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Evaluating Bay Area Methane Emission Inventory

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Energy Technologies Area

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1. Summary

As a regulatory agency, evaluating and improving estimates of methane (CH_4) emissions from the San Francisco Bay Area is an area of interest to the Bay Area Air Quality Management District (BAAQMD). Currently, regional, state, and federal agencies generally estimate methane emissions using bottom-up inventory methods that rely on a combination of activity data, emission factors, biogeochemical models and other information. Recent atmospheric top-down measurement estimates of methane emissions for the US as a whole (e.g., Miller et al., 2013) and in California (e.g., Jeong et al., 2013; Peischl et al., 2013) have shown inventories underestimate total methane emissions by ~ 50% in many areas of California, including the SF Bay Area (Fairley and Fischer, 2015).

The goal of this research is to provide information to help improve methane emission estimates for the San Francisco Bay Area. The research effort builds upon our previous work that produced methane emission maps for each of the major source sectors as part of the California Greenhouse Gas Emissions Measurement (CALGEM) project (http://calgem.lbl.gov/prior_emission.html; Jeong et al., 2012; Jeong et al., 2013; Jeong et al., 2014). Working with BAAQMD, we evaluate the existing inventory in light of recently published literature and revise the CALGEM CH_4 emission maps to provide better specificity for BAAQMD. We also suggest further research that will improve emission estimates. To accomplish the goals, we reviewed the current BAAQMD inventory, and compared its method with those from the state inventory from the California Air Resources Board (CARB), the CALGEM inventory, and recent published literature. We also updated activity data (e.g., livestock statistics) to reflect recent changes and to better represent spatial information. Then, we produced spatially explicit CH_4 emission estimates on the 1-km modeling grid used by BAAQMD. We present the detailed activity data, methods and derived emission maps by sector.

In total, we estimate the anthropogenic emissions for BAAQMD to be 116.4 Gg (1 Gg = 10^9 g) CH_4/yr, with a likely uncertainty of ~ 50% or more (e.g., NRC, 2010; US-EPA, 2015). Including the emissions from wetland (Jeong et al., 2013), the total CH_4 emission estimate for BAAQMD is 120.1 Gg CH_4/yr. Table 1 summarizes the estimated CH_4 emissions for 2011 by sector. The sectors were categorized following those that are used in recent regional emission quantification studies (e.g., Jeong et al., 2013; Peischl et al., 2013; Wecht et al., 2014). However, we note that this result is marginally lower than the top-down estimate of 240 ± 60 Gg CH_4/yr (at 95% confidence) reported by Fairley and Fischer (2015), suggesting some combination of systematic error in the top-down estimate, underestimation of emissions from known sources, or as yet unidentified sources may be present.

With respect to the relative contributions from different source sectors, the CH_4 emissions from the region are dominated by urban activities. Landfill emissions represent 53% of the District's total emission followed by livestock (16%) and natural gas (15%). These three dominant sectors account for 84% of the total anthropogenic emission in BAAQMD. This suggests that mitigation efforts need to focus on these three sources. Figure 1 shows the gridded anthropogenic CH_4 emissions on the BAAQMD's 1-km grid

("others" category was not gridded, see Table 1). In general, the spatial pattern of emissions follows the density of population while strong point sources are also distributed in the rural areas of the District. Detailed methods and emissions for each sector and county are described in the following sections.

Table 1. Summary of CH_4 Emissions for BAAQMD by Sector

Sector	Subsector	Mg (10^6 g) CH_4/yr
Livestock	Dairy¶	9,219
	Major non-dairy¶	8,471
	Poultry (broiler, layer&pullets, turkey)	62
	Domestic and other animals	505
	Sector total	**18,257**
Landfill	Point source	56,888
	Fugitive area source	4,590
	Sector total	**61,478**
Natural gas	Distribution	17,287
	Domestic natural gas	52
	Other external combustion	160
	Sector total	**17,499**
On-road mobile	On-road mobile	2,164
	Sector total	**2,164**
Refinery	Refinery	1,931
	Sector total	**1,931**
Wastewater	Domestic wastewater*	5,027
	Industrial wastewater	1,957
	Sector total	**6,984**
Others**		8,092
Anthropogenic total***		**116,405**
Wetland#		3,738
Total		**120,143**

¶2012 activity data were used to incorporate the United States Department of Agriculture (USDA) Census data which are available every five years (2012, 2007, etc.).
*The 2013 data is used in the 1-km emission map for the anaerobic digester. For the centralized anaerobic and septic system maps, the 2011 data is used.
**Includes emissions from other stationary combustions, aircraft, off-road emissions, etc. This "Others" sector is not mapped on the 1-km BAAQMD grid.
***Includes anthropogenic emissions only.
#Taken from Jeong et al. (2013) for BAAQMD.

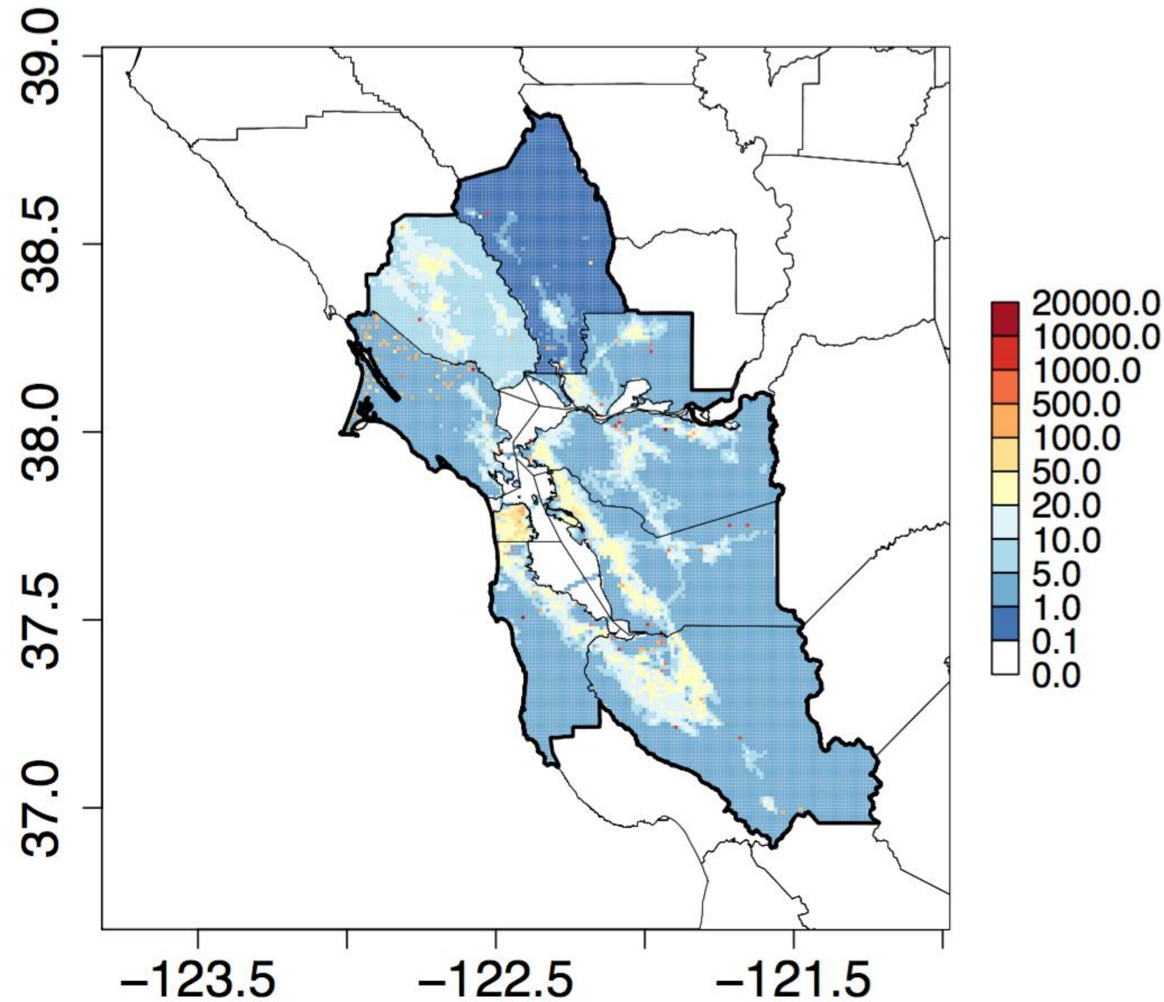


Figure 1. Gridded total anthropogenic CH_4 emission map for BAAQMD on the 1-km BAAQMD grid. The “Others” sector (shown in Table 1) is not mapped on the 1-km BAAQMD grid.

2. Livestock

The livestock sector includes dairy, major non-dairy, poultry, and domestic & other animals. We describe the method and estimated emissions by subsector.

2.1. Dairy Livestock

Dairy livestock CH_4 emissions are estimated using the USDA 2012 cattle inventory and the emission factors based on the CH_4 emissions from the California Air Resources Board (CARB, http://www.arb.ca.gov/cc/inventory/inventory.htm, March 2014 version, Accessed January 2015). CARB's state livestock emissions are provided in Appendix A. The USDA cattle inventory dataset provides the total number of dairy cows for each county. In the USDA cattle inventory, data for some counties are combined to avoid disclosing data for individual farms. We updated the USDA 2012 county cattle data to disaggregate the combined data for several counties (i.e., "Other Counties" category) using recent USDA Census Data (see Appendix B for cattle activity data and data sources). For spatial disaggregation, the dairy population data with dairy farm locations for the year 2005 by Salas et al. (2009) were used (see Figure 2). We adjusted the dairy population data from Salas et al. (2009) to the dairy data in the USDA 2012 cattle inventory by county.

The emission factors for dairy livestock (manure management and enteric fermentation) is derived based on the ratio of the state total emission for each subsector (i.e., enteric and manure, Appendix A) to the state total number of dairy cows (i.e., 1,779,870, see Appendix B for dairy cow statistics). The derived emission factors are shown in Table 2. For counties (e.g., Alameda, Sonoma) where dairy farms do not exist from the data in Salas et al. (2009), we apportioned CH_4 emissions uniformly across the county based on the dairy livestock population in the USDA cattle inventory (http://www.nass.usda.gov/Statistics_by_State/California/Publications/County_Estimates, accessed January 2015). If the county data are not available in the USDA cattle inventory, we used the statistics from the USDA Census data, which are provided every five years (http://www.agcensus.usda.gov/Publications, see Appendix B for details).

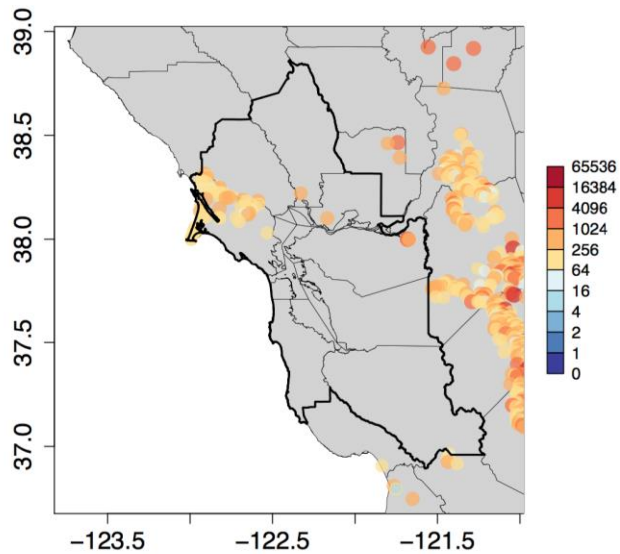


Figure 2. Dairy farm locations with population estimates (number of dairy cows) from Salas et al. (2009) in and around BAAQMD.

Table 2. Emission Factors for the Dairy Livestock Sector

Subsector	State Total Emission (Tg CO_2eq/yr, GWP=25)	State Total Emission (Tg CH_4/yr)	Emission Factor* (Mg** CH_4/head)
Manure Management	10.238	0.410	0.230
Enteric Fermentation	8.220	0.329	0.185
Total	18.458	0.739	0.415

*A total of 1,779,870 dairy cows in Appendix B were used to derive this emission factor.
**Mg = 10^6 g.

Table 3 shows estimated dairy livestock emissions for BAAQMD. Using the emission factors and the USDA cattle inventory, the District's total dairy livestock emission is estimated to be 9219 Mg (megagram or 10^6 g) CH_4/yr. This is only ~1% of the state total CH_4 emission for dairy livestock estimated by CARB, which is 738 Gg (10^9 g) CH_4/yr. Marin and Sonoma Counties account for more than 90% of the District's total dairy CH_4 emissions. In Table 3, the total emission for Solano County is less than 5% of that of Marin County although the dairy cow population of Solano County is ~40% of that of Marin County in the USDA cattle inventory. This is because relatively larger farms (3 out of a total of 4) identified in the dairy population data from Salas et al. (2009) are located in the northeast corner of Solano County, which is outside the official District boundary (see Appendix C for details). A further study may be necessary for more accurate spatial allocation of dairy livestock emissions in Solano County and Sonoma County.

Table 3. Estimated Annual Dairy Livestock CH_4 Emissions by County

County	Mg CH_4/yr
ALAMEDA	2
CONTRA COSTA	5
MARIN	4233
NAPA	102
SAN FRANCISCO	0
SAN MATEO	4
SANTA CLARA	4
SOLANO*	132
SONOMA*	4737
Total	9219

*Emissions within the BAAQMD boundary.

Figure 3 shows the estimated dairy livestock emissions on the 1-km BAAQMD grid (see BAAQMD's 1-km grid in Appendix D). As expected from the emission summary in Table 3, most of the emissions are concentrated in Marin and Sonoma Counties. The emissions in Sonoma are uniformly distributed because there is no strong presence of dairy farms from the dairy population data reported in Salas et al. (2009) while the USDA cattle inventory indicates 29500 dairy cows exist in the entire county. Note that a total of 4737 Mg CH_4/yr for Sonoma County in Table 3 represents the emissions only within the District boundary. The areas of Sonoma and Solano within the District are ~39% and ~48% of the total county areas, respectively.

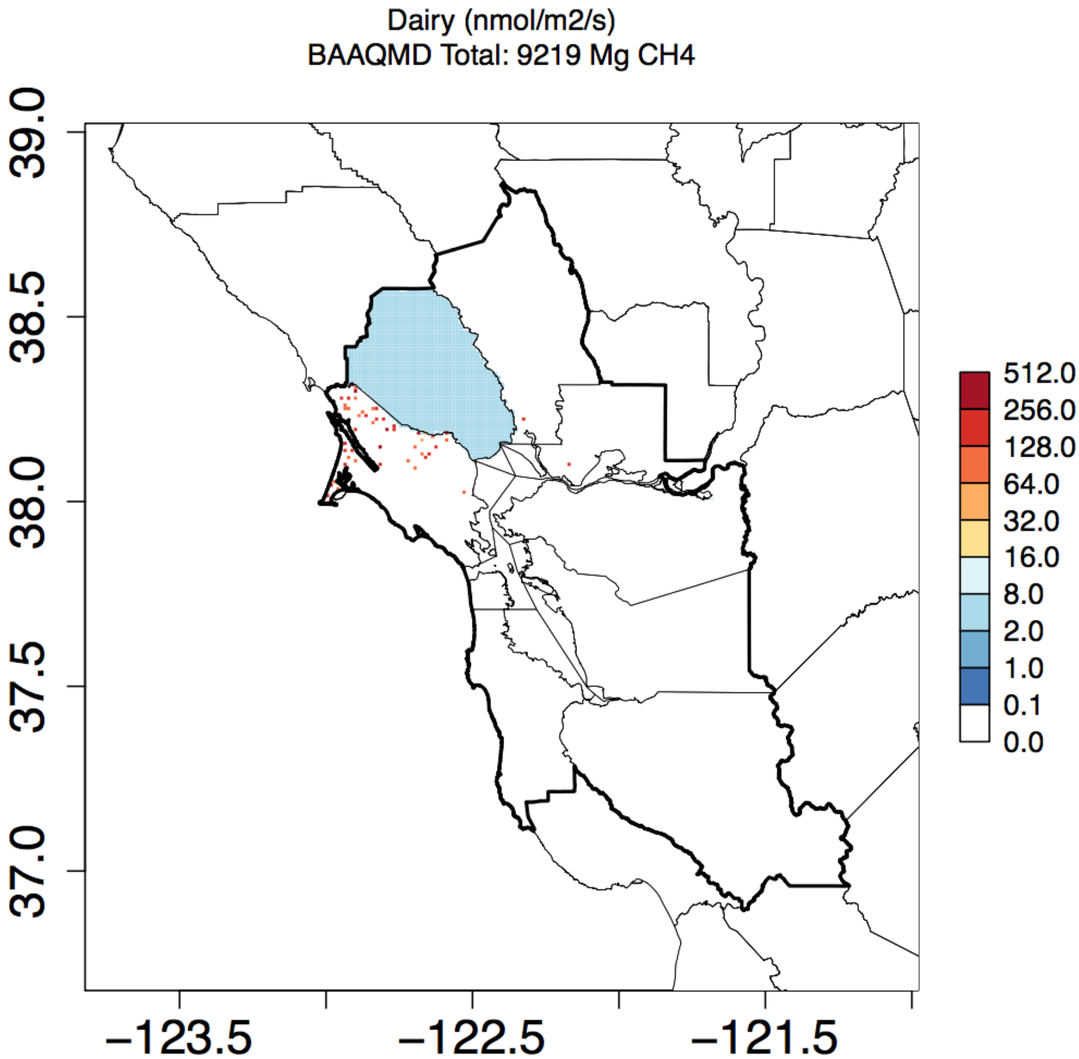


Figure 3. Dairy livestock CH_4 emission (nmol/m^2/s, nmol = 10^{-9} mol) map for BAAQMD (only grid cells within the District boundary are shown).

2.2. Non-dairy Livestock

Major non-dairy emissions are estimated using county-level activity data and estimated emission factors. The major non-dairy sector includes emissions from non-dairy cattle, sheep, goat, horse, and swine (excluding poultry, see Table 4). For non-dairy cattle, activity data are obtained from the USDA cattle inventory as with the dairy sector (see Appendix B). For sheep, goat, horse, and swine, USDA Census (2012, 2007) data are used (see Appendix E for activity data and data sources). The emission factors are derived based on statewide CH_4 emissions from CARB and activity data estimated from this study (see Appendices B and E). The derived emission factors include both enteric fermentation and manure management (Table 4).

Table 4. Summary of Major Non-dairy Emission Factor

Statewide Non-dairy Emissions from CARB (Tg CO_2eq/yr, GWP=25)*					
Type	**Cattle**	**Sheep**	**Goat**	**Horse**	**Swine**
Enteric	3.08	0.114	0.018	0.347	0.004
Manure	0.132	0.01	0.001	0.063	0.044
Total	**3.212**	**0.124**	**0.019**	**0.41**	**0.048**
Statewide Major Non-dairy Livestock Total (head)					
	3,570,130**	**668,558#**	**140,452#**	**142,526#**	**111,893#**
Derived Emission Factor					
Mg CH_4/head	**0.036**	**0.007**	**0.005**	**0.115**	**0.017**

*Source for emissions: http://www.arb.ca.gov/cc/inventory/doc/doc_index.php
**We assumed the total non-dairy cattle population is the total population for cattle minus the dairy cow total in Appendix B (i.e., 3,570,130 = 5,350,000-1,779,870). This assumption is also applied to the county level data.
#See Appendix E for details.

Table 5 shows summarized emissions for the major non-dairy sector by county. The estimated emissions on the 1-km BAAQMD grid are shown in Figure 4 where cattle and total major non-dairy emission maps are shown.

Table 5. Estimated Major Non-dairy CH_4 Emissions (Mg CH_4/yr) for Each County

County	Cattle	Sheep	Goat	Horse	Swine	Total
ALAMEDA	554	9	1	110	0	674
CONTRA COSTA	593	4	38	306	1	942
MARIN	821	40	17	69	3	949
NAPA	232	7	7	85	1	332
SAN FRANCISCO	0	0	0	0	0	0
SAN MATEO	75	1	1	308	0	386
SANTA CLARA	608	9	3	251	1	872
SOLANO	1339	433	20	165	3	1960
SONOMA	1565	209	53	511	17	2356
Total	5787	712	140	1805	26	8471

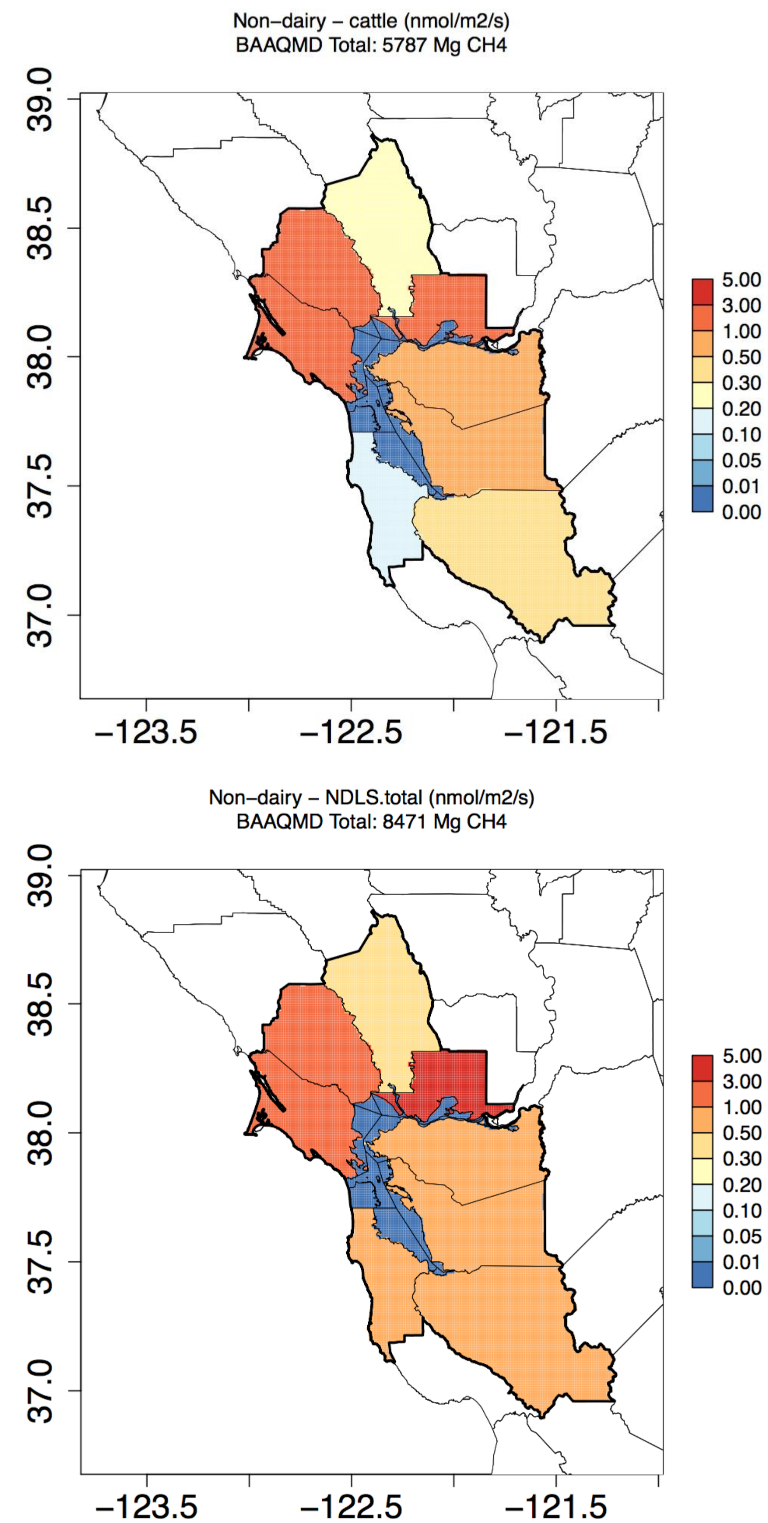


Figure 4. CH_4 emission (nmol/m^2/s) map for non-dairy cattle (top) and major non-dairy livestock including cattle (bottom) on the 1-km BAAQMD grid.

2.3. Poultry

Poultry emissions are estimated by adjusting the 2000 CARB (county-level) livestock husbandry statistics (http://www.arb.ca.gov/ei/areasrc/fullpdf/FULL7-6.PDF) based on the statewide activity data in CARB's 2012 GHG inventory (http://www.arb.ca.gov/cc/inventory/doc/doc_index.php, March 2014, accessed January 2015). The poultry sector includes broiler, turkey, layers and pullets (other domestic animals are described in the following section).

Table 6 shows the emission factors for poultry (separate from the major non-dairy source) as well as the number of poultry animals at the state level. To obtain county-level activity data, we adjusted the county activity data from the 2000 CARB animal husbandry statistics (Appendix F) to match the current state-level total because the current inventory does not have county-level data. See Appendix G for the adjusted county-level activity data for poultry.

Table 6. Summary of CARB's Emission Factors (Year 2012) for Poultry

Poultry Type	Head[#]	Emission Factor (kg CH_4/head)*	Sub-sector	Total Emissions (Mg CH_4)**
Broiler	97,055	0.020	Pasture	1.94
Broiler	9,608,400	0.020	Poultry with bedding	191.95
Subtotal	**9,705,455**	**0.020**		**193.89**
Turkey	51,667	0.075	Pasture	3.88
	5,115,000	0.075	Poultry with bedding	383.75
Subtotal	**5,166,667**	**0.075**		**387.63**
Layers & Pullets	2,411,280	1.287	Anaerobic lagoon/Hens 1+ yr	3,103.00
	1,200	1.393	Anaerobic lagoon / Other chickens	1.67
	17,682,720	0.026	Poultry without bedding / Hens 1+ yr	457.51
	8,800	0.028	Poultry without bedding / Other chickens	0.246
	3,880,800	0.026	Poultry without bedding / Pullets	100.41
	529,200	1.287	Anaerobic lagoon / Pullets	680.94
Subtotal	**23,984,800**	**0.181*** **		**4,343.78**
Total				**4925.3**

These activity data from CARB (Version March 2014) are used to adjust the 2000 CARB animal husbandry statistics (in Appendix F) by county and animal type.

*Source for emission factors: http://www.arb.ca.gov/cc/inventory/doc/doc_index.php (accessed in January 2015).
**Since we are summarizing the reported emission factors and the total emissions for each animal type (with limited significant digits), the multiplication of head and the emission factor may yield slightly different numbers from the total emissions shown in the last column.
***Shows the weighted average emission factor

The estimated emissions for each county are summarized in Table 7 by subsector. The layer and pullet subsector accounts for ~75% of the total poultry emission. Among counties, Santa Clara and Sonoma Counties emit ~80% of the total poultry emission in the District. Figure 5 shows the 1-km poultry emission map where emissions are uniformly distributed at the county scale.

Table 7. Estimated CH_4 Emissions (Mg CH_4/yr) from Poultry

County	Broiler	Layer & Pullet	Turkey	County Total
ALAMEDA	1.5	0.1	0.0	1.6
CONTRA COSTA	0.0	0.1	0.0	0.1
MARIN	0.0	0.0	2.4	2.4
NAPA	7.4	0.2	1.0	8.6
SAN FRANCISCO	0.0	0.0	0.0	0.0
SAN MATEO	0.0	0.1	0.0	0.1
SANTA CLARA	0.0	25.6	0.0	25.6
SOLANO*	0.0	0.0	0.0	0.0
SONOMA*	1.7	20.9	1.0	23.7
Total	**10.6**	**47.0**	**4.5**	**62.1**

*Only within the District.

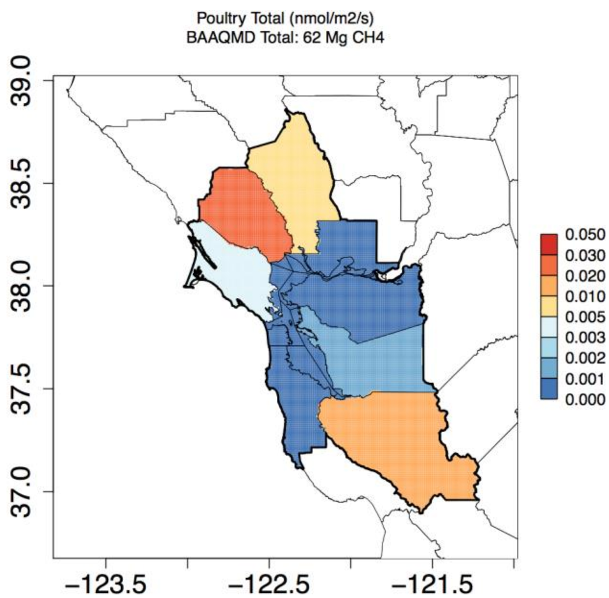


Figure 5. Poultry CH_4 emissions (nmol/m^2/s) on the 1-km BAAQMD grid.

2.4. Domestic and Other Animals

The spatially explicit emissions for domestic and other animals (i.e., dog, cat, deer and wild pig) are generated based on the county-level emission estimates from BAAQMD (see Table 8). BAAQMD provides emission estimates for each subsector by county, and we apportioned them uniformly across county by subsector, matching a total of 505 Mg CH_4/yr for this entire sector. The CH_4 emissions on the 1-km grid are shown in Figure 6.

Table 8. Estimated CH_4 Emissions (Mg CH_4/yr) from Domestic and Other Animals

County	Dog	Cat	Deer	Wild Pig	Total
ALAMEDA	65.52	43.55	0.38	0.01	109.46
CONTRA COSTA	44.59	29.64	0.38	0.01	74.62
MARIN	11.01	7.32	0.41	0.01	18.75
NAPA	5.80	3.85	0.41	0.01	10.07
SAN FRANCISCO	35.36	23.50	0.00	0.00	58.86
SAN MATEO	31.48	20.92	0.23	0.01	52.64
SANTA CLARA	76.81	51.05	0.68	0.02	128.56
SOLANO*	12.70	8.44	0.19	0.01	21.34
SONOMA*	18.22	12.11	0.35	0.01	30.69
Total	301.49	200.38	3.03	0.07	504.98

*Emissions within the District.

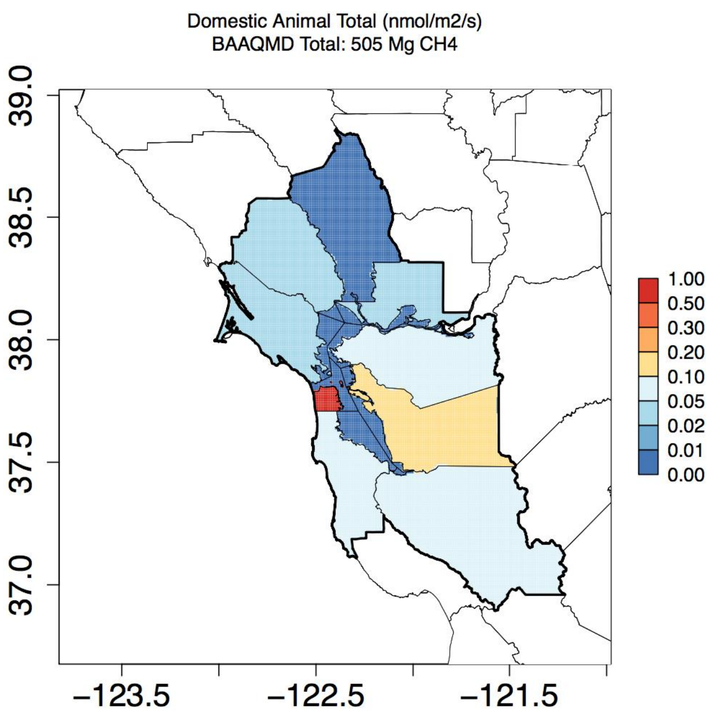


Figure 6. Domestic/other animal CH_4 emission (nmol/m^2/s) map for BAAQMD.

3. Landfill

Landfill emissions are estimated for point sources at the facility level and area sources.

3.1. Point Source

Landfill point source emissions are estimated based on the recent (year 2012) landfill emission dataset from CARB. Using this landfill emission dataset, we estimate the total landfill emission for BAAQMD is 56888 Mg CH_4/yr. This is similar to the District's estimate for landfill point sources, which is 57157 Mg CH_4/yr. Table 9 shows the summarized landfill CH_4 emissions from CARB by county. The CARB landfill emission data suggest that Alameda County emits the largest landfill CH_4 emission followed by Santa Clara County.

Table 9. CH_4 Emissions from Landfill by County

County	CH_4 Emissions (Mg CH_4/yr)
ALAMEDA	14272
CONTRA COSTA	7290
MARIN	7248
NAPA	783
SAN FRANCISCO	0
SAN MATEO	7577
SANTA CLARA	13288
SOLANO	4054
SONOMA	2377
Total	**56888**

The CARB landfill dataset reports estimated CH_4 emissions for each landfill facility across California. Figure 7 shows the CH_4 emissions (in units of Mg CH_4/yr) from the individual landfill facilities within the District's boundary. Figure 8 shows the landfill CH_4 emissions in the flux unit (nmol/m^2/s) on the 1-km BAAQMD grid (see Figure 7 for facility emissions with more clarity). The county-level emissions in Table 9 were calculated by summing all facility emissions from each county shown in Figure 7.

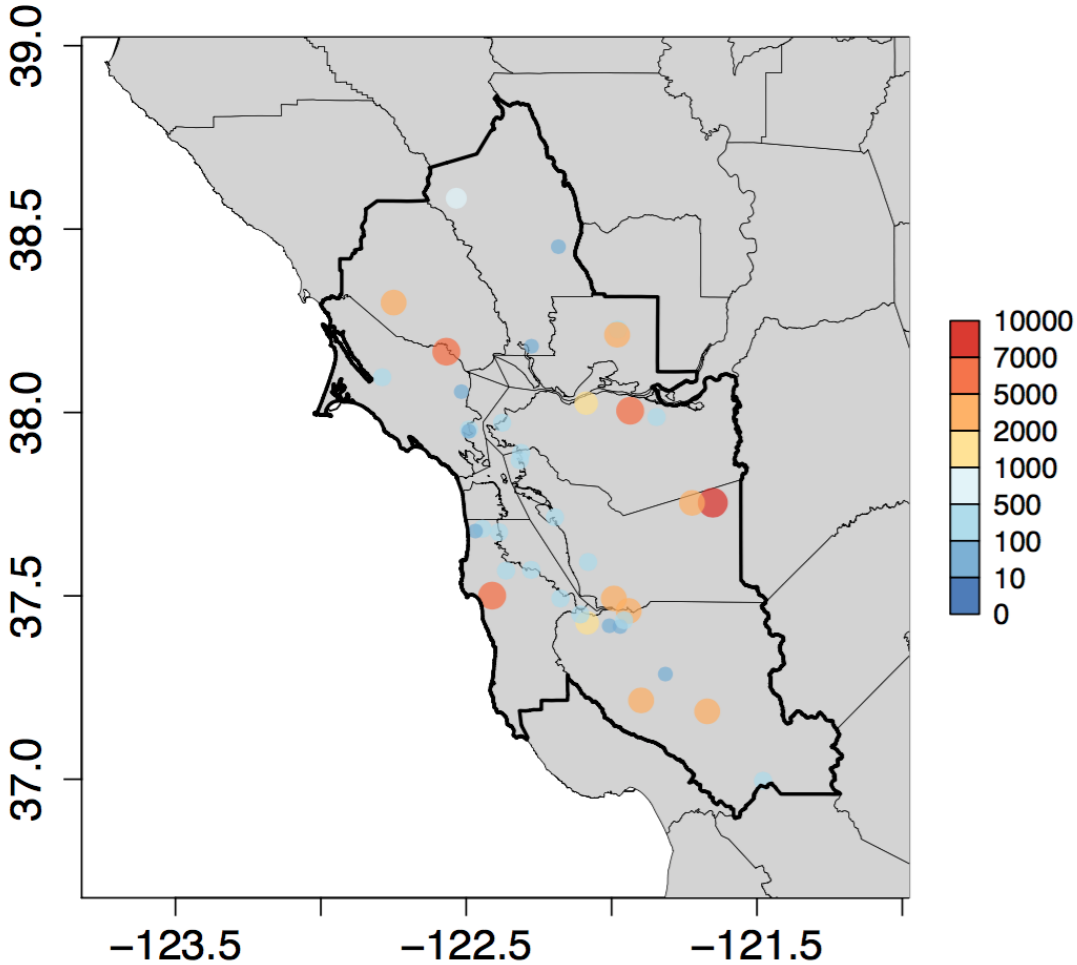


Figure 7. Landfill CH_4 emissions at the facility level within the District. Each filled circle represents the location of each landfill facility with different color indicating different emission levels in units of Mg CH_4/yr.

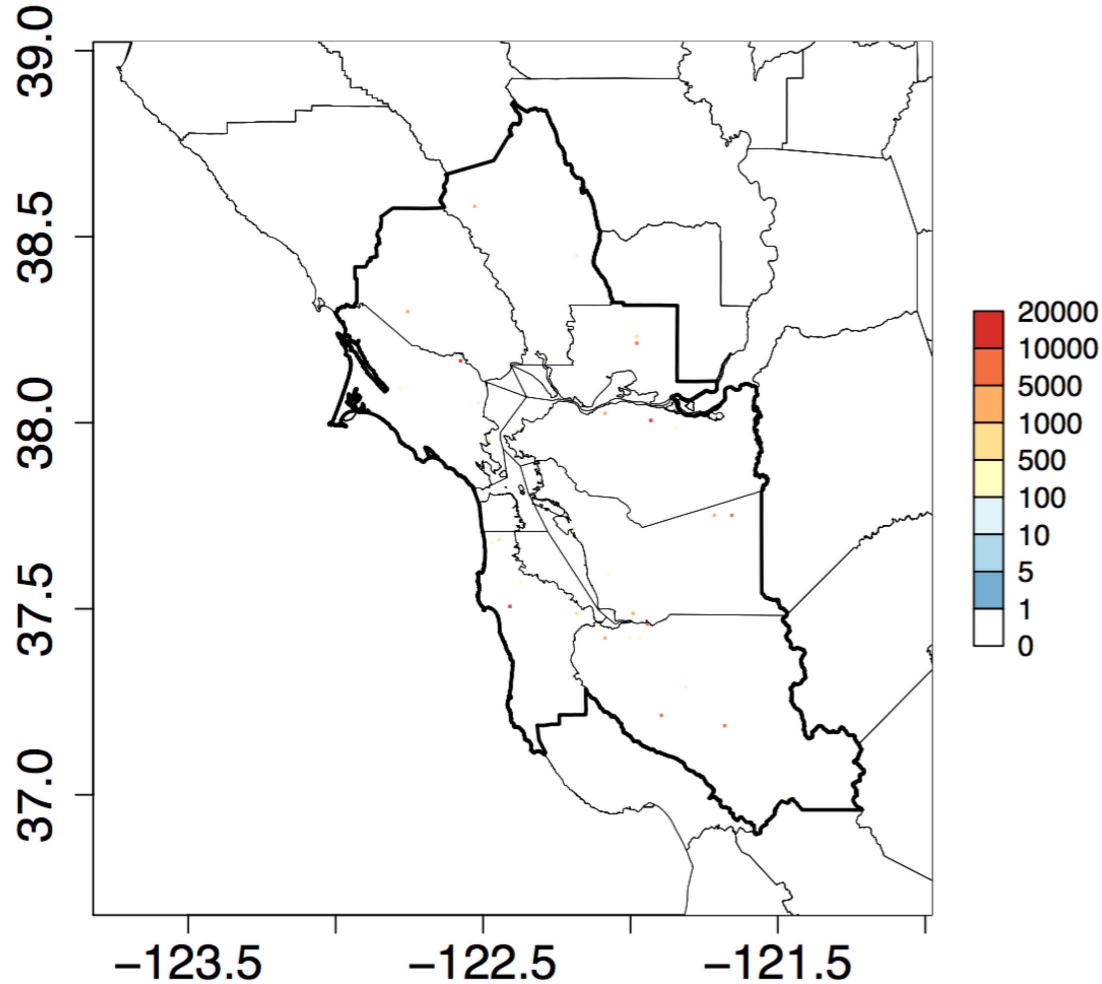


Figure 8. Landfill CH_4 emissions (nmol/m^2/s) on the 1-km BAAQMD grid.

3.2. Area Source

For the fugitive area source sector, we use the 2011 landfill CH_4 emissions estimated by the District because we don't have a separate estimate for this sector. The District estimates the total CH_4 emission from landfill fugitive sources for the year 2011 is 4590 Mg CH_4/yr. Table 10 summarizes the estimated CH_4 emissions for the landfill fugitive area sector by county. To obtain spatially explicit emissions, we apportioned the total emission for each county uniformly. The emission map on the BAAQMD grid is shown in Figure 9. Figure 10 shows the total landfill emissions that combine point and fugitive area source emissions.

Table 10. CH_4 Emission for the Landfill Fugitive Area Source Sector*

County	Activity Fraction	2011 CH_4 Emissions ($Mg\ CH_4$)
Alameda	0.23	1056
Contra Costa	0.13	597
Marin	0.12	551
Napa	0.06	275
San Francisco	0.03	138
San Mateo	0.13	597
Santa Clara	0.18	826
Solano	0.05	230**
Sonoma	0.07	321**
Total	**1**	**4590**

*The original dataset was provided by the District.
**Represents the emissions within the District boundary.

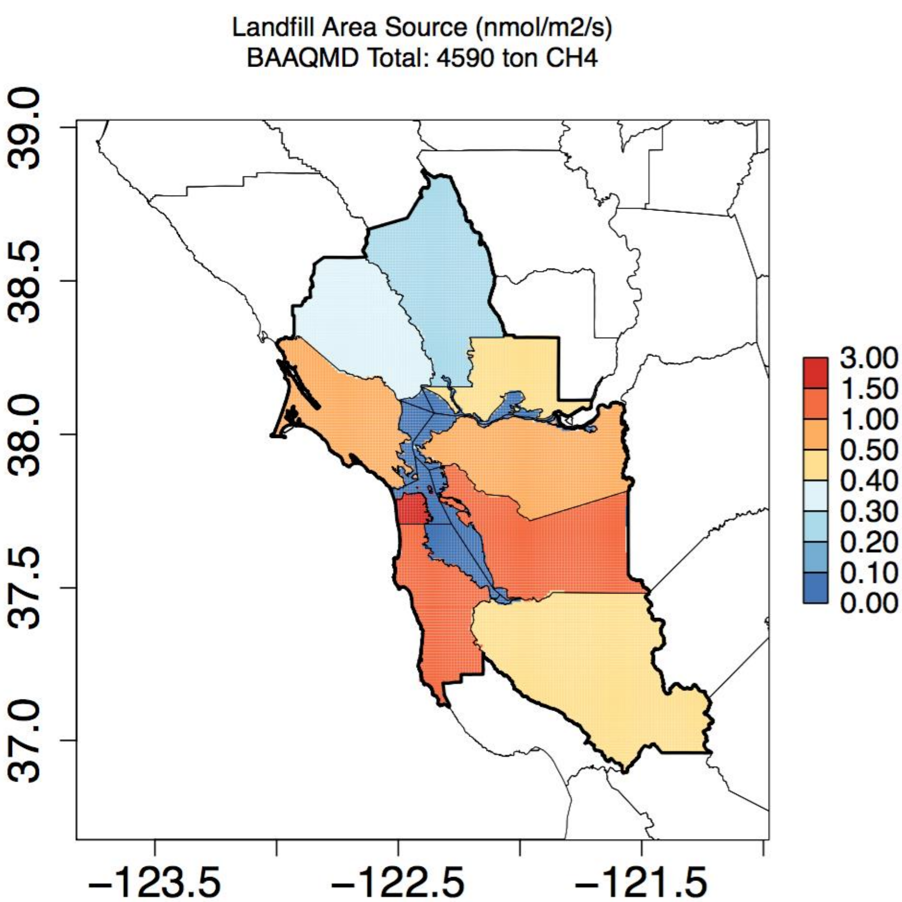


Figure 9. CH_4 emission ($nmol/m^2/s$) map (year 2011) for the landfill fugitive area source on the 1-km grid**.**

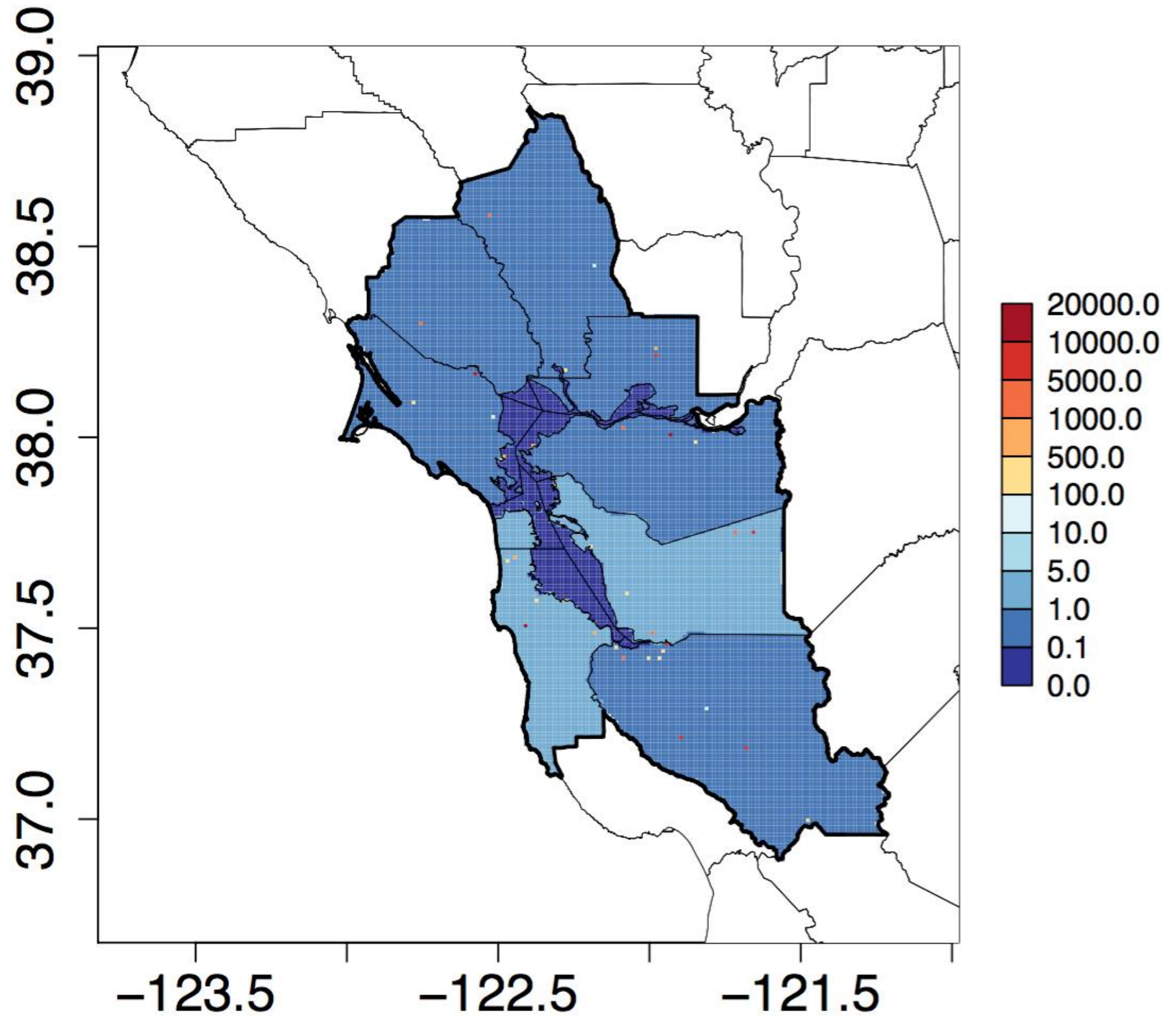


Figure 10. Total (point + area sources) landfill emissions (nmol/m^2/s) on the 1-km BAAQMD grid.

4. Natural Gas

Natural gas emission maps were generated for eight subsectors using the emissions estimated by BAAQMD (Table 11). Among the eight subsectors, the emission map for the natural gas point source sector was prepared at the facility level. For the other subsectors, the District's total emissions were apportioned by population density. The details for the 1-km population density map are provided in Appendix I. The natural gas distribution subsector accounts for the majority (~98%) of the total natural gas emission in BAAQMD.

Table 11. Summary of CH_4 Emissions for the Natural Gas Sector Estimated by BAAQMD

Sector	Subsector	Category	Emissions (Mg CH_4/yr)
Natural Gas Distribution	Power Plant Fuel Use	61	4
	Other Fuel Use	868	17213
	Space Heating	283	70
Domestic Natural Gas	Water Heating	284	47
	Cooking	285	5
Other External Combustion	Natural Gas (point source)	307	32
	Industrial	1590	68
	Commercial	1591	60
Total			**17499**

Figure 11 shows the 1-km CH_4 emission maps for the subsectors of power plant fuel use (Category 61), other fuel use (868), space heating (283), and water heating (284). As described, the emissions for each subsector were apportioned in proportion to the 1-km population density matching the subsector total. For example, the emission map for "Other Fuel Use", which represents fugitive emissions in the natural gas distribution system, was generated distributing a total of 17213 Mg CH_4 according to the population density map for the District (see Appendix I for population density).

Also, Figure 12 shows the emission maps for cooking (Category 285), point source (307), industrial combustion (1590), and commercial combustion (1591). The natural gas point source emissions (Category 307) were originally estimated at the facility scale by the

District and were mapped onto the 1-km BAAQMD grid (similar to those of landfill emissions). The original facility-level emissions (in units of Mg CH_4) are shown in Figure 13 where the 1-km point source emissions (in units of nmol/m^2/s) are also repeated on a larger map (for clarity).

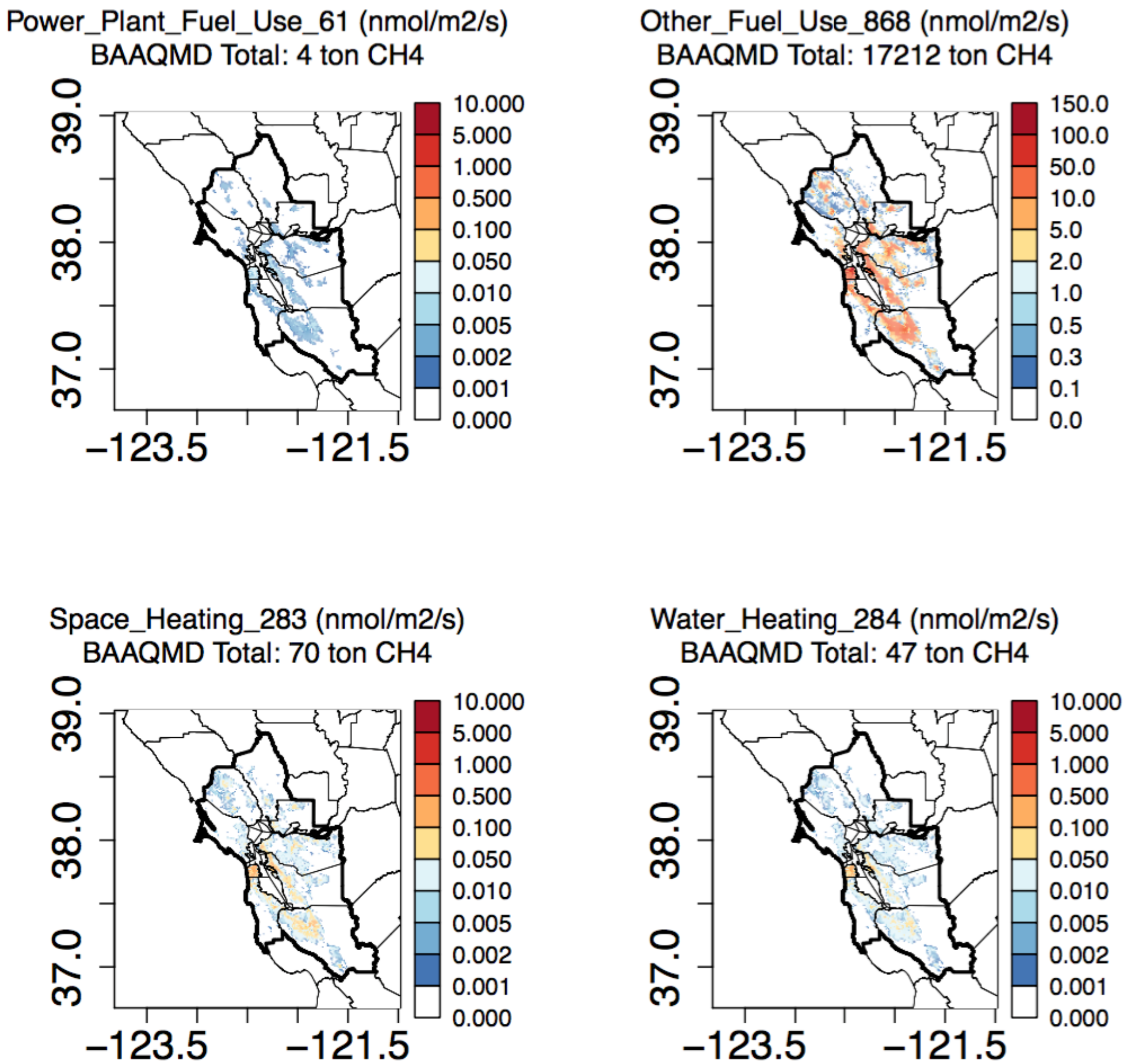


Figure 11. Natural gas emissions (nmol/m^2/s) on the 1-km BAAQMD grid for power plant fuel use (Category 61), other fuel use (868), space heating (283), and water heating (284).

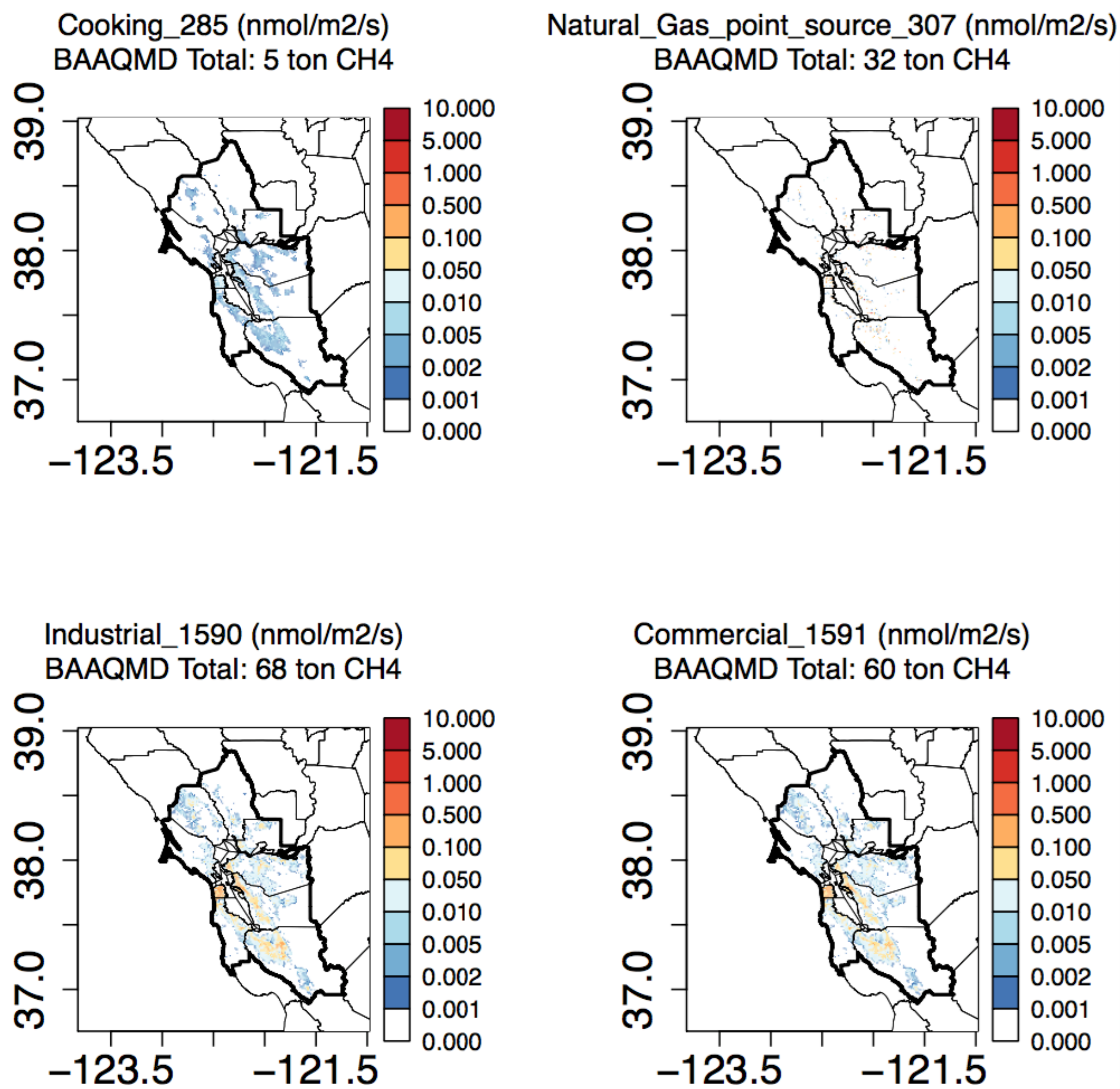


Figure 12. 1-km natural gas emission maps (nmol/m^2/s) for cooking (Category 285), point source (307), industrial combustion (1590), and commercial combustion (1591). An enlarged version of the point source emission map is provided in Figure 13.

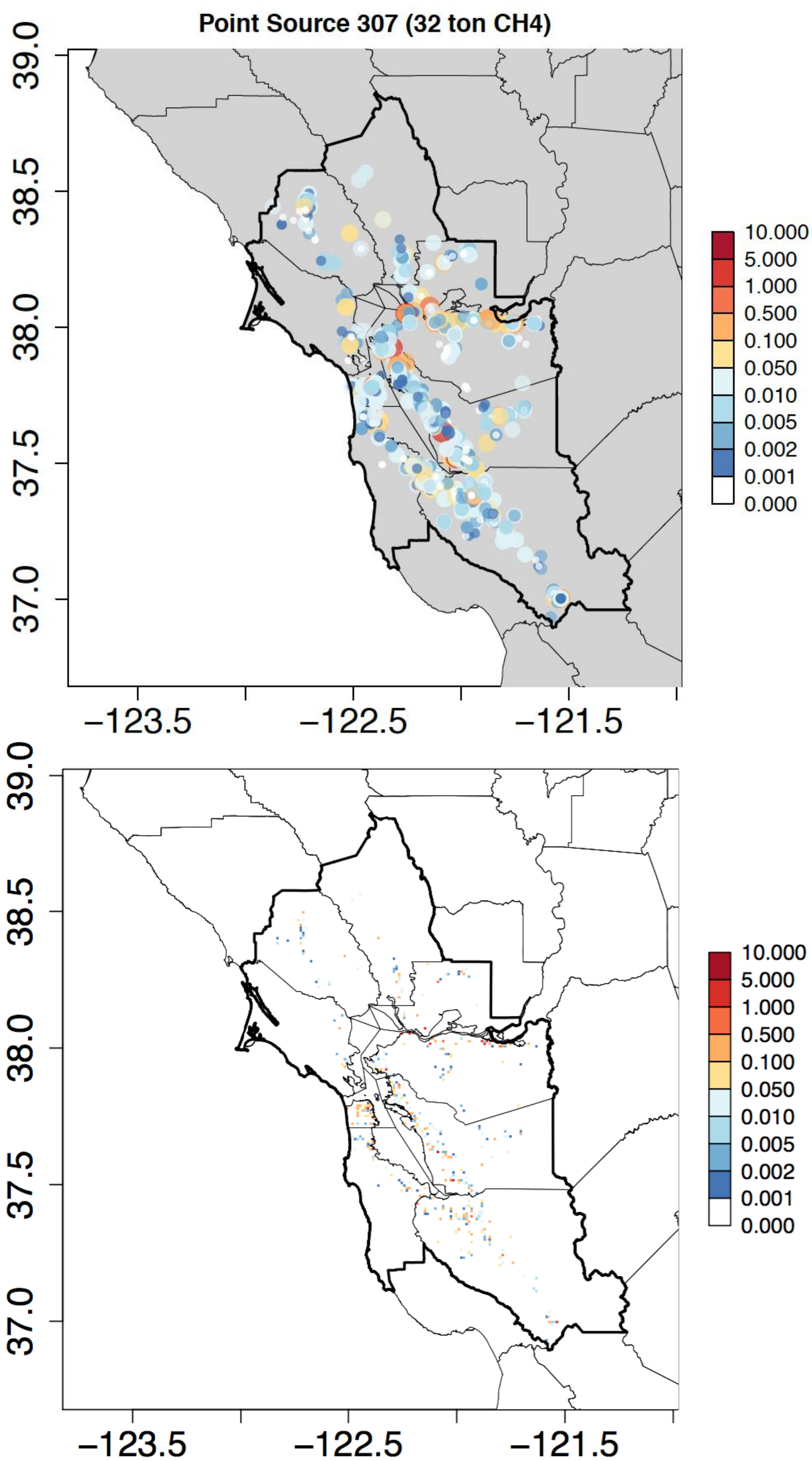


Figure 13. Natural gas point source (Category 307) emissions at the facility level (top; in units of Mg CH_4/yr) and on the 1-km BAAQMD grid (bottom; in units of nmol/m^2/s; enlarged version of the point source map in Figure 12).

The total natural gas emission map was produced by combining the eight subsector emission maps (Figure 14). Summing the emissions in Figure 14, we estimate the District's total emission for the natural gas sector to be 17498 Mg CH_4/yr. As expected from the proportion (98% of total natural gas emission) of the distribution sector (Category 868), the spatial distribution of total natural gas emissions closely follows the population density distribution in BAAQMD.

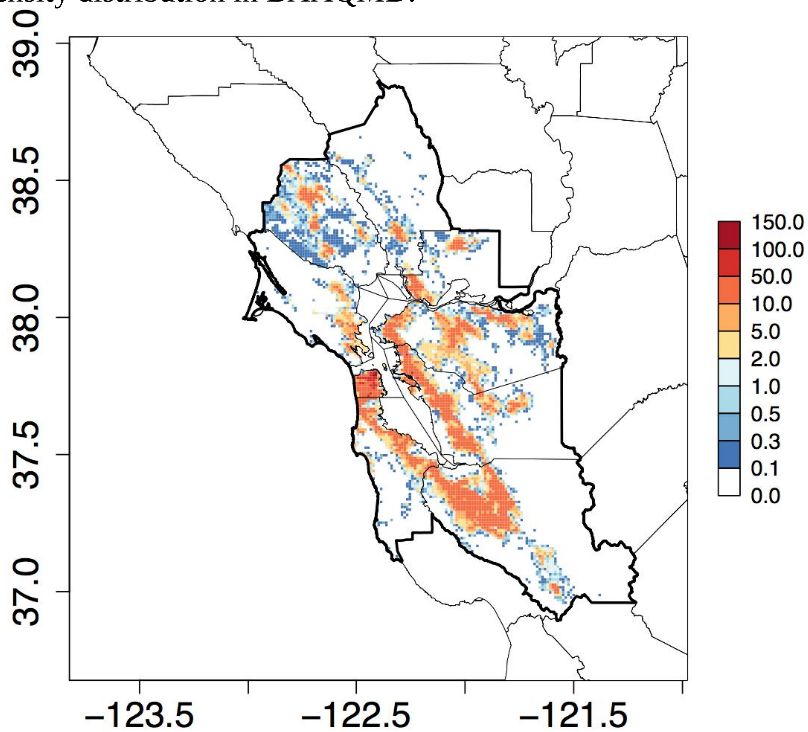


Figure 14. Natural gas total emissions on the 1-km BAAQMD grid.

Table 12. Summary of CH_4 Emissions for the Natural Gas Sector by County

County\Sector	Power Plant Fuel Use (61*)	Other Fuel Use (868)	Space Heating (283)	Water Heating (284)	Cooking (285)	Natural Gas Point Source (307)	Indus-trial (1590)	Com-mercial (1591)	Total
ALAMEDA	1	3733	15	10	1	9	15	13	**3797**
CONTRA COSTA	1	2593	11	7	1	10	10	9	**2641**
MARIN	0	624	3	2	0	0	2	2	**634**
NAPA	0	337	1	1	0	1	1	1	**343**
SAN FRANCISCO	0	1990	8	5	1	3	8	7	**2022**
SAN MATEO	0	1776	7	5	1	1	7	6	**1803**
SANTA CLARA	1	4404	18	12	1	5	17	15	**4474**
SOLANO	0	710	3	2	0	2	3	2	**722**
SONOMA	0	1046	4	3	0	1	4	4	**1062**
Total	**4**	**17212#**	**70**	**47**	**5**	**32**	**68**	**60**	**17498**

*The number in the parentheses indicates District's category number
#The total from the 1-km emission map is slightly different from the original total (17213 Mg CH_4) due to summation of gridded emissions.

5. Refinery

Refinery emissions were estimated using CARB's facility-level refinery emission dataset, which was prepared for the year 2009 by CARB. We scaled individual facility emissions such that the total CH_4 emission from all facilities matches CARB's recent (March 2014 version, http://www.arb.ca.gov/cc/inventory/doc/doc_index.php, accessed in January 2015) refinery state total emission (3608 Mg CH_4/yr), which represents the year 2012.

We estimate the total CH_4 emission for BAAQMD is 1931 Mg CH_4/yr, which is 54% of the state total refinery emission. Figure 15 shows the CARB-scaled refinery emission at each facility (in units of Mg CH_4/yr). As shown in Figure 15, refinery facilities are concentrated in Contra Costa County with a few facilities in Solano County. The corresponding emission map on the 1-km BAAQMD grid (in units of nmol/m^2/s) is shown in Figure 16. A summary of the refinery emissions by county is provided in Table 13 where Contra Costa County accounts for 93% of the District's total refinery emission.

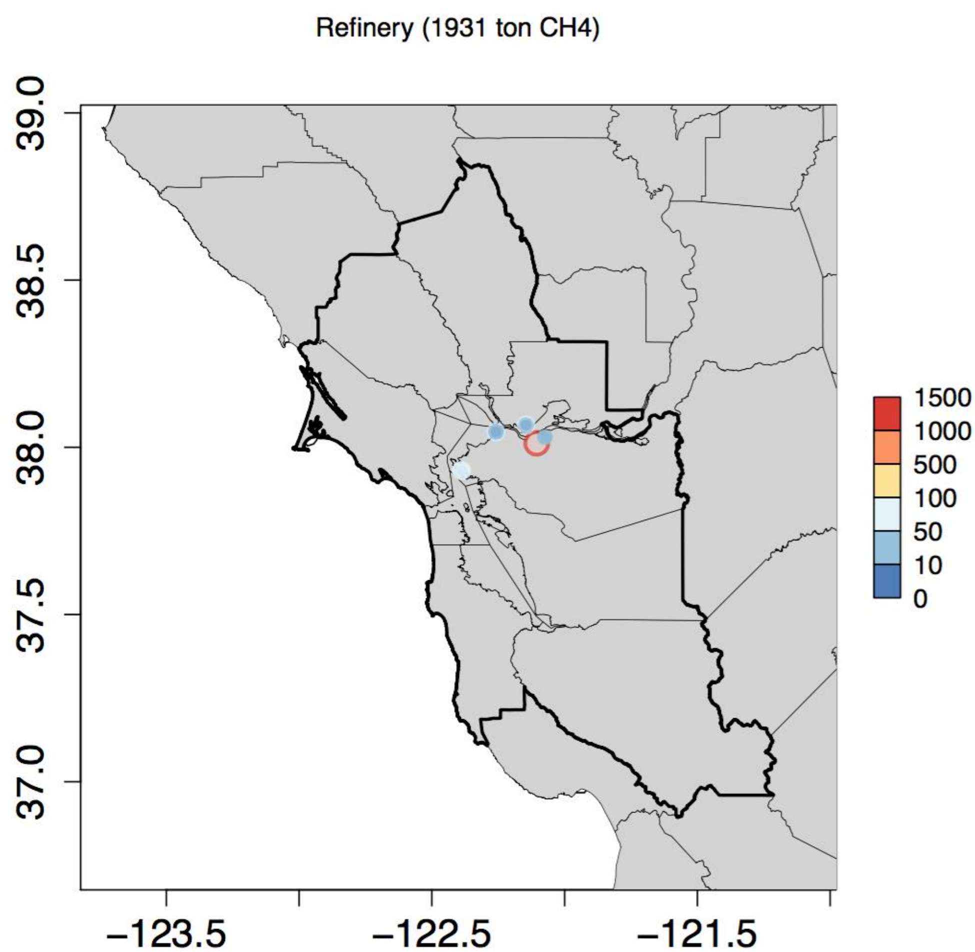


Figure 15. Refinery CH_4 emissions (Mg CH_4/yr) at the facility level for BAAQMD. Some facilities are shown overlaid with others because of their proximity to each other.

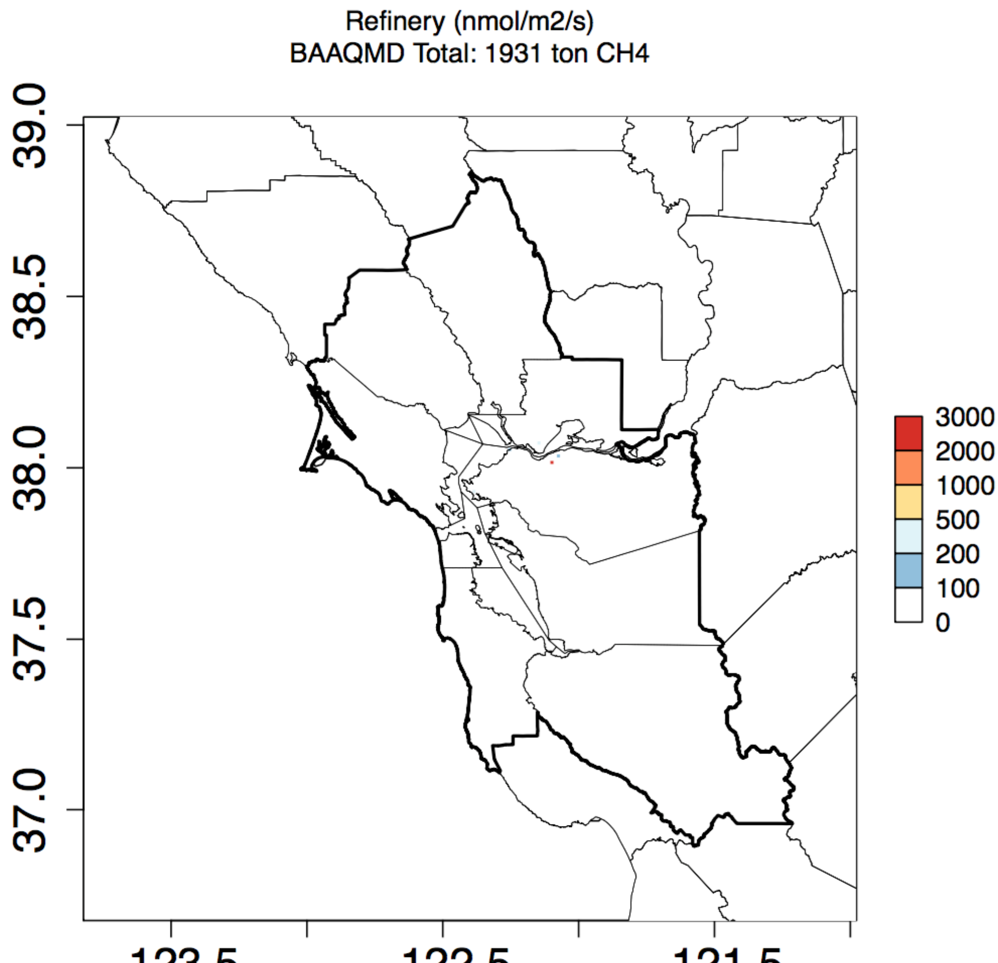


Figure 16. Refinery CH_4 emission (nmol/m^2/s) map for BAAQMD

Table 13. Summary of CH_4 Emissions for the Refinery Sector by County

County	Mg CH_4/yr
ALAMEDA	0
CONTRA COSTA	1796.6
MARIN	0
NAPA	0
SAN FRANCISCO	0
SAN MATEO	0
SANTA CLARA	0
SOLANO	134.8
SONOMA	0
District Total	1931.4

6. On-road Mobile

On-road mobile emissions were estimated based on the traffic volume data for the year 2011 (http://www.dot.ca.gov/hq/tsip/gis/datalibrary/Metadata/AADT.html, accessed July 2015). The traffic volume data represent annual average daily traffic (AADT, total volume for the year divided by 365 days) recorded at count locations on the California state highway system, which include state highway and major local roads. The original AADT data for the year 2011 are shown in Figure 17 where most of the Bay Area's major highways show more than 10^5 counts per day.

Because the AADT data are available only at limited locations on the state highway system, linear interpolation was applied to estimate AADT for the pixels on the 1-km BAAQMD grid for which recorded AADT data are not available. The linear interpolation technique used two neighborhood points nearest to a point of interest on the same route (e.g., I-80) for which an estimated value is needed. Then, the largest AADT count within a given 1-km pixel was chosen to represent the pixel's AADT. The estimated AADT on the highway system and major local roads is shown in Figure 18.

The generated AADT map is essentially a traffic density map we can use to apportion the District's total on-road emissions although we did not consider non-major roads in this study. Distributing the total on-road emission (2164 Mg CH_4/yr) estimated by the District proportional to the traffic density, we created an on-road CH_4 emission map on BAAQMD's 1-km grid (Figure 19).

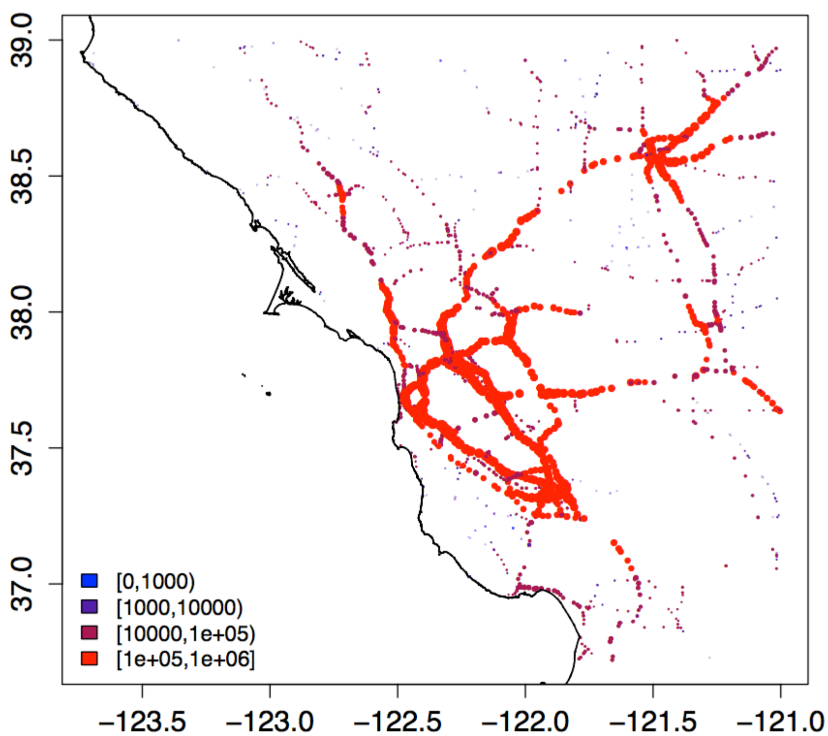


Figure 17. AADT counts in and around the Bay Area. Each circle represents the relatively traffic volume (size proportional to the traffic volume).

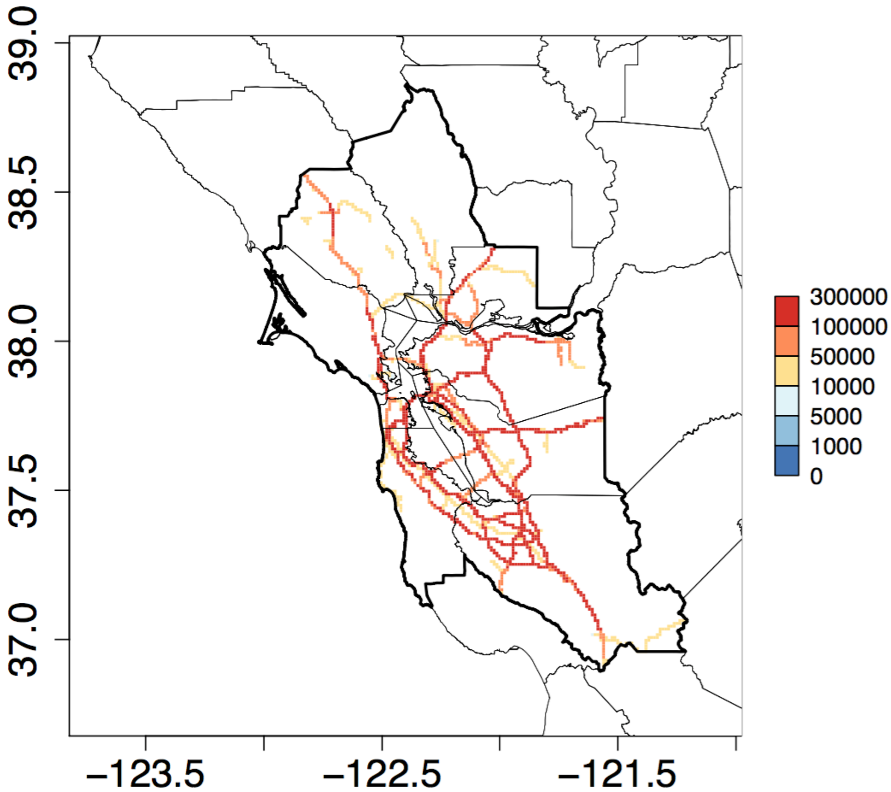


Figure 18. Interpolated traffic volume (AADT) counts for the BAAQMD.

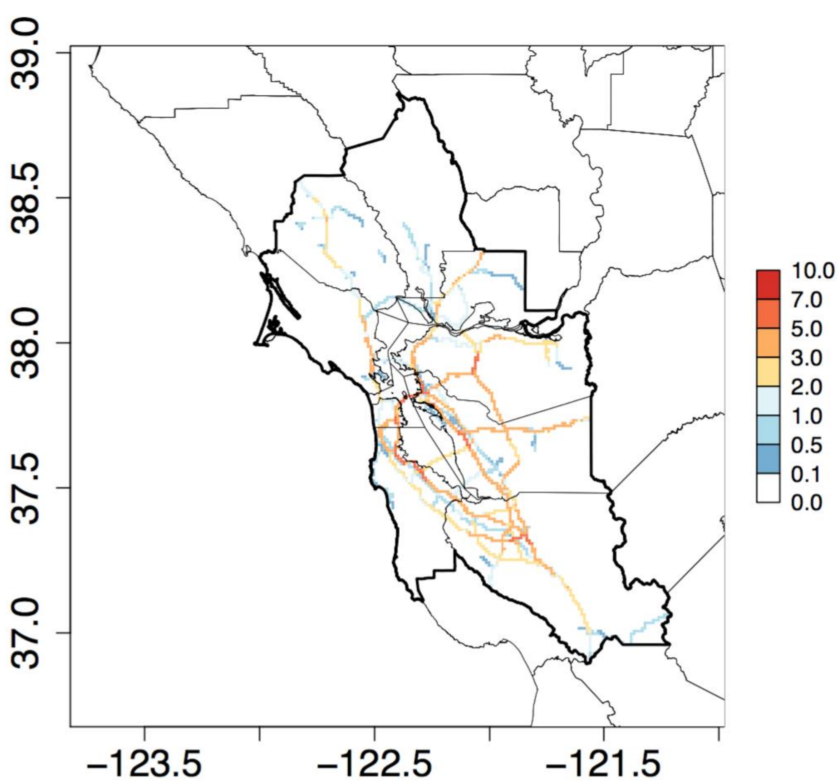


Figure 19. On-road CH_4 emissions (nmol/m^2/s) on the 1-km BAAQMD grid.

Table 14 shows the on-road CH_4 emissions by county within the District, which were calculated by summing all the pixel values in each county shown in Figure 19. As can be seen in Figure 19, approximately 50% of the total emission is attributed to Alameda and Santa Clara Counties. As described, we considered only highways and major local roads where traffic county data are available. More complete spatially explicit on-road emissions that include local roads would require further studies.

Table 14. Summary of On-road Emissions by County

County	Mg CH_4/yr
ALAMEDA	578
CONTRA COSTA	318
MARIN	105
NAPA	28
SAN FRANCISCO	95
SAN MATEO	301
SANTA CLARA	515
SOLANO	130*
SONOMA	93*
Total	**2163****

*Represents the total emission within BAAQMD's boundary.
**The total estimated from the gridded emission map is 1 Mg less than the District total (2164 Mg).

7. Wastewater

Wastewater emission maps on BAAQMD's 1-km grid were prepared for the domestic and industrial wastewater subsectors by incorporating the District's emission estimates.

7.1. Domestic Wastewater

The domestic wastewater emissions are provided in three different categories: (1) anaerobic digesters, (2) centralized anaerobic treatment, and (3) septic systems. The anaerobic digester emission map was generated using the 2013 biogas production information at each plant (available from the District), matching a total of 426.5 Mg CH_4/yr. For centralized anaerobic and septic systems**,** the District's total emissions were apportioned proportional to the population density for the District (see Appendix I for population density).

Table 15 shows the total CH_4 emissions (estimated by the District) from the domestic wastewater treatment by sector. Figure 20 shows CH_4 emissions (units of Mg CH_4/yr) from anaerobic digesters based on the available 2013 digester gas production at each facility. Figure 21 shows CH_4 emissions (units of nmol/m^2/s) for the anaerobic digester subsector on the District's 1-km grid. Summing all emissions from pixels belonging to each county in Figure 21, we calculated the total CH_4 emission for each county, which is summarized in Table 16. The District total emission for the anaerobic digester subsector in Table 16 matches that of the 2013 total in Table 15.

Table 15. CH_4 Emissions from the Domestic Wastewater Treatment Sector

Domestic Wastewater Treatment Operations	CH_4 Emissions (Mg/yr)	
	Year 2011	Year 2013
Anaerobic Digester	465.86	426.52
Centralized Anaerobic Treatment	3,369.64	3,428.23
Septic System	1,230.06	1,251.45
Total	5,065.56	5,106.20

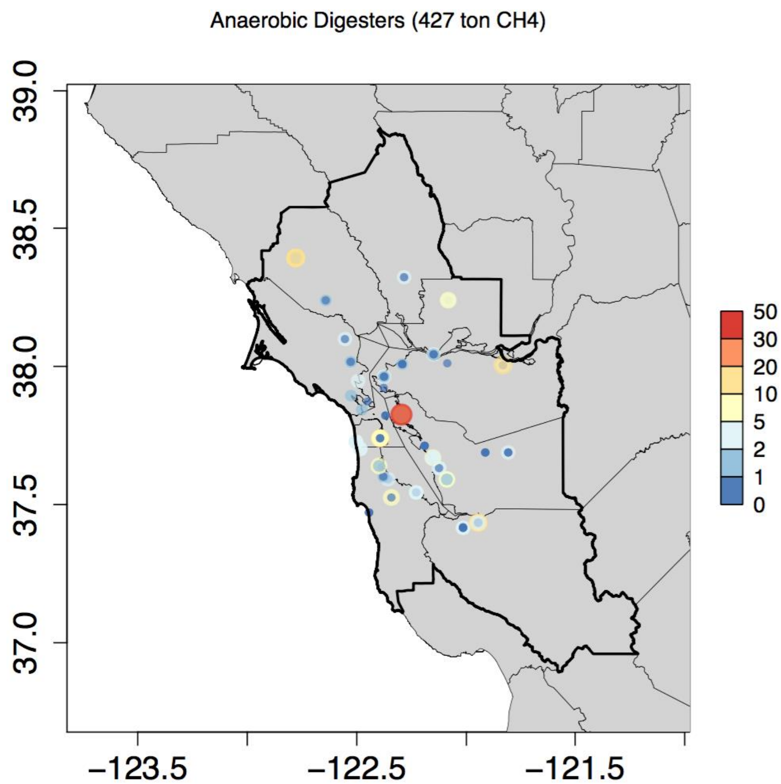


Figure 20. CH_4 emissions (Mg CH_4/yr) from anaerobic digesters based on the 2013 digester gas production at each facility.

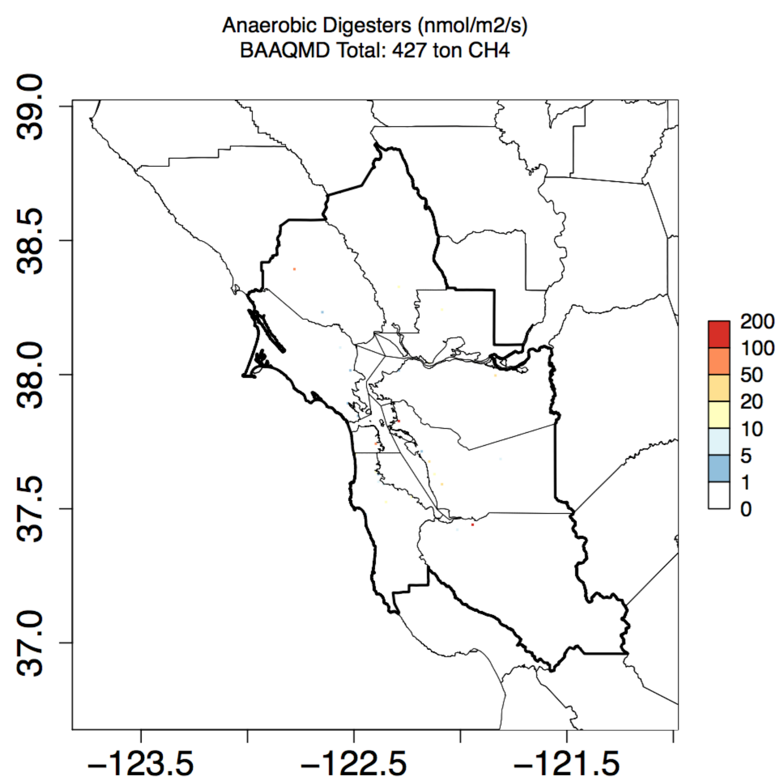


Figure 21. Anaerobic digester CH_4 emissions (nmol/m^2/s) on the 1-km BAAQMD grid.

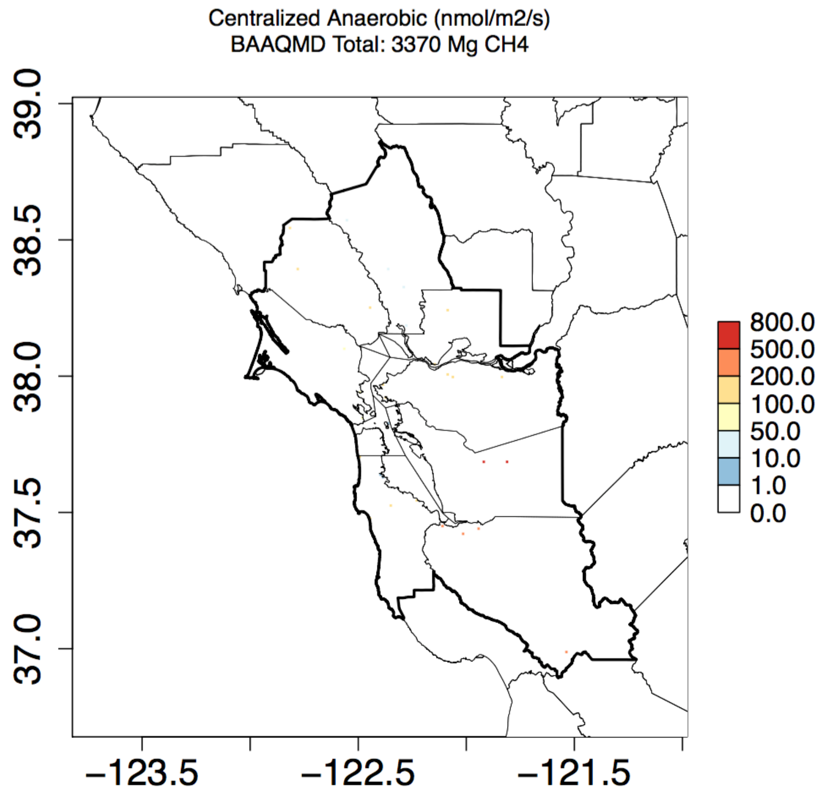
Table 16. Anaerobic Digester CH_4 Emissions by County

County	Mg CH_4/yr
ALAMEDA	156
CONTRA COSTA	19
MARIN	11
NAPA	6
SAN FRANCISCO	64
SAN MATEO	42
SANTA CLARA	62
SOLANO	15
SONOMA	51
District Total	427

The CH_4 emission maps for the centralized anaerobic treatment and septic system subsectors are shown in Figure 22. BAAQMD provides a list for centralized anaerobic facilities, which are summarized in Appendix K. Based on the facility information, the gridded emission map was generated, uniformly distributing emissions for each facility within each county (county totals are shown in Table 17). The emission map for the septic system was generated based on the population density matching the District's total for the year 2011. The emission summary for the centralized anaerobic treatment and septic system subsectors is provided in Table 17. This emission summary by county was calculated by summing emissions from the 1-km emission maps shown in Figure 22 and matches the total in Table 15.

Table 17. Summary of Centralized Anaerobic and Septic System Emissions

County	Centralized Anaerobic Treatment (Mg CH_4/yr)	Septic System (Mg CH_4/yr)
ALAMEDA	731	267
CONTRA COSTA	508	185
MARIN	122	45
NAPA	66	24
SAN FRANCISCO	390	142
SAN MATEO	348	127
SANTA CLARA	862	315
SOLANO	139	51
SONOMA	205	75
Total	**3370**	**1230**



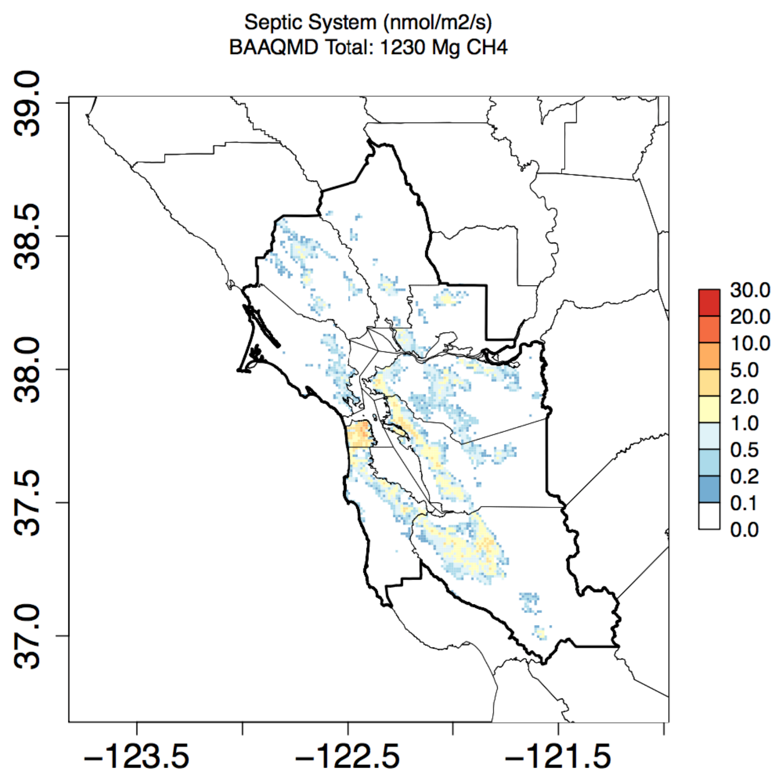


Figure 22. CH_4 emission map (nmol/m^2/s) for the centralized anaerobic treatment subsector (top) and the septic system subsector (bottom).

7.2. Industrial Wastewater

Emission maps for the industrial wastewater sector were created by incorporating the estimated CH_4 emissions (total = 1957 Mg CH_4/yr) by the District at the county level. The emission source subsectors for industrial wastewater treatment include pulp processing, refinery wastewater treatment, and food and agricultural product processing (see Appendix J for details). Except for the poultry subsector, we used the emission fraction for each county (county total vs. District total) provided by the District (for each subsector) to estimate the county total emissions from the District's total emission. The county fraction for the poultry subsector was estimated based on the estimated poultry statistics (see Appendix G for poultry statistics). Then we apportioned the estimated emission for each county uniformly. Except for pulp processing, the estimated county total emission for each subsector was uniformly distributed over each county to make a 1-km emission map (Figure 23). For the pulp processing subsector, the total emission (546 Mg CH_4/yr) was equally assigned to the two facilities in Santa Clara County.

Figure 23 shows the 2011 county-level emission map for non-refinery industrial wastewater treatment (refinery wastewater is described later). Summing all pixel values from the 1-km emission map by county, we calculated the county sum for the non-refinery industrial wastewater sector as shown in Table 18 where the District's total is 894 Mg CH_4/yr. Santa Clara County accounts for ~70% of the District's total emission for the non-refinery industrial wastewater sector. This is because the pulp industry in Santa Clara County emits a significant amount of emissions (546 Mg CH_4/yr).

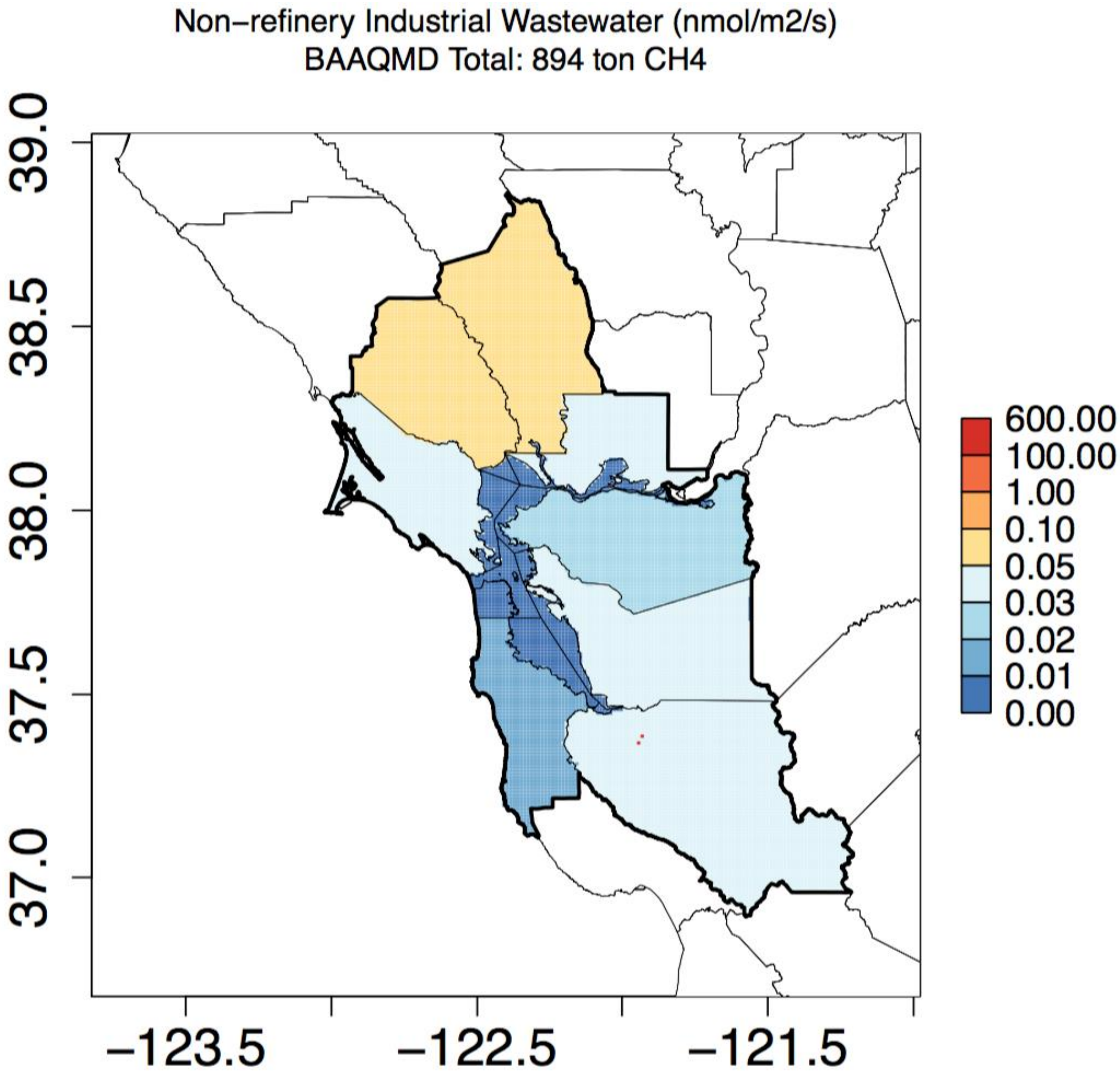


Figure 23. CH_4 emissions (nmol/m^2/s) for non-refinery industrial wastewater treatment on the 1-km BAAQMD grid. The point source emissions for the pulp processing facilities in Santa Clara County are noticeable.

Table 18. Summary of Non-refinery Industrial Wastewater CH_4 Emissions

County	Mg CH_4/yr
ALAMEDA	44
CONTRA COSTA	20
MARIN	33
NAPA	95
SAN FRANCISCO	0
SAN MATEO	7
SANTA CLARA	609
SOLANO	15
SONOMA	70
District Total	894

For refinery wastewater emissions, we apportioned the total CH_4 emission for each of the two counties with presence of refining facilities (Contra Coast and Solano) based on the county fraction (see Appendix J), matching the District's total emission (1063 Mg CH_4/yr for 2011). Then, the total emission for each county was distributed to the 1-km pixels where refining facilities exist in proportion to the refinery CH_4 emissions (calculated in Section 5). This approach assumes that the refinery wastewater emissions occur within the 1-km pixel where individual refining facilities are located. Based on this assumption for spatial allocation of emissions, Figure 24 shows the CH_4 emissions (Mg CH_4/yr) at the facility level (see Figure 25 for emission flux in units of nmol/m^2/s).

Table 19 shows the emission sum for the refinery wastewater sector by county. The District's total emission for the refinery wastewater sector is 1063 Mg CH_4/yr. The CH_4 emission for the refinery wastewater sector accounts for 54% of the total emission for the industrial wastewater sector (1957 Mg CH_4/yr). As one might expect from the refinery emissions (Section 5), Contra Costa County accounts for more than 80% of the total emission.

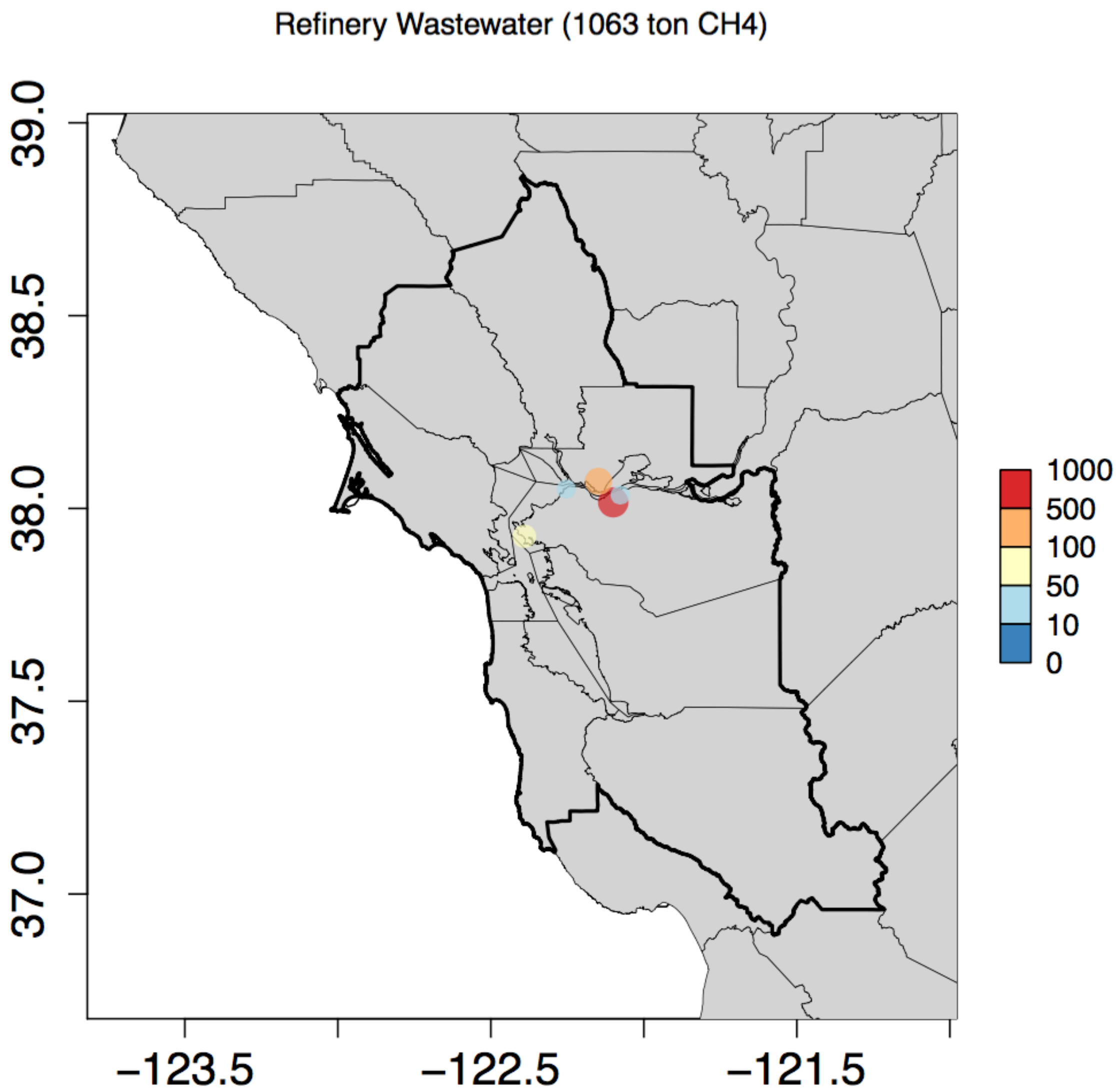


Figure 24. CH_4 emissions (Mg CH_4/yr) from the refinery wastewater processing for the year 2011.

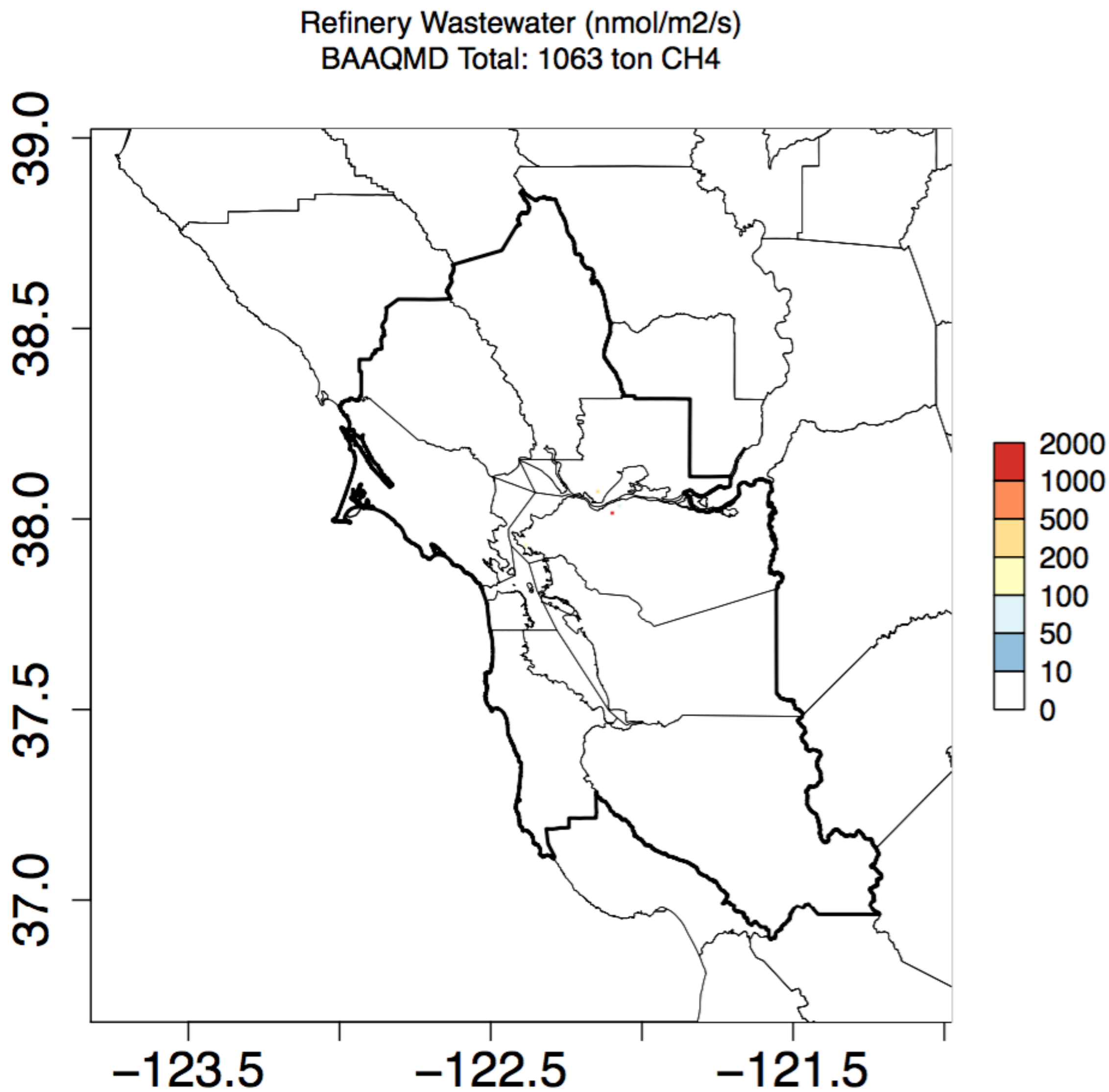


Figure 25. CH_4 emissions (nmol/m^2/s) for refinery industrial wastewater treatment on the 1-km BAAQMD grid. See Figure 24 for facility-level emissions with more clarity.

Table 19. Refinery Wastewater CH_4 Emissions by County

County	Mg CH_4/yr
ALAMEDA	0
CONTRA COSTA	882
MARIN	0
NAPA	0
SAN FRANCISCO	0
SAN MATEO	0
SANTA CLARA	0
SOLANO	181
SONOMA	0
Total	1063

8. Uncertainty Estimates

We use US EPA's CH_4 uncertainty estimates as the basis of uncertainty estimates for our bottom-up inventory because uncertainty estimates for emission factors or activity data are not readily available at the sub-regional or state level (US EPA, 2016). We note that some of the activity data used in this study are obtained from national databases (e.g., livestock data) and part of the emission factors are derived based on those of CARB, which adopts EPA emission factors for many sectors. EPA's uncertainty for each sector (e.g., natural gas system) is provided as the percentage deviation above and below the mean emission estimate (Table 20). For example, the percentage deviations below and above the mean estimate for the natural gas system are 19% and 30% (at 95% confidence), respectively. Because of this asymmetric property in uncertainty we assume a lognormal probability density function (PDF) for the distribution of emissions among the five different alternatives considered by EPA (US EPA, 2016).

Given our bottom-up estimates (i.e., mean estimates) and the percentage deviations (from the mean) provided by EPA, we can characterize the lognormal distribution by estimating the standard deviation (sd). For example, for the natural gas sector with mean of 17.5 Gg CH_4 and percentage deviations of 19% and 30% below and above the mean (see Table 20), we can approximate its lognormal distribution with mean 2.85 and sd 0.13 (in $\log_e$ scale). In order to estimate the uncertainty for the total CH_4 in BAAQMD, we need to combine the lognormal PDFs for individual sectors. However, there is no closed-form solution to combining multiple lognormal distributions. Therefore, we use a numerical method to estimate the combined uncertainty for the total CH_4 emission based on our bottom-up estimates (as mean) and the estimated standard deviations. Assuming uncorrelated errors among the sectors, we generated random samples (10^5 samples for each sector) based on the lognormal distributions that we characterized for each sector and combined them to obtain a set of random samples for the total CH_4 emission for the District. To remove possible autocorrelations in samples we selected one sample in every ten samples using a process known as thinning in a Markov chain Monte Carlo (MCMC) method. Figure 26(a) shows the autocorrelation function for the samples of the combined total CH_4 emissions, which suggests that the samples are not significantly correlated. Also, Figure 26(b) shows the correlations between different sectors for each of which 10^5 samples were generated as described. As shown in the figure, the cross-correlation between each pair of the sectors are near zero in this MCMC simulation, suggesting independent MCMC samples between sectors.

The distribution of the combined total CH_4 emissions for BAAQMD is shown in Figures 26(c) and 26(d) using different assumptions on the uncertainty (1 vs. 2 standard deviation (sd)) applicable to the sub-regional scale (i.e., BAAQMD). Note that while Table 20 shows the 95% confidence interval (CI), we calculated the 1 sd value to characterize the PDF for each sector's emissions. Recall that the uncertainty shown in Table 20 was estimated at the national scale as a fraction of the mean estimate. At the sub-regional scale such as BAAQMD, the uncertainty is likely larger than that of the national scale. Thus, we increased the fractional uncertainty shown in Table 20 by a factor of 2 (i.e., using 2 sd) and performed the MCMC simulation to be compared with the case of 1 sd.

When 2 sd was used in the MCMC simulation (Figure 26(d)), the CH_4 total emission is estimated to be 77 – 193 Gg CH_4/yr (at 95% confidence), which is larger than the case of 1 sd (93 – 157 Gg CH_4). This estimate with increased uncertainty is marginally consistent with a recent top-down estimate (180 – 300 Gg CH_4/yr) by Fairly and Fischer (2015). We note that in this uncertainty estimation we considered the uncertainty estimates only at the source sector level and then for the total of the District. However, it is possible that there exists spatial correlation in the gridded emissions between different pixels, which may affect the overall uncertainty for each sector and the District total. Also, there might be temporal variations in uncertainty as well as emissions for some sectors (e.g., landfill, manure management), which were not considered in this study (or in the CARB and EPA inventories). In addition, it is likely that the emissions for some of the sectors will vary due to inter-annual climate variations (e.g., California's recent drought). Investigation of all of the above issues would be useful for more accurate quantification of emissions in future studies.

Last, we also estimated the CIs for the lower and upper bounds (e.g., CIs for 77 (lower) and 193 (upper) Gg for the 2 sd case) using a bootstrapping technique (resampling with replacement and 1000 replicates). We find that the CIs for the lower and upper bounds are small, ranging from 1 to 2 Gg (at 95% confidence).

Table 20. CH_4 Emissions for BAAQMD by Sector and US EPA Inventory Uncertainty

Sector[¶]	CH_4 Emissions for BAAQMD (Mg/yr)	Low (%)*	High (%)*
NG	17499	19	30
LF	61478	56[†]	49[†]
LS	18257	18	20
OM	2164	13	21
PR	1931	24[‡]	149[‡]
WW	6984	39	21
WL	3738	100	100
Others	8092	42[§]	157[§]

[¶]The sector categories are similar to those of Table 1: natural gas (NG), landfill (LF), livestock (LS), on-road mobile (OM), petroleum refinery (PR), wastewater (WW), and wetland (WL).
*provided as the percentage deviation above and below the mean emission estimate (here, the second column).
[†]For LS (manure management + enteric fermentation), we use the values for manure management, which has larger uncertainty than enteric fermentation.
[‡]The overall uncertainty for the petroleum system category is used because a separate uncertainty for refinery is not available.
[§]The values for stationary combustion are used because the "Others" category mostly includes miscellaneous stationary combustion.

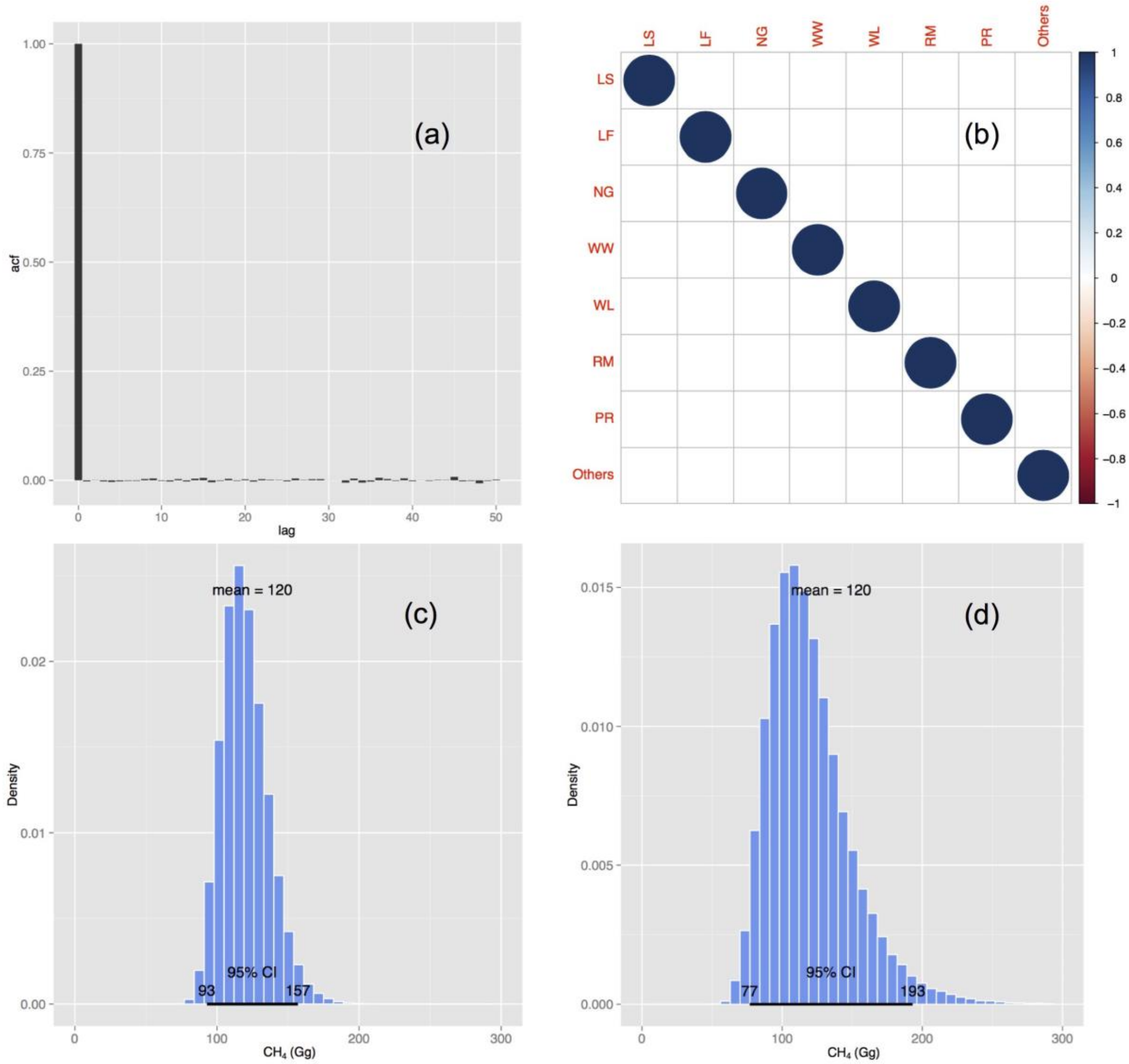


Figure 26. (a) autocorrelation function for the combined total CH_4 samples, (b) cross-correlation between different sectors (white color indicates no correlation), (c) histogram for the combined total CH_4 using 1 sd error from the US EPA uncertainty, and (d) histogram for the combined total CH_4 using 2 sd error from the US EPA uncertainty.

9. Recommendations for Future Work

This project has both compiled detailed activity data and emission factors for the bottom-up inventory of CH_4 emissions in BAAQMD, and implemented spatial disaggregation of the inventory at 1 km × 1 km spatial resolution. This high-resolution spatially explicit inventory can be used as a priori estimate of emissions for atmospheric inverse modeling that incorporates atmospheric observations, allowing these observations to further improve the inventory for the District.

Several areas of research are needed to improve estimation of GHG emissions for the purpose of inventory evaluation in BAAQMD:

- While the emission inventory from this study significantly improves understanding of emission sources for BAAQMD providing a spatially disaggregated emissions model, more accurate activity data (e.g., dairy farm locations in Sonoma County) are needed for detailed spatial disaggregation.
- In addition, utilization of auxiliary datasets (e.g., land type for non-dairy livestock) would improve spatial disaggregation for sectors for which direct spatial information is not available.
- For comparison between bottom-up and top-down methods, bottom-up inventory methods could be expanded to include 1^{st} order estimates of temporal variations, and uncertainty estimates including correlations for varying spatial and temporal scales (e.g., pixels to region total).
- The regional multi-site CH_4 measurement network that the District recently implemented could be expanded to include select volatile organic compounds (VOCs) for emission source speciation.
- Beyond the current ground-based measurement network, acquisition and assessment of measurements from upcoming space-borne remote sensing (e.g., TROPOspheric Monitoring Instrument (TROPOMI)) have the potential to enhance the spatial coverage of observations, providing more constraints on emissions.
- Spot checks of emissions from localized facilities (e.g., landfills, refineries, gas storage) using airborne/ground-mobile measurements in a mass-balance approach may be useful for testing reporting by industry or improving facility-level emission factors.
- Integrating measurements from different platforms, atmospheric inverse modeling would greatly improve evaluation of regional bottom-up CH_4 emissions by source sector. As part of this effort, additional focus on key atmospheric transport variables, wind profiles and boundary layer mixing height, would be of high value for refining and evaluating the transport model used for the GHG mixing ratio prediction.

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APPENDICES

Appendix A. CARB's Livestock Emissions (Tg CO_2eq, GWP = 25) by Sector (March 2014 version)

Livestock	Dairy	Cattle	Sheep	Goat	Horse	Swine	Poultry	Total
Enteric	8.22	3.08	0.11	0.02	0.35	0.00	0.00	11.78
Manure	10.24	0.13	0.01	0.00	0.06	0.04	0.12	10.61
Total	**18.46**	**3.21**	**0.12**	**0.02**	**0.41**	**0.05**	**0.12**	**22.39**

Appendix B. Cattle Activity Data

Note for the color-code numbers in the table below:

Black: Original USDA 2012 cattle inventory from http://www.nass.usda.gov/Statistics_by_State/California/Publications/County_Estimates/2013lvsceF.pdf

Red: 2012 USDA Census from http://www.agcensus.usda.gov/Publications/2012/

Green: 2007 USDA Census http://www.agcensus.usda.gov/Publications/2007/

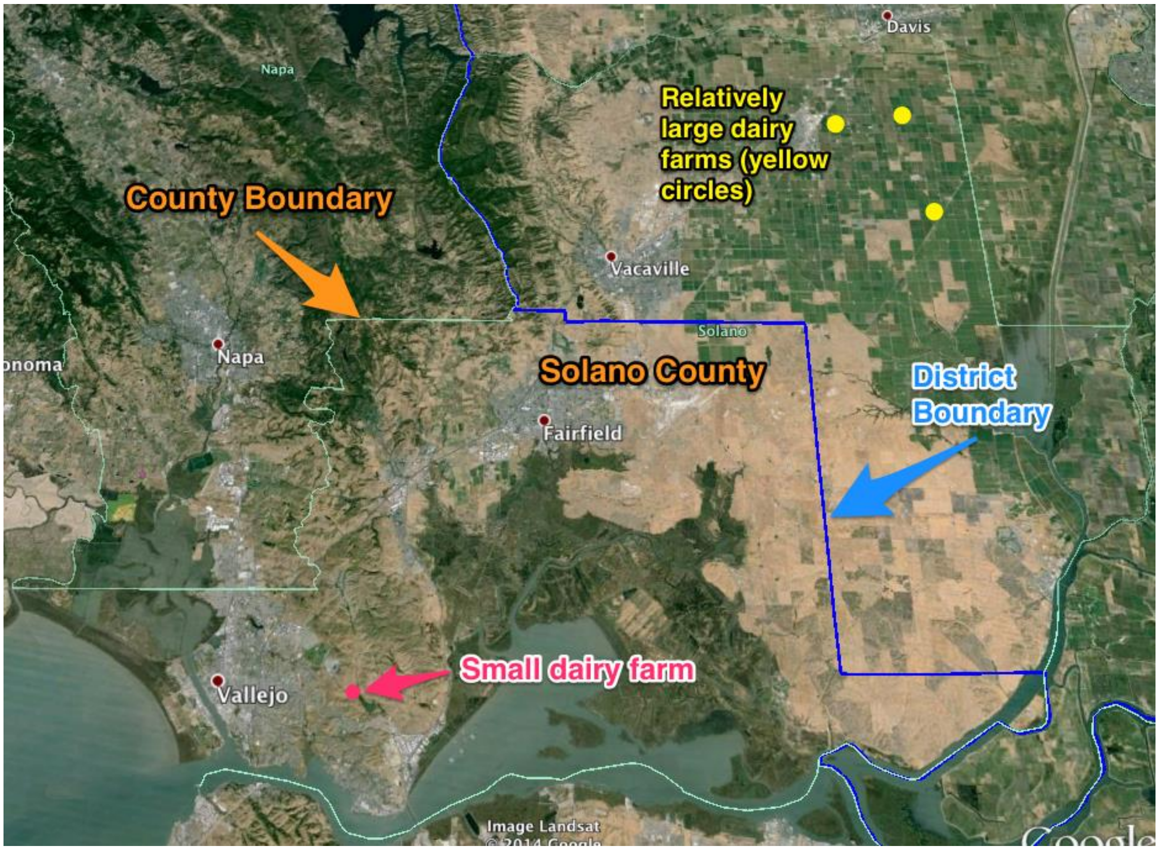
Blue: 2002 USDA Census http://www.agcensus.usda.gov/Publications/2002

County	All Cattle	Beef Cows	Milk Cows*
Del Norte	17600	1,000	5,100
Humboldt	57000	16,600	13,700
Mendocino	18600	8,800	1,900
Shasta	33500	17,900	192
Siskiyou	54000	29,500	900
Trinity	2900	2,500	13
Lassen	44000	21,500	48
Modoc	58000	33,500	**15**
Plumas	11400	**5766**	**7**
Alameda	15400	9,000	**6**
Contra Costa	16500	9519	12
Lake	3200	2,000	3
Marin	33000	8,300	10,200
Monterey	56000	20,500	1,600
Napa	6700	**4300**	**245**
San Benito	31500	12,200	**2128**
San Francisco	0	0	0
San Luis Obispo	55000	29616	259
San Mateo	2100	1,000	10
Santa Clara	16900	8,500	10
Santa Cruz	1000	1,000	0
Sonoma	73000	11,300	29,500
Butte	15500	7346	427
Colusa	15900	8358	102
Glenn	61000	12,200	21,500
Sacramento	68000	13,200	18,500
Solano	41500	17421	4300
Sutter	7700	3513	6
Tehama	56000	23,500	4,000
Yolo	21000	**6773**	**2012**
Yuba	22000	5,000	3,200
Fresno	415000	19,300	120,000

Kern	330000	31,500	160,000
Kings	355000	7,200	165,000
Madera	190000	18,500	75,000
Merced	535000	29,500	255,000
San Joaquin	240000	19,700	100,000
Stanislaus	415000	36,000	180,000
Tulare	1030000	27,500	440,000
Alpine	1000	400	0
Amador	13300	8,800	**8**
Calaveras	21000	9,300	3
El Dorado	6500	3,000	27
Inyo	13900	9165	13
Mariposa	18900	**10204**	**245**
Mono	6400	4,100	0
Nevada	5500	2,700	58
Placer	14500	**0**	**0**
Sierra	4200	2,100	**0**
Tuolumne	11800	6,800	15
Imperial	435000	4,900	10,600
Los Angeles	5800	1,000	**4457**
Orange	700	400	0
Riverside	105000	2,000	51,000
San Bernardino	200000	3,000	92,000
San Diego	16500	5,700	3,400
Santa Barbara	37500	15,200	**3129**
Ventura	6600	4,000	20
Total	5,350,000	633,581	1,779,870

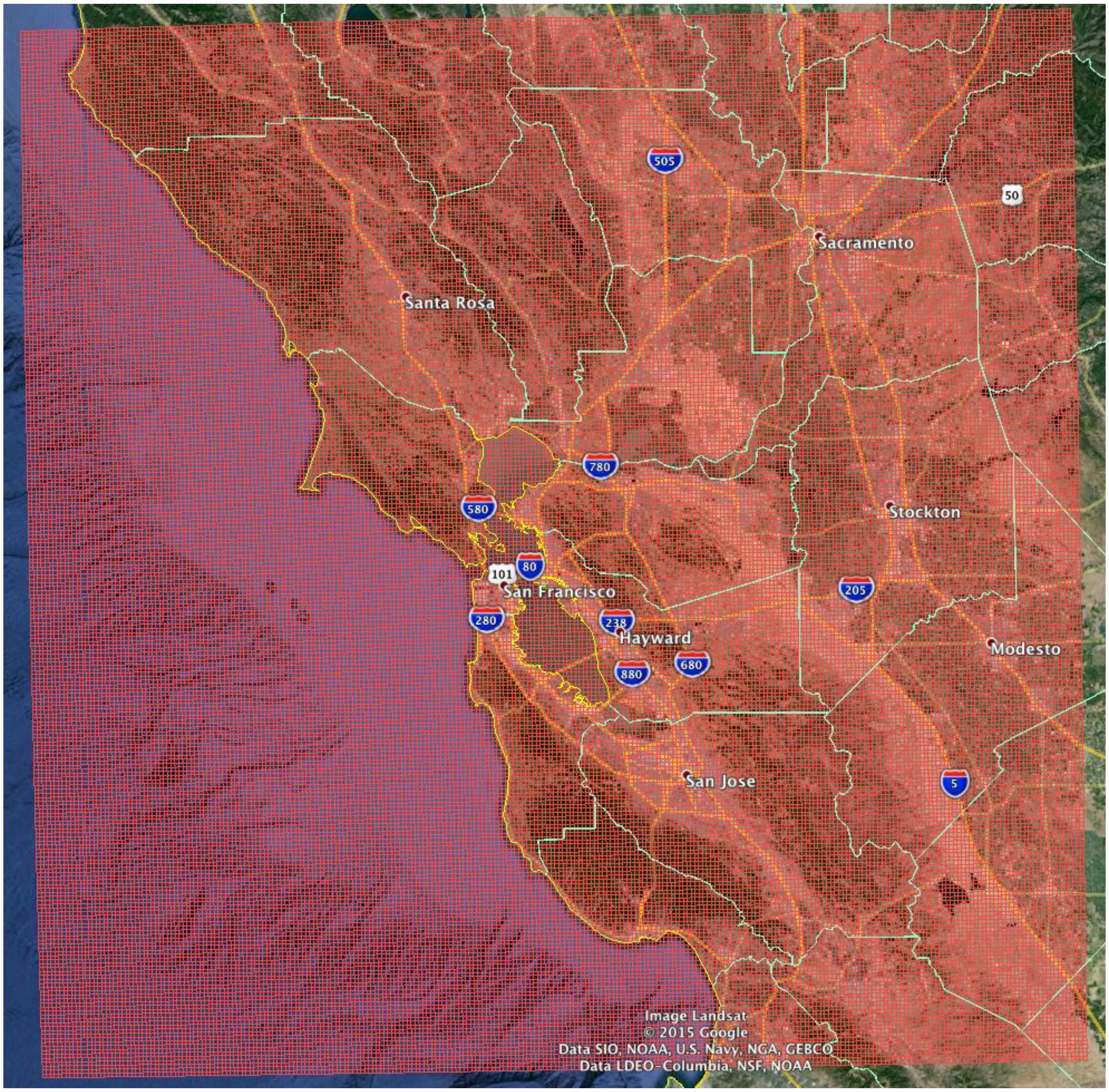
*USDA Census data do not have young dairy cows (that haven't calved) at the county level. Therefore, we estimated the dairy emissions only using the data in this column (i.e., "Milk Cows") after disaggregating them spatially.

Appendix C. Dairy Farms in Solano County



The county area within the District's boundary is ~48% of the total area of Solano County, and most of the identified large dairy farms are located outside the District boundary.

Appendix D. 1-km BAAQMD Grid



Appendix E. Activity Data for Horse, Swine, Sheep, and Goat

Data source: http://www.agcensus.usda.gov/Publications/

Note: When the 2012 data are not available, 2007 data were used

County	Horse	Swine	Sheep*	Goat
ALAMEDA	955	25	1199	229
ALPINE	21	NA	NA	NA
AMADOR	788	15	656	1778
BUTTE	1958	3202	3923	1430
CALAVERAS	1323	104	1572	2422
COLUSA	501	586	1890	665
CONTRA COSTA	2658	56	571	6993
DEL NORTE	142	85	223	194
EL DORADO	2826	300	1257	3309
FRESNO	5027	2910	67212	7109
GLENN	1166	308	3219	1119
HUMBOLDT	1732	440	4281	2980
IMPERIAL	156	8	56723	304
INYO	1108	19	220	NA
KERN	3512	1181	114571	2841
KINGS	1116	114	17501	6004
LAKE	948	212	1278	1757
LASSEN	1498	104	7992	418
LOS ANGELES	6018	239	999	1277
MADERA	1807	402	1539	966
MARIN	601	155	5338	3185
MARIPOSA	1197	46	1098	1109
MENDOCINO	1975	762	10742	1660
MERCED	1978	586	23246	5276
MODOC	1271	NA	13462	2016
MONO	183	0	378	60
MONTEREY	1981	68	3122	637
NAPA	739	34	903	1319
NEVADA	1552	180	2363	1452
ORANGE	1852	31	73	NA
PLACER	2600	602	5361	3360
PLUMAS	359	14	239	46
RIVERSIDE	12685	1147	36846	5090
SACRAMENTO	5837	407	4706	7594
SAN BENITO	1585	19	1347	1087
SAN BERNARDINO	4452	1030	673	1962

SAN DIEGO	8447	1705	2857	2345
SAN FRANCISCO	0	NA	NA	NA
SAN JOAQUIN	3402	2328	21256	2843
SAN LUIS OBISPO	6283	426	13276	1301
SAN MATEO	2678	17	185	99
SANTA BARBARA	6453	672	543	882
SANTA CLARA	2177	60	1234	638
SANTA CRUZ	592	0	3208	3556
SHASTA	4385	231	1689	3220
SIERRA	244	0	104	NA
SISKIYOU	1956	918	3494	969
SOLANO	1437	179	58338	3753
SONOMA	4439	1001	28224	9747
STANISLAUS	5455	29017	3825	20939
SUTTER	809	585	9555	848
TEHAMA	4123	1028	6238	6221
TRINITY	475	744	404	87
TULARE	4510	56377	93479	1204
TUOLUMNE	879	90	979	1213
VENTURA	3256	183	1068	322
YOLO	1500	711	15113	1017
YUBA	2919	230	6766	1600
Total	142526	111893	668558	140452

*Includes lambs.

Appendix F. CARB 2000 Poultry Statistics by County and Animal

Data source: http://www.arb.ca.gov/ei/areasrc/fullpdf/FULL7-6.PDF

County	Broiler	Layer & Pullets	Turkey	Total Poultry
california, alameda	331,655	318	8	331,981
california, contra costa	24	343	-	367
california, marin	-	170	55,862	56,032
california, napa	1,653,743	920	24,034	1,678,697
california, san francisco	-	-	-	-
california, san mateo	-	353	169	522
california, santa clara	113	141,897	23	142,033
california, solano	54	376	40	470
california, sonoma	979,101	297,372	62,312	1,338,785
District Total	2,964,690	441,749	142,448	3,548,887
State Total	**43,145,455**	**24,056,000**	**9,000,000**	**76,201,455**

Appendix G. Adjusted Poultry Total by County and Animal

County	Broiler	Layer & Pullets	Turkey	Poultry Total
california, alameda	74,605	317	5	74,927
california, contra costa	5	342	-	347
california, marin	-	169	32,069	32,238
california, napa	372,005	917	13,797	386,720
california, san francisco	-	-	-	-
california, san mateo	-	352	97	449
california, santa clara	25	141,477	13	141,516
california, solano*	12	375	23	410
california, sonoma*	220,246	296,492	35,772	552,510
Total	**666,899**	**440,442**	**81,776**	**1,189,116**

*multiply by 0.48 (Solano County area fraction within the District boundary) and 0.39 (Sonoma) to obtain numbers within the District only.

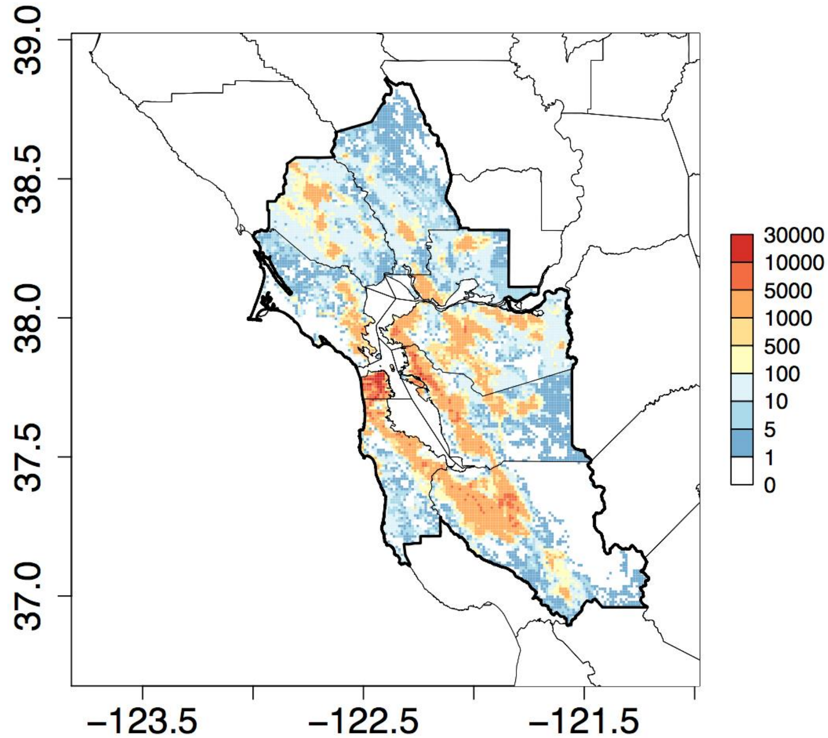
Appendix H. Bay Area Population Census Data by County

Source: http://www.bayareacensus.ca.gov/bayarea.htm. The 2010 census data were used to adjust the 2000 1-km gridded population map.

County	2010	2000
ALAMEDA	1510271	1443741
CONTRA COSTA	1049025	948816
MARIN	252409	247289
NAPA	136484	124279
SAN FRANCISCO	805235	776733
SAN MATEO	718451	707161
SANTA CLARA	1781642	1682585
SOLANO	413344	394542
SONOMA	483878	458614
Total	**7150739**	**6783760**

Appendix I. Population Density (persons/pixel) for BAAQMD (~1 km resolution)

The 1-km population density map for BAAQMD was generated by aggregating the 30-m population map for the 2000 available from http://geography.wr.usgs.gov/science/dasymetric/data.htm. The aggregated 1-km population map was adjusted by county to represent the 2010 census data (http://www.bayareacensus.ca.gov/bayarea.htm, see Appendix H).



Population by County from the 1-km Population Density Map

County	Population
ALAMEDA	1510271
CONTRA COSTA	1049025
MARIN	252409
NAPA	136484
SAN FRANCISCO	805235
SAN MATEO	718451
SANTA CLARA	1781642
SOLANO	287060*
SONOMA	423280*
Total	**6963856**

*Represents the estimated total population within the District boundary.

Appendix J. County Fraction (county total vs. District total CH_4) for Industrial Wastewater Treatment by Subsector

County	Pulp	Meat	Poultry*	Non-citrus	Citrus	Apple	Grapes	Vegetable	Potato	Refinery
Alameda	0.00	0.29	0.06	0.06	0.00	0.00	0.03	0.00	0.00	0.00
Contra Costa	0.00	0.00	0.00	0.07	0.16	0.00	0.00	0.22	0.00	0.83
Marin	0.00	0.27	0.03	0.01	0.00	0.01	0.01	0.01	0.39	0.00
Napa	0.00	0.00	0.33	0.59	0.16	0.00	0.35	0.00	0.10	0.00
San Francisco	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
San Mateo	0.00	0.03	0.00	0.00	0.03	0.01	0.00	0.06	0.10	0.00
Santa Clara	1.00	0.27	0.12	0.03	0.34	0.06	0.04	0.48	0.10	0.00
Solano	0.00	0.00	0.00	0.02	0.27	0.02	0.04	0.21	0.11	0.17
Sonoma	0.00	0.14	0.46	0.22	0.06	0.89	0.53	0.01	0.20	0.00
Total (fraction)	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
Total emission (Metric Ton CH_4)	546.1	116.9	15.1	138.2	0.0	1.4	27.0	49.3	0.2	1062.9

*The county fraction for the poultry sector is based on the estimated (adjusted) poultry statistics in the livestock section. The fractions for the other sectors were provided by the District.

Appendix K. 2014 Potential Centralized Anaerobic Facilities in BAAQMD

Plant Number	Plant Name	Address	City	Longitude	Latitude
479	Treasure Island - US Navy BRAC PMO-W	Treasure Island	San Francisco	-122.370	37.822
617	Palo Alto Regional Water Quality Control Plant	2501 Embarcadero Way	Palo Alto	-122.112	37.451
653	Central Marin Sanitation Agency	Andersen Drive, East end	San Rafael	-122.494	37.947
733	City of Sunnyvale Water Pollution Control	1440 Borregas Avenue	Sunnyvale	-122.015	37.416
778	San Jose/Santa Clara Water Pollution Control	700 Los Esteros Road	San Jose	-121.946	37.434
861	San Mateo Water Quality Control Plant	2050 Detroit Drive	San Mateo	-122.342	37.526
907	Central Contra Costa Sanitary District	5019 Imhoff Place	Martinez	-122.067	37.996
1228	Sonoma County Water Agency	22675 8th St, East	Sonoma	-122.444	38.250
1236	Town of Windsor	8400 Windsor Road	Windsor	-122.811	38.545
1258	Delta Diablo Sanitation District	2500 Pittsburg & Antioch Hwy	Antioch	-121.833	38.004
1271	West County Wastewater District	2377 Garden Tract Rd	Richmond	-122.375	37.963
1275	Novato Sanitary District	500 Davidson Street	Novato	-122.554	38.099
1371	Dublin San Ramon Services District - Wastewater TP	7399 Johnson Drive	Pleasanton	-121.914	37.688
1381	So County Regional Wastewater Auth c/o CH2M Hill	1500 Southside Dr	Gilroy	-121.537	36.988
1403	City of Santa Rosa Wastewater Treatment	4300 Llano Road	Santa Rosa	-122.779	38.392
1404	Fairfield-Suisun Sewer District	1010 Chadbourne Road	Fairfield	-122.083	38.240
1507	North San Mateo County Sanitation Dist	153 Lake Merced Blvd	Daly City	-122.484	37.701
1533	Sewer Authority Mid-Coastside	1000 N Cabrillo Highway	Half Moon Bay	-122.444	37.471
1534	South Bayside System Authority	Radio Road, End of	Redwood City	-122.229	37.544
1784	San Francisco International Airport	SF Int'l Airport	San Francisco	-122.387	37.635
1791	City of Benicia	614 5th Street	Benicia	-122.149	38.044

2053	Sausalito-Marin City Sanitary District	#1 Fort Baker Road	Sausalito	-122.477	37.843
2482	City of Richmond Water Pollution Control District	601 Canal Boulevard	Richmond	-122.377	37.922
3169	City of Livermore Sewage Treatment Plant	101 W Jack London Blvd	Livermore	-121.809	37.688
4116	San Francisco, City & County, PUC	3500 Great Highway	San Francisco	-122.504	37.727
4408	Mt View Sanitary District	3800 Arthur Road	Martinez	-122.087	38.011
5876	South San Francisco-San Bruno Water Quality Plant	195 Belle Air Road	South San Francisco	-122.399	37.640
6967	Town of Yountville	7501 Solano Avenue	Yountville	-122.360	38.393
7101	Napa Sanitation District - Soscol	1515 Soscol Ferry Rd	Napa	-122.284	38.323
12231	City of American Canyon	151 Mezzetta Court	American Canyon	-122.278	38.189
3471	City of Calistoga	Dunaweal Lane	Calistoga	-122.555	38.570