**3.2 Landfill emissions**

We consider in more detail the 53% increase in our posterior landfill emissions relative to the GHGI. GHGI landfill estimates scale the total emissions reported to the GHGRP by a factor to account for non-reporting landfills (EPA, 2022a). GHGRP requirements applied to 1297 landfills emitting more than 1 Gg a-1 across the U.S. in 2019 (EPA GHGRP, 2019), over 500 of which had gas recovery systems (EPA LMOP, 2019). GHGRP requires that landfills use two methods to report emissions. Facilities without gas collection use two approaches that rely on landfill attributes and a first-order decay model based on landfilled mass so that emissions peak the year after waste disposal. However, a survey of 128 California landfills with gas recovery systems found that methane was produced at relatively constant rates over time (Spokas et al., 2015). Landfills with gas collection use one of these methods with recovered methane removed from the modeled emissions in addition to a back-calculation approach that estimates emissions as a function of recovered methane given an estimated collection efficiency based on cover and operation methods. A default efficiency of 0.75 is assumed if cover information is unavailable (EPA, 2022a). Both the model and back-calculation methods have high uncertainties and have not been field validated (NAS, 2018).

We compare our posterior landfill emissions to GHGRP facilities reporting more than 2.5 Gg a-1 methane. Of these 531 landfills, we limit our analysis to the 87 0.25° × 0.3125° grid cells where TROPOMI provides an averaging kernel sensitivity greater than 0.20 and where landfills explain more than 50% of prior emissions so that we are confident of our ability to separate landfill emissions from other sources. We exclude 33 facilities in grid cells containing multiple landfills because we are unable to separate the individual contributions to total emissions. Figure 5 shows the posterior emissions and corrections to the GHGRP for the remaining 73 facilities and Table 3 shows GHGRP and posterior information for the top 10 methane-producing landfills as ranked by posterior emissions.

We validate our posterior landfill results by comparison to aircraft-derived estimates for nine facilities as shown in Figure 5. We find agreement within error bounds at the Seneca Meadows Landfill in New York (landfill c in Figure 5; Catena et al., 2022) and at the Kiefer (d), Frank R. Bowerman (f), Altamont (g), Newby Island (h), and Keller Canyon (i) Landfills in California (CARB, 2021; Duren et al., 2019). We find much larger emissions than previous studies at the South Side Landfill (a) in Indiana (Cambaliza et al., 2015) and at the West Miramar Sanitary (b) and Puente Hills (e) Landfills in California (CARB, 2021; Duren et al., 2019). The discrepancy at the South Side Landfill could reflect changed emissions since the 2011 aircraft campaign, including the construction of a large landfill gas facility beginning in June 2019 (EPA LMOP, 2019), emissions from which were not captured by the 2011 aircraft campaign. Methane concentrations of 8662 ppm were recorded at a leak at the West Miramar Sanitary Landfill in November 2019 (San Diego Air Pollution Control District, 2019), suggesting that estimates from other years may not be representative of 2019 emissions. The Puente Hills Landfill closed in 2013 but was previously one of the largest landfills in CONUS (EPA GHGRP, 2019). Our landfill attribution approach, which relies on a prior estimate from 2012, may therefore misallocate emissions to the Puente Hills Landfill instead of to co-located oil and gas operations.

We find mean facility emissions of 13 Gg a-1 compared to the GHGRP mean of 7.2 Gg a-1 for the 73 landfills considered here, with a median 77% increase in reported emissions. As reflected in Table 3, we find no correlation (R2 = 0.00) between GHGRP emissions and our posterior estimates, which does not improve when we consider only facilities that do or do not capture landfill gas. This implies that the bottom-up approaches used for emissions estimation have little predictability.

For the 38 facilities that recover gas, we use avoided methane emissions calculated from the volume of recovered gas reported to the EPA Landfill Methane Outreach Program (LMOP) in 2019 together with posterior and GHGRP emissions to calculate a posterior and reported recovery efficiency, respectively. We find a low correlation (R2 = 0.17) between the efficiencies that does not depend on facility size but improves slightly for facilities constructed within the last decade (R2 = 0.31). The average posterior recovery efficiency of 0.50 (0.33 - 0.54) is much smaller than the GHGRP mean of 0.61, and both are much smaller than the 0.75 default (EPA, 2022a). Across the six landfill gas facilities at the top 10 methane-producing landfills, we find a mean posterior recovery efficiency of 0.33 that is half the GHGRP value of 0.65. Indeed, four of the six facilities report methane emission and recovery values consistent with efficiencies larger than the 0.75 default. We find a similar but still lower efficiency at the Seminole Road MSW Landfill (landfill 8) and a marginally higher recovery efficiency only at Sampson County Disposal, LLC (10).

We consider in detail the 34 facilities for which posterior emissions show a significant 50% difference from the GHGRP. We find larger emissions for 29 of these facilities, with the largest discrepancies occurring in nine of the top 10 methane-producing landfills. Three of these nine facilities experienced significant operational changes in the last decade. The South Shelby (landfill 2 in Figure 5) and South Side (3) Landfills constructed large landfill gas facilities in 2019 (EPA LMOP, 2019; Russell, 2019), suggesting that emissions from gas infrastructure development may be large. The City of Dothan Sanitary Landfill (6) has been full since 2014 (Wise, 2019). Reported emissions peaked at 7.4 Gg a-1 that year (EPA GHGRP, 2019), a value almost five times smaller than our posterior emissions, suggesting that the first order decay model is inadequate to reproduce methane emissions over time. We also find a record of air quality and landfill standard violations at these 34 facilities. At the West Miramar Sanitary Landfill (b), a leak emitting 8662 ppm methane was recorded in November 2019 (San Diego Air Pollution Control District, 2019). The Sussex County Landfill in Virginia was fined USD 99000 in 2016 for failing to address cracks in the landfill cover (Vera, 2016). We find emissions 2.3 (1.6 - 3.4) times larger than reported. Lastly, the Newby Island Landfill (h), received 30 violation notices from 2014 to 2020, including for gas collection system shutdowns (Bay Area Air Quality Management District, 2022).

There are five facilities for which our posterior emissions are significantly smaller than the 2019 GHGRP by 50%. Three report large decreases in estimated methane emissions from 2019 to 2020 that result from changed methodology. The updated estimates are consistent with our posterior emissions within error estimates in two cases and within 30% of our posterior emissions in the third case.