

## Facility scale inventory of dairy methane emissions in California: Implications for mitigation

### Responses to Reviewers

Thank you very much for your reviews and for the ability to resubmit our paper, “Facility scale inventory of dairy methane emissions in California: Implications for mitigation.” In addition to addressing the reviewer comments, detailed below, we have also updated our list of dairy facilities based on new information regarding dairy farm closures and confined animal facility fee documentation. We now have 1326 dairy facilities, down from 1727, which we believe to be more accurate. Despite this change, spatial patterns still show the majority of emissions in the Central Valley of California, with smaller emissions in the North Coast and Southern regions. None of our other results have significantly changed either, as the number of animals stayed relatively constant.

#### Reviewer 1

The paper reports the first (to my knowledge and as stated by the authors) spatially explicit database of dairies in California. Such detailed information is of great relevance for improving bottom-up emissions estimates, comparing bottom-up to top-down methods and assessing the effectiveness of mitigation options. The method is written up in a transparent way that will also allow relatively easy adjustment of individual parameters in the future. The paper is generally clearly written, but also relatively long. I sometimes got a bit lost in paragraphs where the individual parameters are described one after the other and suggest that you refer to the tables more efficiently, if possible. The underlying choices are substantiated by relevant references to existing literature or databases. There are some places where information from the introduction (motivation) is repeated in results, and in particular in the conclusions section. I encourage the authors to reduce repetitions and focus in the conclusions mainly on the results from this study, or otherwise shorten these paragraphs in the introduction. My second request is to pay attention to the units, they do not always fit throughout the paper (some omissions in the text, which seem to be correct in the tables). Specific suggestions:

Line 150-155: Is it really necessary to list all the counties? I suggest to delete this and refer to Table S2.

Thank you for this suggestion. We have deleted the county names and refer to Table S2.

Line 232: unit: should be kg/cow/yr, correct in Table, all numbers in these paragraph miss the time interval in the denominator (per year)

We have corrected the units by adding the per year denominator to the numbers.

Line 243 and at other places: It is mathematically correct to add the letter i under the sum symbol to indicate the parameter that is summed over

We changed the formatting to indicate that the sum is for all i.

Line 248: units: DMI should be kg/cow/day, value and unit (g/kgDMI) should be stated in the text for E2

We have updated the units to kg/head/day.

Line 257: “and” missing before milkfat

We added this word.

Line 257: . . .we also include emission factors

Emission factors have a very specific definition, and the factors for DMI, NDF, and mf are not technically emission factors.

Line 260: The index "I" is missing for mf and f\_mf

We added the index "I" to the terms in this equation

Line 267: To make the units fit in the equation, you should multiply by 365 days/yr

We added this to the description

Line 282: Density: unit is wrong, must be g/l, or g/dm<sup>3</sup>

We have updated the units on the density

Line 283: Provide value and unit for B<sub>0</sub>, describe what the Max CH<sub>4</sub> production capacity is

We have added the unit, value, and description for Bo: B<sub>0</sub> is the maximum methane production capacity per unit of VS in dairy manure (0.24 m<sup>3</sup> CH<sub>4</sub>/kg VS), We also state the Bo is a theoretical maximum value for the given manure type.

Line 284: Refer to Tables here. Are the VS values in tables?

We refer to Table 4 here, and the VS values are in this table.

Line 296 ff: Refer to tables for better overview

We removed some text and refer to the tables and glossary.

Line 299: B<sub>0</sub>: 0 should be subscript

We subscripted the 0.

Line 299 ff: for MCF refer to tables for better overview

We refer to the table 4 instead of presenting the values in the table.

Page 13; line numbers missing in my copy, line 1: Are these units correct? More than 2 tons per day? Add B<sub>0</sub> values to a table.

We updated the units to be kg/year, rather than kg/day, and added Bo to the glossary.

Line 341: I think it is adequate to neglect the variation of methane density, but is this also true for maximum methane production? Please also clarify what this parameter is, see comment line 283.

This is an excellent question. We have incorporated uncertainty in Bo to the text.

Line 359, stick to symbol rho for density as in other equations

We have updated the symbol here.

Line 404: seems to be a typo, value and error are exactly the same number

Thank you, we have updated the numbers.

Line 423: I suggest that you may want to comment on whether or not the smaller uncertainty of M1 means that method M1 is better than methods M2 and M3, and what could be the reason for this large difference in uncertainty.

We added the following to the description: "While the uncertainty for M1 is smaller than M2 and M3, this is due to the relative simplicity of the equation, with fewer propagated errors, rather than being the inherently best model. A recent report determined that the CARB methodology underestimates manure methane emissions (NASEM, 2018)."

Line 439 f: the value that is described as highest here, 0.25 for Central Valley, is smaller than the 1.6 for the North Coast. Must be a mix up of numbers.

Thank you for noticing this mix up. This is correct – we have updated the numbers and now the Central Valley data is higher than for the North Coast.

Line 448: Full stop missing

Thank you for catching that. We added the period.

Line 449: . . . differences in enteric : manure emissions . . .

We added the word emissions

Line 525: leave out this sentence? You implicate in the next sentence that the statewide numbers can also be derived with the older methods (maybe add somewhere in the discussion earlier that this is not so surprising at least for enteric, since you use the same numbers of animals).

We feel that this statement is an important caveat to note, but have reorganized and reworded to make the point more clearly.

Line 531-536: Repeated from introduction (motivation) and not necessary to repeat here.

We removed this section

Line 539-542: Repeated from method/results and not necessary to repeat here.

We removed these sentences.

Line 545-554: shorten/reword this paragraph focused to the sentence; We are most confident. . . you could strengthen the point that better reporting would help for your new inventory. Sentence with reference to Hamilton could be moved to methods.

Thank you for this suggestion. We reorganized the paragraph and moved the suggested sentence to the methods section.

Table 3: Make sure that units reported are consistent (factor 1/cow)

We updated the appropriate units to be 1/head.

Table 4: Provide units for all parameters

Thank you for this suggestion. We have updated the table to include units for the parameters.

Line 598: delete “the ratio of”

We deleted these words.

Figure 4: describe unit of color bar (-0.3 to 0.3). Are these relative or absolute differences?

We clarified the legend of the color bar

Line 615: M3 should be Calgem

We have updated this in the manuscript.

Supplementary material: L24: water board reports L33: . . . counties that did not

L34 ff: do you need this long list of counties (refer to table?)

We have removed the counties and refer to Table S2.

Line 64 ff: Maybe you can make the point that n is actually the easiest variable to improve knowledge on, so better constraints on n will be valuable especially since some final numbers depend strongly on n. This also holds for dairies in VISTA.

The information on the number of cows is actually proprietary information that is not consistently reported by any one agency, and the agencies do not communicate with each other. Further, the number of milk cows changes interannually (as they only lactate for part of the year, and are considered dry cows the remainder of the year), and the animals are sold and traded. These factors make this information surprisingly difficult to estimate. Nevertheless, we were able to obtain updated information on the number of cows, which we included in the manuscript. We have added this information to the supplemental material (lines 14-19).

Line 84: Not clear why SE is based on  $n=77$

Thank you for noticing this lack of background. These data with the n provided by the reference, which we have clarified.

Line 104: Can you illustrate for this one concrete example explicitly how you come from the two values 69.8% and 78.2 % to the standard error of 26.2%? This is not immediately clear to me.

We have updated the numbers in this section and believe it will be more clear.

Line 106, 114, and few other places: correct mathematical way of writing this result is (34.0 +/- 12.0) %

We have updated the formatting to this style.

Line 131: but also for E2, M1, and M2 in S1.2.2: Provide the final value for SE in text, or refer to table. Now you only state the confidence bounds, but not the final SE.

We have updated the section to include the SE as well as the confidence bounds.

Line 160 ff: S2.1 could potentially be a table in the main paper, would allow to shorten text there

The text describes the definitions of the animals in the different sources of data, but not the definitions that we use. However, we combined Supplement S2.1 and S2.3 and included it in the main paper.

Line 169 ff: S2.2 could be shown along Fig. 1 in the main paper

We removed this section from the supplemental and incorporated it in the description for Fig 1.

Line 183 ff: I strongly suggest that S2.3 should be shown in the main paper, units should be added, and for constant values also the values here.

We combined S2.1 and S2.3, and moved it to be an appendix in the main paper. We have also added units and the values for the constants.

Line 185: you use rho rather than density in the equations, adapt here

We updated density to use rho.

Reviewer 2

Interesting paper. However, the paper is long and sometimes is difficult to follow the idea started at the beginning of the section. A better presentation of results could be possible. Some comments are listed below:

Thank you for your reading of the manuscript. We removed several sentences from the discussion (see comments below), and updated our presentation of the results by moving many of the quantitative details to tables. Your specific comments are addressed below.

1. Point.2.2 – Authors show that they are using 3 data sources for the herd population. Are these sources complementary and which periods are they covering? Or the years under consideration are 2005, 2011 and 2017? It is not clear.

We have incorporated a new data source – from confined animal facility fee documentation - for ncows, which has enabled us to clarify the text: “We determined herd population sizes primarily from the 2019 CAF fees list. However, some dairies did not pay a fee in 2019, but still have animals, so for these facilities we integrated data from three sources to estimate herd numbers and demographic categories at each dairy: Regional Water Quality Control Board permits, SJVAPCD permits, and individual facility documentation” (lines 217-233).

2. A comparison between these sources might be interesting

These sources are not directly overlapping, so a direct comparison is unfortunately not possible. However, we have updated our source of ncows (see comment 1) which we believe to be more holistic and accurate.

3. Methods applied to calculate CH<sub>4</sub> emissions should get a reference with methods (Tier 1 and Tier 2) described at the IPCC 2006 Guidelines. Line 229-231 describe method E1 which seems to correspond to the IPCC 2006 Tier 1 method.

We have clarified that the CARB inventory is based on the IPCC Tier 1 method.

4. When writing an equation use separate paragraphs to list the components of this equation starting with where:

The variables in the equations are described before the equations to aid in flow and understanding (from Dynamic Models in Biology book; Ellner and Gukenheimer 2006).

5. Line 237 – which is the source of the assumed EFs?

We added a reference to this statement (Charrier et al. 2016).

6. Lines 247-250: it is clearer if EFs are presented in table format

We added reference to Table 3 in this section.

7. Line 275 – which are methods M1, M2 and M3? The methods in points 1,2 and 3? Link better the explanation of methods with their names. The same for enteric fermentation

We added the names of the methods in parenthesis to the end of the explanations, which we think is now a lot clearer. Thank you for pointing this out!

8. Point 4. Data availability can be part of supplementary material

Data availability is required in the main text by the journal.

9. Point 3.4 – can you explain why the uncertainty and standard errors are higher for manure compared to enteric fermentation?

Great point. We added the sentence: “The higher uncertainty in the manure emissions than enteric emissions is due primarily to our uncertainty in facility-level manure management practices and the limited information on lagoon MCF.” (line 879-880)

10. Line 282 - Correct Methane density that is 0.657 kg/m<sup>3</sup> (0.657 g/dm<sup>3</sup>) and not 0.662 g/cm<sup>3</sup>

The conversion factor for methane as reported in the IPCC and the CARB inventory documentation is 0.662 m<sup>3</sup> / kg. We have clarified the sources in the text.

11. DMI units in kg/day/cow

Thank you, we have updated the units of DMI.

12. Long conclusions and repetitive with introduction and methods insert

We have removed several repetitive sentences from the conclusion section to shorten it, including the section: “The farm-specific Vista-CA Dairies emission product is the first spatially-explicit database of CH<sub>4</sub> emissions from dairy at the farm scale. By separately mapping enteric fermentation emissions and manure management emissions, our product is valuable for source attribution and for determining the effects of changes to management on greenhouse gas budgets. At the state level, manure and enteric fermentation CH<sub>4</sub> emissions from the farm-specific method were not significantly different than previous analyses (Appuhamy, 2018; CARB, 2014; Hristov et al., 2017; Maasackers et al., 2016), which supports the validity of the farm-specific methodology. However, at the facility scale, state or county-level assumptions by EPA and CARB often do not match on-farm reality (Arndt et al., 2018), particularly given that they use statewide average emissions factors that cannot capture regional differences in climate or management.”

13. Fig.2 – Specify the region in the figure title

We added California to the figure title for Figure 2 and 4.

14. It seems that the CH<sub>4</sub> emissions from all cattle and from dairy cows estimated using three methods in manure management are the same. This situation is not in enteric fermentation. Can you explain?

Non-lactating cows produce a substantial amount of methane via enteric fermentation, but because their manure is primarily managed as solids, their contributions to manure methane emissions are minimal. We have added the following text to the manuscript to clarify this point: “The difference in enteric emissions between the milk cows and total cows is due to the fact that non-milk cows produce significant amounts of enteric methane emissions” (Line 729-731). We also include the similar sentence “ This is because the manure of non-milk cows is primarily managed in ways with very low methane emissions, including daily spread, on dry lots, or on pasture” in the manure management section (Line 846-848).