California Dairy Greenhouse Gas and Air Quality Research: Summary

What are the policy drivers for dairy greenhouse gas (GHG) and air quality (AQ) research?

AB 32 and SB 32 – GHG reduction targets; SB 605 – Short-Lived Climate Pollutant (SLCP) strategy; SB 1383 – methane (CH_4) reduction target; AB 1496 – statewide CH_4 survey; AB 617 – community air quality monitoring and protection; and meeting State Implementation Plan (SIP) targets.

What California relevant dairy GHG and AQ research has been done?

Experimental measurements and model simulations have been used to determine the environmental impacts of dairy-related air pollutants (including GHGs) that are typically emitted through various stages of its operation. Air pollutants include GHGs such as CH_4 and nitrous oxide (N_2O), and other important AQ drivers such as volatile organic compounds (VOCs), ammonia (NH_3), hydrogen sulfide (H_2S), oxides of nitrogen (NO_x), and particulate matter (PM)[1-8]. These efforts include, but are not limited to: estimating air pollutant emission rates/factors to evaluate and improve emission inventories[2, 9-11]; developing process-based emission models[12-14]; assessing impacts on regional air quality and climate change[1, 5, 15-17]; and investigating various mitigation practices for air pollution emission reductions[18-20].

For summary of agricultural emissions research in California, please visit: https://www.arb.ca.gov/ag/2017apr21agresearch.pdf

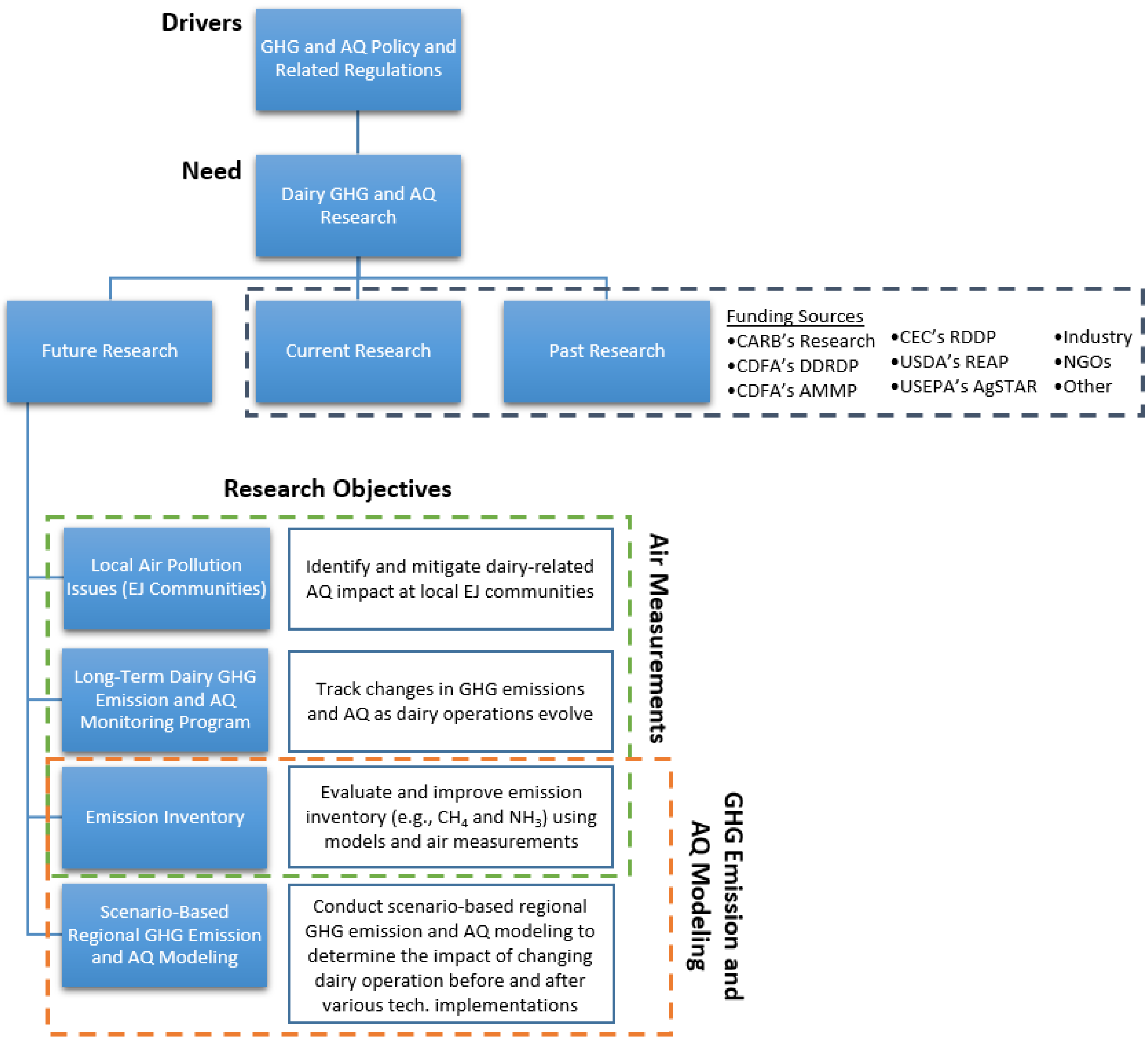
What were the conclusions from these studies?

- Dairies and livestock are the largest sources of methane emissions in the San Joaquin Valley[21, 22].
- Dairy-related emissions such as VOCs and NH_3 contributes to a significant fraction of the secondary air pollutants that are formed in the San Joaquin Valley (e.g., ozone, PM)[16, 23].
- There are considerable variabilities in when, where, and how much air pollutant emissions occur from dairies[24-26].
- Emission inventories appear to underestimate CH_4 and NH_3 emissions associated with dairies[27-30].
- Process-based emission models are useful in quantitatively estimating air pollutant emissions from dairies, but are not complete and need additional improvements to better represent real-world conditions (i.e., chemical, biological, and physical processes that affect emissions)[13, 31, 32].
- Available dairy-related air measurements are spatially sparse and lack temporal resolution.
- Potential mitigation options (such as alternative manure management strategies and renewable energy) are available, but need further review to evaluate impacts[33-38].

What future research are needed to move toward effective reduction of GHG emissions and improved AQ?

- **Assess localized air pollution issues associated with dairies, especially in environmental justice communities**.
- **A Long-term dairy GHG emission and AQ monitoring program** should be implemented to track air pollutant emissions from dairies (e.g., quantify baseline concentrations of air pollutants such as CH_4, and then evaluate the effectiveness of air pollution mitigation strategies).
- California-specific data should be used to conduct a comprehensive reassessment of the current **emission inventories** (e.g., CH_4, NH_3, etc.). This includes improvement of process-based emission models and additional air measurements to support their development.
- **Scenario-based regional GHG emission and AQ modeling** should be used to evaluate the environmental impacts of changing dairy operations (e.g., potential GHG and AQ benefits of producing renewable energy from dairies) to identify the most effective and feasible air pollution mitigation strategies.

The figure below provides an overview of the research needs using the four main research objectives as outlined in this section:



References

1. Shaw, S. L.; Mitloehner, F. M.; Jackson, W.; DePeters, E. J.; Fadel, J. G.; Robinson, P. H.; Holzinger, R.; Goldstein, A. H. Volatile organic compound emissions from dairy cows and their waste as measured by proton-transfer-reaction mass spectrometry. *Environmental science & technology* **2007,** *41*, (4), 1310-1316; DOI: 10.1021/es061475e.
2. Alanis, P.; Sorenson, M.; Beene, M.; Krauter, C.; Shamp, B.; Hasson, A. S. Measurement of non-enteric emission fluxes of volatile fatty acids from a California dairy by solid phase micro-extraction with gas chromatography/mass spectrometry. *Atmospheric Environment* **2008,** *42*, (26), 6417-6424; DOI: 10.1016/j.atmosenv.2008.05.015.
3. Alanis, P.; Ashkan, S.; Krauter, C.; Campbell, S.; Hasson, A. S. Emissions of volatile fatty acids from feed at dairy facilities. *Atmospheric Environment* **2010,** *44*, (39), 5084-5092; DOI: 10.1016/j.atmosenv.2010.09.017.
4. El-Mashad, H. M.; Zhang, R.; Arteaga, V.; Rumsey, T.; Mitloehner, F. Volatile fatty acids and alcohols production during anaerobic storage of dairy manure. *Transactions of the ASABE* **2011,** *54*, (2), 599-607; DOI: 10.13031/2013.36463.
5. Rabaud, N. E.; Ebeler, S. E.; Ashbaugh, L. L.; Flocchini, R. G. Characterization and quantification of odorous and non-odorous volatile organic compounds near a commercial dairy in California. *Atmospheric Environment* **2003,** *37*, (7), 933-940; DOI: 10.1016/S1352-2310(02)00970-6.
6. Chung, M. Y.; Beene, M.; Ashkan, S.; Krauter, C.; Hasson, A. S. Evaluation of non-enteric sources of non-methane volatile organic compound (NMVOC) emissions from dairies. *Atmospheric Environment* **2010,** *44*, (6), 786-794; DOI: 10.1016/j.atmosenv.2009.11.033.
7. Fitz, D. R.; Pisano, J. T.; Malkina, I. L.; Goorahoo, D.; Krauter, C. F. A passive flux denuder for evaluating emissions of ammonia at a dairy farm. *Journal of the Air & Waste Management Association* **2003,** *53*, (8), 937-945; DOI: 10.1080/10473289.2003.10466243.
8. Garcia, J.; Bennett, D. H.; Tancredi, D.; Schenker, M. B.; Mitchell, D.; Mitloehner, F. M. A survey of particulate matter on California dairy farms. *Journal of environmental quality* **2013,** *42*, (1), 40-47; DOI: 10.2134/jeq2012.0169.
9. Battye, W.; Aneja, V. P.; Roelle, P. A. Evaluation and improvement of ammonia emissions inventories. *Atmospheric Environment* **2003,** *37*, (27), 3873-3883; DOI: 10.1016/S1352-2310(03)00343-1.
10. Pinder, R. W.; Strader, R.; Davidson, C. I.; Adams, P. J. A temporally and spatially resolved ammonia emission inventory for dairy cows in the United States. *Atmospheric Environment* **2004,** *38*, (23), 3747-3756; DOI: 10.1016/j.atmosenv.2004.04.008.
11. Kebreab, E.; Johnson, K.; Archibeque, S.; Pape, D.; Wirth, T. Model for estimating enteric methane emissions from United States dairy and feedlot cattle. *Journal of animal science* **2008,** *86*, (10), 2738-2748; DOI: 10.2527/jas.2008-0960.
12. Pinder, R. W.; Pekney, N. J.; Davidson, C. I.; Adams, P. J. A process-based model of ammonia emissions from dairy cows: improved temporal and spatial resolution. *Atmospheric Environment* **2004,** *38*, (9), 1357-1365; DOI: 10.1016/j.atmosenv.2003.11.024.
13. Li, C.; Salas, W.; Zhang, R.; Krauter, C.; Rotz, A.; Mitloehner, F. Manure-DNDC: a biogeochemical process model for quantifying greenhouse gas and ammonia emissions from livestock manure systems. *Nutrient Cycling in Agroecosystems* **2012,** *93*, (2), 163-200; DOI: 10.1007/s10705-012-9507-z.
14. Mitloehner, F.; Sun, H.; Karlik, J. Direct measurements improve estimates of dairy greenhouse-gas emissions. *California agriculture* **2009,** *63*, (2), 79-83; DOI: 10.3733/ca.v063n02p79.
15. Chow, J. C.; Watson, J. G.; Park, K.; Robinson, N. F.; Lowenthal, D. H.; Park, K.; Magliano, K. A. Comparison of particle light scattering and fine particulate matter mass in central California. *Journal of the Air & Waste Management Association* **2006,** *56*, (4), 398-410; DOI: 10.1029/2005JD006457.
16. Howard, C. J.; Kumar, A.; Malkina, I.; Mitloehner, F.; Green, P. G.; Flocchini, R. G.; Kleeman, M. J. Reactive organic gas emissions from livestock feed contribute significantly to ozone production in central California. *Environmental science & technology* **2010,** *44*, (7), 2309-2314; DOI: 10.1021/es902864u.

17. Ying, Q.; Lu, J.; Kleeman, M. Modeling air quality during the California Regional PM 10/PM 2.5 Air Quality Study (CPRAQS) using the UCD/CIT source-oriented air quality model–Part III. Regional source apportionment of secondary and total airborne particulate matter. *Atmospheric Environment* **2009,** *43*, (2), 419-430; DOI: 10.1016/j.atmosenv.2008.08.033.
18. Meyer, D.; Mullinax, D. D. Livestock nutrient management concerns: Regulatory and legislative overview. *Journal of Animal Science* **1999,** *77*, (suppl_2), 51-62; DOI: 10.2527/1999.77suppl_251x.
19. Meyer, D.; Reed, B.; Batchelder, C.; Zallo, I.; Ristow, P.; Higginbotham, G.; Arana, M.; Shultz, T.; Mullinax, D.; Merriam, J. Water use and winter liquid storage needs at central valley dairy farms in California. *Applied engineering in agriculture* **2006,** *22*, (1), 121-126; DOI: 10.13031/2013.20188.
20. Zapata, C.; Muller, N.; Kleeman, M. J. PM2. 5 co-benefits of climate change legislation part 1: California's AB 32. *Climatic change* **2013,** *117*, (1-2), 377-397; DOI: 10.1007/s10584-012-0545-y.
21. Guha, A.; Gentner, D.; Weber, R.; Provencal, R.; Goldstein, A. Source apportionment of methane and nitrous oxide in California's San Joaquin Valley at CalNex 2010 via positive matrix factorization. *Atmospheric Chemistry and Physics* **2015,** *15*, (20), 12043-12063; DOI: 10.5194/acp-15-12043-2015.
22. Gentner, D.; Ford, T.; Guha, A.; Boulanger, K.; Brioude, J.; Angevine, W.; De Gouw, J.; Warneke, C.; Gilman, J.; Ryerson, T. Emissions of organic carbon and methane from petroleum and dairy operations in California's San Joaquin Valley. *Atmospheric Chemistry and Physics* **2014,** *14*, (10), 4955; DOI: 10.5194/acp-14-4955-2014.
23. Hu, J.; Howard, C. J.; Mitloehner, F.; Green, P. G.; Kleeman, M. J. Mobile source and livestock feed contributions to regional ozone formation in Central California. *Environmental science & technology* **2012,** *46*, (5), 2781-2789; DOI: 10.1021/es203369p.
24. Moore, K. D.; Young, E.; Wojcik, M. D.; Martin, R. S.; Gurell, C.; Bingham, G. E.; Pfeiffer, R. L.; Prueger, J. H.; Hatfield, J. L. Ammonia measurements and emissions from a California dairy using point and remote sensors. *Transactions of the ASABE* **2014,** *57*, (1), 181-198; DOI: 10.13031/trans.57.10079.
25. Lonsdale, C. R.; Hegarty, J. D.; Cady-Pereira, K. E.; Alvarado, M. J.; Henze, D. K.; Turner, M. D.; Capps, S. L.; Nowak, J. B.; Neuman, J. A.; Middlebrook, A. M. Modeling the diurnal variability of agricultural ammonia in Bakersfield, California, during the CalNex campaign. *Atmospheric Chemistry and Physics* **2017,** *17*, (4), 2721-2739; DOI: 10.5194/acp-17-2721-2017.
26. Miller, D. J.; Sun, K.; Tao, L.; Pan, D.; Zondlo, M. A.; Nowak, J. B.; Liu, Z.; Diskin, G.; Sachse, G.; Beyersdorf, A. Ammonia and methane dairy emission plumes in the San Joaquin Valley of California from individual feedlot to regional scales. *Journal of Geophysical Research: Atmospheres* **2015,** *120*, (18), 9718-9738; DOI: 10.1002/2015JD023241.
27. Zhao, C.; Andrews, A. E.; Bianco, L.; Eluszkiewicz, J.; Hirsch, A.; MacDonald, C.; Nehrkorn, T.; Fischer, M. L. Atmospheric inverse estimates of methane emissions from Central California. *Journal of Geophysical Research: Atmospheres* **2009,** *114*, (D16); DOI: 10.1029/2008JD011671.
28. Owen, J. J.; Silver, W. L. Greenhouse gas emissions from dairy manure management: a review of field-based studies. *Global change biology* **2015,** *21*, (2), 550-565; DOI: 10.1111/gcb.12687.
29. Kelly, J. T.; Baker, K. R.; Nowak, J. B.; Murphy, J. G.; Markovic, M. Z.; VandenBoer, T. C.; Ellis, R. A.; Neuman, J. A.; Weber, R. J.; Roberts, J. M. Fine-scale simulation of ammonium and nitrate over the South Coast Air Basin and San Joaquin Valley of California during CalNex-2010. *Journal of Geophysical Research: Atmospheres* **2014,** *119*, (6), 3600-3614; DOI: 10.1002/2013JD021290.
30. Nowak, J.; Neuman, J.; Bahreini, R.; Middlebrook, A.; Holloway, J.; McKeen, S.; Parrish, D.; Ryerson, T.; Trainer, M. Ammonia sources in the California South Coast Air Basin and their impact on ammonium nitrate formation. *Geophysical Research Letters* **2012,** *39*, (7); DOI: 10.1029/2012GL051197.
31. Place, S. E.; Mitloehner, F. Invited review: Contemporary environmental issues: A review of the dairy industry's role in climate change and air quality and the potential of mitigation through improved production efficiency. *Journal of Dairy Science* **2010,** *93*, (8), 3407-3416; DOI: 10.3168/jds.2009-2719.
32. Salas, W.; Li, C.; Mitloehner, F.; Pisano, J. Developing and applying process-based models for estimating greenhouse gas and air emission from California dairies. **2008**. (Accessed: November 2017).

33. Madden, N.; Southard, R.; Mitchell, J. Conservation tillage reduces PM 10 emissions in dairy forage rotations. *Atmospheric Environment* **2008,** *42*, (16), 3795-3808; DOI: 10.1016/j.atmosenv.2007.12.058.
34. Sun, H.; Pan, Y.; Zhao, Y.; Jackson, W. A.; Nuckles, L. M.; Malkina, I. L.; Arteaga, V. E.; Mitloehner, F. M. Effects of sodium bisulfate on alcohol, amine, and ammonia emissions from dairy slurry. *Journal of environmental quality* **2008,** *37*, (2), 608-614; DOI: 10.2134/jeq2006.0446.
35. Zhang, R.; McGarvey, J. A.; Ma, Y.; Mitloehner, F. M. Effects of anaerobic digestion and aerobic treatment on the reduction of gaseous emissions from dairy manure storages. *International Journal of Agricultural and Biological Engineering* **2008,** *1*, (2), 15-20; DOI: 10.3965/j.issn.1934-6344.2008.02.015-020.
36. Camarillo, M. K.; Stringfellow, W. T.; Hanlon, J. S.; Watson, K. A. Investigation of selective catalytic reduction for control of nitrogen oxides in full-scale dairy energy production. *Applied energy* **2013,** *106*, 328-336; DOI: 10.1016/j.apenergy.2013.01.066.
37. Hamilton, S. W.; DePeters, E. J.; McGarvey, J. A.; Lathrop, J.; Mitloehner, F. M. Greenhouse gas, animal performance, and bacterial population structure responses to dietary monensin fed to dairy cows. *Journal of environmental quality* **2010,** *39*, (1), 106-114; DOI: 10.2134/jeq2009.0035.
38. Stackhouse, K.; Rotz, C.; Oltjen, J.; Mitloehner, F. Growth-promoting technologies decrease the carbon footprint, ammonia emissions, and costs of California beef production systems. *Journal of animal science* **2012,** *90*, (12), 4656-4665; DOI: 10.2527/jas.2011-4654.