquin-valley/

Fernandez-Bou A, Ortiz-Partida J, Dobbin K, Flores-Landeros H, Bernacchi L & Medellín-Azuara J (2021). Underrepresented, understudied, underserved: Gaps and opportunities for advancing justice in disadvantaged communities. *Environmental Science and Policy*, 122, 92-100. https://doi.org/10.1016/j.envsci.2021.04.014

Flores-Landeros H, Pells C, Campos-Martinez MS, Fernandez-Bou AS, Ortiz-Partida JP & Medellín-Azuara J (2021). Community perspectives and environmental justice in California's San Joaquin Valley. *Environmental Justice*, 15(6). https://doi.org/10.1089/env.2021.0005

Fowlie M, Walker R, & Wooley D (2020). Climate policy, environmental justice, and local air pollution. *University of California, Berkeley*. https://www.brookings.edu/research/climate-policy-environmental-justice-and-local-air-pollution/

Fu J (May 19, 2022). Is California giving its methane digesters too much credit?). The Counter. https://thecounter.org/is-california-giving-its-methane-digesters-too-much-credit/

GAO (2019). Dairy Cooperatives: Potential Implications of Consolidation and Investments in Dairy Processing for Farmers. GAO-19-695R. Publicly Released:. https://www.gao.gov/products/gao-19-695r

Gu B, Zhang L, Van Dingenen R, Massimo Vieno M, Van Grinsven HJM, Zhang X, Zhang S, Chen Y, Wang S, Ren C, Rao S, Holland M, Winiwarter W, Chen D, Xu J & Sutton MA (2021). Abating ammonia is more cost-effective than nitrogen oxides for mitigating PM2.5 air pollution, *Science* 374, 758–762 (2021). https//10.1126/science.abf8623

Ha S, Martinez V & Chan-Golston AM (2022). Air pollution and preterm birth: A time-stratified case-crossover study in the San Joaquin Valley of California. *Paediatric Perinatal Epidemiology*, 36, 80-89. https://doi.org/10.1111/ppe.12836

Hafner SD, Howard C, Muck RE & Franco RB (2013). Emission of volatile organic compounds from silage: Compounds, sources, and implications. *Atmospheric Environment,* 77, 827-839. http://dx.doi.org/10.1016/j.atmosenv.2013.04.076

Harter, T, Lund JR, Darby J, Fogg GE, Howitt R, Jessoe KK, Pettygrove GS, Quinn JF, Viers JH, Boyle DB, Canada HE, De La Mora N, Dzurella KN, Fryjoff-Hung A, Hollander AD, Honeycutt KL, Jenkins MW, Jensen VB, King AM, Kourakos G, et al. (2012). Addressing Nitrate in California's Drinking Water with a Focus on Tulare Lake Basin and Salinas Valley Groundwater. Report for the State Water Resources Control Board Report to the Legislature. Center for Watershed Sciences, University of California, Davis. http://groundwaternitrate.ucdavis.edu

Hayes RB, Lim C, Zhang Y, Cromar K, Shao Y, Reynolds HR, Silverman DT, Jones RR, Yikyung Park Y, Jerrett M, Ahn J &Thurston GD (2020). PM2.5 air pollution and cause-specific cardiovascular disease mortality. International Journal of Epidemiology, 49(1), 25-35. https://doi.org/10.1093/ije/dyz114

IDFA. U.S. dairy consumption hits all-time high in 2021 as growing category evolves toward yogurt, cheese, butter. https://www.idfa.org/news/recorddairyconsumption.

Jaffe AM & Dominguez-Faus R (2016). Final Draft Report on The Feasibility of Renewable Natural Gas as a Large-Scale, Low Carbon Substitute. Prepared for the California Air Resources Board and the California Environmental Protection Agency. STEPS Program, Institute of Transportation Studies, UC Davis.

Karlsson M, Alfredsson E & Westling N (2020). Climate policy co-benefits: a review, *Climate Policy*, 20:3, 292-316. https://10.1080/14693062.2020.1724070

Kebreab E, Frank Mitloehner FM & Sumner DA (2022). Meeting the Call: How California is Pioneering a Pathway to Significant Dairy Sector Methane Reduction. https://clear.ucdavis.edu/sites/g/files/dgvnsk7876/files/inline-files/Meeting-the-Call-California-Pathway-to-Methane-Reduction_0.pdf

Kelly JT, Parworth CL, Zhang Q, Miller DM, Sun K, Zondlo MA, Baker KR, Wisthaler A, Nowak JB, Pusede SE, Cohen RC, Weinheimer AJ, Beyersdorf AJ, Tonnesen GS, Bash JO, Valin LC, Crawford JH, Fried A & Walega JG (2018). Modeling NH4NO3 Over the San Joaquin Valley During the 2013 DISCOVER-AQ Campaign. *Journal of Geophysical Research: Atmospheres*, 123(9), 4727-4745. https://doi.org/10.1029/2018JD028290

Lazenby R, et al. (October 27, 2021). Petition for Rulemaking to exclude all fuels derived from biomethane from dairy and swine manure from the low carbon fuels standard program. https://food.publicjustice.net/wp-content/uploads/sites/3/2021/10/Factory-Farm-Gas-Petition-FINAL.pdf

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

Lievanos RS (2019). Racialized Structural Vulnerability: Neighborhood Racial Composition, Concentrated Disadvantage, and Fine Particulate Matter in California. *Int. J. Environ. Res. Public Health*, 16*(*17), 3196; https://doi.org/10.3390/ijerph16173196.

Lighthall D & Capitman J (2007). The Long Road to Clean Air in the San Joaquin Valley: Facing the Challenge of Public Engagement. Fresno, CA: California State University, Fresno. https://chhs.fresnostate.edu/cvhpi/documents/cvhpi-air-quality-report07.pdf

Liu S, Proudman J & Mitloehner FM (2021). Rethinking methane from animal agriculture. *CABI Agriculture and Bioscience*, 2, Article 22. https://doi.org/10.1186/s43170-021-00041-y

London J, Karner A, Sze J, Rowan D, Gambirazzio G & Niemeier D (2013). Racing climate change: Collaboration and conflict in California's global climate change policy arena. *Global Environmental Change*, 23(4), 791-799. https://doi-org.10.1016/j.gloenvcha.2013.03.001

Melamed ML, Schmale J & von Schneidemesser (2016). Sustainable policy—key considerations for air quality and climate change. *Current Opinion in Environmental Sustainability*, 23, 85–91.

MacDonald JA, Law J & Mosheim R (2020). Consolidation in U.S. Dairy Farming, July 2020. Economic Research Report No. (ERR-274). https://www.ers.usda.gov/webdocs/publications/98901/err-274.pdf?v=9365

Martin EW, Chester MV & Vergara SE (2015). Attributional and consequential life-cycle assessment in biofuels: a review of recent literature in the context of system boundaries. *Current Sustainable Renewable Energy Reports*, 2, 82–89. https://10.1007/s40518-015-0034-9

Matthews WA & Sumner DA (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

Meng YY, Rull RP, Wilhelm M, Lombardi C, Balmes CJ & Ritz B (2010). Outdoor air pollution and uncontrolled asthma in the San Joaquin Valley, California. *Journal Epidemiology Community Health*, 64, 142-147. https://doi:10.1136/jech.2009.083576

Miller DJ, Sun K, Tao L, Pan D, Zondlo MA, Nowak JB, Liu Z, Diskin G, Sachse G, Beyersdorf A, Ferrare R & Scarino AJ (2015). Ammonia and methane dairy emission plumes in the San Joaquin Valley of California from individual feedlot to regional scales. *Journal of Geophysical Research: Atmospheres,* 120(18), 9718-9738. https://doi.org/10.1002/2015JD023241

Naranjo A, Johnson A, Rossow H & Kebreab E (2020). Greenhouse gas, water, and land footprint per unit of production of the California dairy industry over 50 years. *Journal of Dairy Science***,** 103(4), 3760-3773. https://doi.org/10.3168/jds.2019-16576

OEHHA (October 2021). Analysis of Race/Ethnicity and CalEnviroScreen 4.0 Scores. https://oehha.ca.gov/media/downloads/calenviroscreen/document/calenviroscreen40raceanalysisf2021.pdf.

OEHHA. https://oehha.maps.arcgis.com/apps/instant/sidebar/index.html?appid=e876515e2b614784928db3f0789494c5.

Orzi V, Riva C, Scaglia B, D'Imporzano G, Tambone F & Adani F (2018). Anaerobic digestion coupled with digestate injection reduced odour emissions from soil during manure distribution. *Science of the Total Environment*, 621, 168-176. https://dx.doi.org/10.1016/j.scitotenv.2017.11.249

Owen JJ & Silver WL (2015). Greenhouse gas emissions from dairy manure management: a review of field-based studies. *Global Change Biology*, 21, 550–565. https://doi.org/10.1111/gcb.12687

Page LH, Ni JQ, Zhang H, Heber AJ, Mosier NS, Liu X, Joo HS, Ndegwa PM & Harrison JH (2014). Characteristics of volatile fatty acids in stored dairy manure before and after anaerobic digestion. *Biosystems Engineering*, 118(1) 16-28. http://dx.doi.org/10.1016/j.biosystemseng.2013.11.004

Page LH, Ni JQ, Zhang H, Heber AJ, Mosier NS, Liu X, Joo HS, Ndegwa PM & Harrison JH (2015). Reduction of volatile fatty acids and odor offensiveness by anaerobic digestion and solid separation of dairy manure during manure storage. *Journal of Environmental Management*, 152, 91-98. https://dx.doi.org/10.1016/j.jenvman.2015.01.024

Paulot F, Jacob DJ, Pinder RW, Bash JO, Travis K & Henze DK (2014). Ammonia emissions in the United States, European Union, and China derived by high-resolution inversion of ammonium wet deposition data: Interpretation with a new agricultural emissions inventory (MASAGE_NH3), Journal of Geophysical Research: Atmospheres, 119, 4343–4364. https://doi.org/10.1002/2013JD021130

Ross EG, Peterson CB, Zhao Y, Panand Y & Mitloehner FM (2021). Manure flushing vs. scraping in dairy freestall lanes reduces gaseous emissions. *Sustainability*, 13(10), 5363. https://doi.org/10.3390/su13105363

Schiferl LD, Heald CL Nowak, JB Holloway, JS Neuman, JA Bahreini, R, Pollack IB, Ryerson TB, Wiedinmyer C & Murphy JG (2014). An investigation of ammonia and inorganic particulate matter in California during the CalNex campaign. *Journal of Geophysical Research*, 119(4), 1883-1902. https://doi.org/10.1002/2013JD020765

Seaton P, et al. (March 15, 2023). Comments on Potential Changes to the Low Carbon Fuel Standard Program. https://www.arb.ca.gov/lists/com-attach/115-lcfs-wkshp-feb23-ws-UzlXPgBoVmtXJQNc.pdf

Shaw SL, Mitloehner FM, Jackson W, Depeters EJ, Fadel JG, Robinson PH, Holzinger R & Goldstein AH (2007). Volatile organic compound emissions from dairy cows and their waste as measured by proton-transfer-reaction mass spectrometry. *Environmental Science and Technology*, 41(4), 1310-1316. https://doi.org/10.1021/es061475e

Shonkoff SB, Morello-Frosch R, Pastor M & Sadd J (2009). Minding the Climate Gap: Environmental Health and Equity Implications of Climate Change Mitigation Policies in California. *Environmental Justice 2(4).* https://doi.org/10.1089/env.2009.0030

Smith A (February 3, 2021). What's Worth More: A Cow's Milk or its Poop? *Ag Data News Blog.* https://asmith.ucdavis.edu/news/cow-power-rising

Smith A (April 14, 2023). The Value of Methane from Cow Manure. *Ag Data News Blog.* https://asmith.ucdavis.edu/news/digester-update

Smith A (April 7, 2023). Are Manure Subsidies Causing Farmers to Milk More Cows? *Ag Data News Blog.* https://asmith.ucdavis.edu/news/are-digesters

SoCalGas (2019). Calgren Dairy Fuels. https://www.socalgas.com/sustainability/renewable-gas/rng-success-stories/calgren-dairy-fuels.

Sumner DA (2020). California Dairy: Resilience in a Challenging Environment. https://s.giannini.ucop.edu/uploads/pub/2021/01/21/chapter_6_dairy_2020.pdf

TEEB (2017). https://trueprice.org/milk-teeb/

Thoma G, Popp J, Nutter D, Shonnard D, Ulrich R, Matlock M, Kim DS, Neiderman Z, Kemper N, East C & Adom F (2013). Greenhouse gas emissions from milk production and consumption in the United States: A cradle-to-grave life cycle assessment circa 2008. *International Dairy Journal,* 31(S1), S3-S14. https://doi-org.libproxy.berkeley.edu/10.1016/j.idairyj.2012.08.013

Trousdell JF, Caputi D, Smoot J, Conley SA &Faloona IC (2019). Photochemical production of ozone and emissions of NOx and CH4 in the San Joaquin Valley. *Atmospheric Chemistry Physics*, 19(6), 10697–10716. https://doi.org/10.5194/acp-19-10697-2019

U.S. Dairy Net Zero Initiative. https://www.usdairy.com/sustainability/environmental-sustainability/net-zero-initiative.

United Nations Environment Program and Climate and Clean Air Coalition (2021). Global Methane Assessment: Benefits and Costs of Mitigating Methane Emissions. Nairobi: United Nations Environment Program. https://www.ccacoalition.org/en/resources/global-methane-assessment-full-report .

Viers JH, Liptzin D, Rosenstock TS, Jensen VB, Hollander AD, McNally A, King AM, Kourakos G, Lopez, EM, De La Mora N, Fryjoff-Hung A, Dzurella KN, Canada HE, Laybourne S, McKenney C, Darby J, Quinn JF & Harter T (2012). Nitrogen Sources and Loading to Groundwater. Technical Report 2 in: Addressing Nitrate in California's Drinking Water with a Focus on Tulare Lake Basin and Salinas Valley Groundwater. Report for the State Water Resources Control Board Report to the Legislature. Center for Watershed Sciences, University of California, Davis. http://groundwaternitrate.ucdavis.edu.

Walker JM, Philip S, Martin RV, & Seinfeld JH (2012). Simulation of nitrate, sulfate, and ammonium aerosols over the United States, *Atmospheric Chemistry and Physics*, 12, 11213–11227. https://doi.org/10.5194/acp-12-11213-2012

Wang T, Jiang Z, Zhao B, Gu Y, Liou KN, Kalandiyur N, Zhang D & Zhu Y (2020). Health co-benefits of achieving sustainable net-zero greenhouse gas emissions in California. Nature Sustainability, 3, 597–605. https://doi.org/10.1038/s41893-020-0520-y

West JJ, Fiore AM, Horowitz LW & Mauzerall DL (2006). Global health benefits of mitigating ozone pollution with methane emission controls, *PNAS*, 103(11), 3988-3993. https://doi.org/10.1073/pnas.06002011

Westerling L, Medellin-Azuara J & Viers J (2018). San Joaquin Valley Summary Report. California's Fourth Climate Change Assessment. Publication number: SUMCCCA4-2018-003. (University of California, Merced). https://www.energy.ca.gov/sites/default/files/2022-01/CA4_CCA_SJ_Region_Eng_ada.pdf

Whistance J, Thompson W & Meyer S (2017). Interactions between California's Low Carbon Fuel Standard and the National Renewable Fuel Standard. *Energy Policy,* 101, 447–455. http://dx.doi.org/10.1016/j.enpol.2016.10.040

World Bank. September 1, 2022. What You Need to Know About Climate Change and Air Pollution. https://www.worldbank.org/en/news/feature/2022/09/01/what-you-need-to-know-about-climate-change-and-air-pollution.

Younes A & Fingerman K (2021). Quantification of Dairy Farm Subsidies Under California's Low Carbon Fuel Standard Version 1.2. Prepared For: Union of Concerned Scientists, Washington DC. https://www.arb.ca.gov/lists/com-attach/24-lcfs-wkshp-dec21-ws-AHVSN1MhVlpXNQRl.pdf

Younes A, Fingerman KR, Barrientos C, Carman J, Johnson K, Wallach EA (2022). How the U.S. Renewable Fuel Standard could use garbage to pay for electric vehicles. *Energy Policy,* 166*,* 112916. https://doi.org/10.1016/j.enpol.2022.112916

Zhao C, Andrews AE, Bianco L, Eluszkiewicz J, Hirsch A, MacDonald C, Nehrkorn T, & Fischer ML (2009). Atmospheric inverse estimates of methane emissions from Central California. *Journal of Geophysical Research,* 114, 1-13. https://doi.org/10.1029/2008JD011671

Zhu L, Henze DK, Cady-Pereira KE, Shephard MW, Luo M, Pinder RW, Bash JO & Jeong GR (2013). Constraining U.S. ammonia emissions using TES remote sensing observations and the GEOS-Chem adjoint model. *Journal of Geophysical Research Atmospheres* 118(8), 3355-3368. https://doi.org/10.1002/jgrd.50166