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Facility-scale inventory of dairy methane emissions in California: implications for mitigation

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SUPPLEMENT:

S1. Supplemental Methods

S1.1 Uncertainty analysis

S1.1.1 Facility level uncertainty

n: We assume that the uncertainty in the cattle populations is 20%, as recommended by the IPCC. For dairies with cattle permits, the water quality board assumes 15% uncertainty in population (California Regional Water Quality Control Board, 2013). This uncertainty is likely an underestimate, as there are likely dairies in VISTA that are no longer extant, due to the declining dairy industry, and it is possible that there are dairies that exist that are not included in the database. We do not expect the uncertainty to follow a normal distribution; rather there are likely a few dairies where the estimates are far from correct. The data regarding the number of cows are proprietary information that are not consistently reported by any one agency, and the agencies do not communicate with each other. Further, the number of milk cows vary 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.

E1: The EPA 2017 reports the 95% confidence bounds as -11 to 18% of the mean enteric emissions uncertainty at the national level (US EPA, 2017). We assume this is the same uncertainty as the uncertainty in ef_1 at the facility level, as this is the only factor besides the number of cows in this model. We convert 95% CI into SE by assuming that 95% CI = 3.92 * SE.

E2: Hristov et al. 2017 provides the 95% confidence bounds as a % of the mean for the parameters in the model (Hristov et al., 2017). For DMI, The confidence bounds are 34.4-35.1% for DMI and 38.3-39.0% for ef_2. We convert 95% CI into SE by assuming that 95% CI = 3.92 * SE, resulting in 0.18% for DMI and 0.20 for ef_2.

E3: CARB provides the minimum and maximum of DMI, NDF, and mf (Appuhamy, 2018). We assume the range rule, which assumes a normally distributed population, such that SD = (max-min)/4 and SE = SD/sqrt(n), and calculate SE based on n=77, the number of sources in the literature with methane emissions representative of California dairy cows, as reported in Appuhamy 2018. The range rule works best when data are normally distributed and n ~ 30. Error ranges are also provided for f_{DMI}, f_{NDF}, and f_{mf}, which we assume to be standard error.

M1: The IPCC states that the uncertainty range for emissions using regional MCF, Bo, and VS is 20%. We therefore assume 20% uncertainty in $CH_{4,m1}$ (Dong et al., 2006).

M2: Hristov *et al.* (Hristov et al., 2017) report the 95% confidence bounds for manure management to be 65%-63.3%, though their estimate includes swine and poultry in addition to cattle. We convert 95% CI into SE by assuming that 95% CI = 3.92 * SE.

M3: For manure method three, we assess the uncertainty in time on concrete, volatile solid production, and methane conversion factors as described below. We propagate the error using partial derivatives.

Time on concrete: We estimated the standard error for time on concrete for freestall, nonfreestall dairies, and for nonlactating animals from a report that provided time on concrete at four dairies in the Central Valley (Meyer, 2019). We calculated standard error as the standard deviation divided by the square root of the number of samples. For the freestall dairies (n=2), one dairy had 78.2% time on concrete and the other dairy had 69.8% time on concrete. We calculated the mean and standard error of these two measures of time on concrete, which were (74.0 +/- 5.9)%. For the nonfreestall lanes (n=2), the two dairies had 31.0-37.0% time on concrete, which is the mean of (34.0 +/- 4.4)% . For the nonlactating cows, the average time on concrete from the four facilities were 26.5 +/- 6.5, based on 23.8, 25.1, 21.0, and 35.9% at the four facilities.

Volatile solid production: To estimate the standard error in volatile solid production, we calculated the mean and standard error of the VS production by lactating lactating cows and replacement heifers using data from 2000-2012 from the CARB inventory (US EPA, 2017).

Methane Conversion Factor: Owen and Silver 2014 report a field-derived methane conversion factor of (84+/- 44) % (confidence intervals) from a total of 9 observations for lagoon storage and 2.9 +/- 2.5 from a total of 4 observations for solid storage (Owen & Silver, 2014). We convert the confidence intervals into standard errors, and fractional uncertainty by dividing the error by the estimate.

f_{bed}: We estimate the standard error in the fraction of manure solids that are used as bedding to be 100%, as some dairies may not use any manure solids for bedding, and others may use all manure solids as bedding.

B_o: The IPCC states a 15% uncertainty in B_o; however, a meta-analysis of methane conversion factors from lagoons showed a standard error of 23% (Miranda et al. 2016).

S1.1.2 Statewide uncertainty

Because of the large number of dairies, propagating the error throughout the state calculates an improbably small statewide error. Therefore, we use previously published estimates for E1, E2, M1, and M2. We use IPCC recommendations for E3 and M3 (Dong et al., 2006).

E1: The EPA 2017 reports the 95% confidence bounds as -11 to 18% (+/- 7.4%) of the mean enteric emissions uncertainty at the national level (US EPA, 2017). We assume this uncertainty is the same in California as in the national scale. We convert 95% CI into SE by assuming that 95% CI = 3.92 * SE.

E2: Hristov et al. 2017 (Hristov et al., 2017) report the 95% confidence intervals of average annual enteric emissions from the continental United States to be 15.6-16.9% (+/- 8.3%). We assume this uncertainty is the same in California as in the national scale. We convert 95% CI into SE by assuming that 95% CI = 3.92 * SE.

E3: The IPCC suggests using +/- 20% using Tier 2 methodology, which we assume is the uncertainty for our statewide assessment (Dong et al., 2006).

M1: The EPA reports -18 to 20% (+/- 9.7%) uncertainty for manure management CH4 emissions, which we use here (US EPA, 2017). We assume this uncertainty is the same in California as in the national scale. We convert 95% CI into SE by assuming that 95% CI = 3.92 * SE.

M2: Hristov et al. 2017 (Hristov et al., 2017) report the 95% confidence intervals of average annual manure emissions from the continental United States to be -65.0 to 63.3% (+/-32.7%). We assume this uncertainty is the same in California as in the national scale. We convert 95% CI into SE by assuming that 95% CI = 3.92 * SE.

M3: The IPCC suggests using +/- 30% as confidence intervals using Tier 2 methodology, which we assume is the uncertainty for our statewide assessment (Dong et al., 2006).

Table S1. Manure partitioning for method M3. The time on concrete number includes the time in milking parlor. San Joaquin Valley, with air quality data.

MCF		SJV: with freestalls	SJV: No freestalls	North Coast	Southern
	Time in milking parlor (tomp)	0.125	0.125	0.125	0.125
	Time on concrete (toc)	0.70	0.34	0.34	0.34
0.04	**Solid**	1-toc	1-toc	0	0
0.015	**Pasture**	0	0	1-toc	0
0.731	**Lagoon**	toc	toc	tomp	toc
0.323	**Slurry**	0	0	toc-tomp	0
0.015	**Drylot**	0	0	0	1-toc

Table S2. Fraction of manure entering each management type for replacement heifers and calves, statewide.

Management type	M1	M2	M3
Daily spread	10.8%	11%	0%
Solid storage	0%	0%	100%
Liquid slurry	0.9%	1%	0%
Anaerobic lagoon	0%	0%	0%
Dry lot	87.4%	88%	0%
Pasture	0.9%	1%	0%
Anaerobic digester	0%	0%	0%

Table S3. Number of farms and milk cows in database with usda reports and in total database for each county (USDA NASS, 2017).

County	Nfarms_usda	Ncows_usda	nfarms_vista	ncows_vista
Butte	10	427	3	468
Colusa	4	80	1	80
Del Norte	7	6452	8	6448
Fresno	65	102796	81	102790
Glenn	28	15533	36	15534
Humboldt	96	23894	63	23877
Imperial	2	0	16	0
Kern	41	116605	53	129794
Kings	101	173404	153	173409
Lassen	8	22	2	22
Los Angeles	1	0	1	0
Madera	34	66038	46	67661
Marin	31	10895	26	10894
Mendocino	13	1182	5	1180
Merced	202	272534	289	272545
Modoc	2	0	1	0
Monterey	7	1445	1	1445
Placer	25	946	2	946
Riverside	36	38033	33	38049
Sacramento	34	16027	36	16026
San Bernardino	40	52554	76	52592
San Diego	9	4330	4	4328
San Joaquin	97	106375	129	106366
San Luis Obispo	16	256	1	256
San Mateo	4	10	1	10
Santa Barbara	3	0	1	1600
Siskiyou	15	1193	3	1194
Solano	8	22	2	611
Sonoma	125	33059	68	33048
Stanislaus	190	183496	255	183464
Sutter	4	5	1	5
Tehama	35	3249	12	3253
Tulare	235	500402	312	500395
Yolo	4	0	2	105
Yuba	6	0	4	1417

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