Supplemental

S1 CH_4 Background Estimation

A background value was calculated for each CH_4 instrument independently and subtracted from each gas concentration time series. The background CH_4 timeseries are used to calculate methane enhancements and are shown in Figure S1.

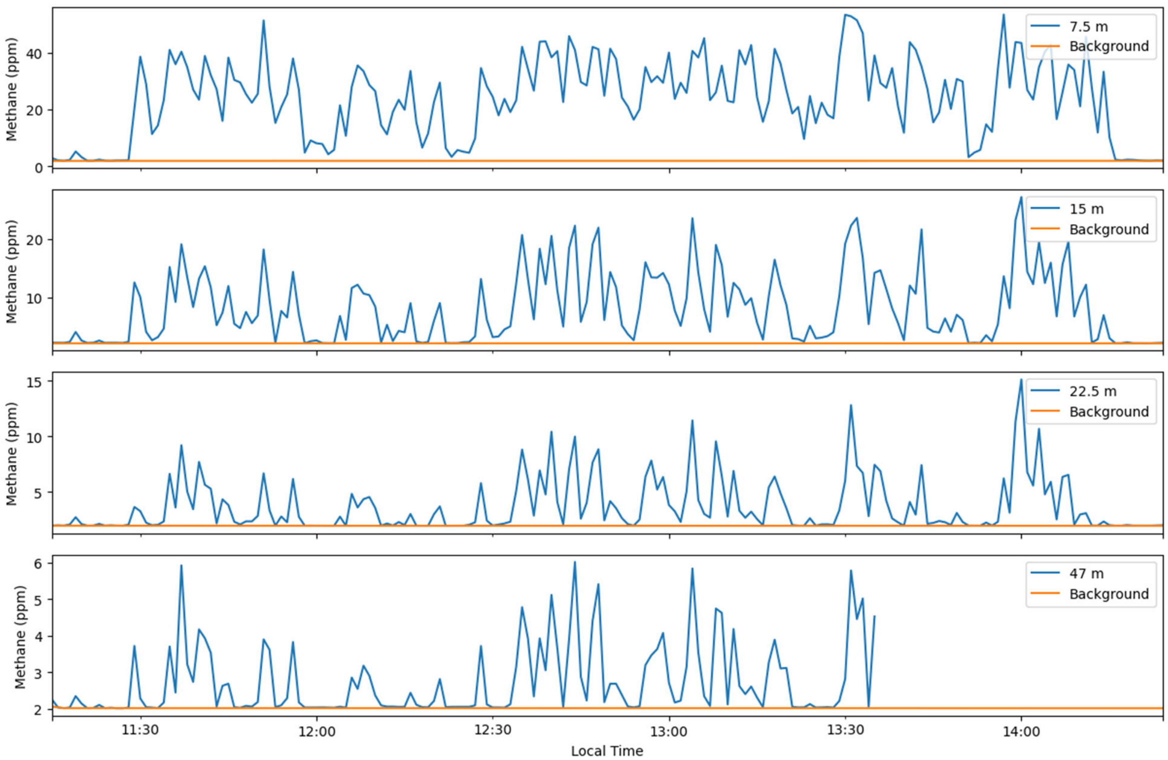

Figure S1: Timeseries of background estimates of methane concentration at each sampling location.

S2 Uncertainty Analysis of Gaussian Plume Model

The Gaussian plume model (equation 1) has various uncertainties embedded within and a thorough uncertainty analysis was performed on the data using Orthogonal Distance Regression (ODR). We analyze uncertainties in the concentration estimation from the Gaussian distribution of the methane concentration and wind direction (Figure 4). As well as analyzing the uncertainties in wind speed, wind direction, plume rise, and the fits associated with Sy and Sz. When accounting for all uncertainties, the calculated emissions rate is 10.53 ± 1.16 kg CH_4 h^{-1}. Including certain model processes also impact the inferred emission rates. For example, plume rise and ground reflection were both included in our model. If plume rise was not included the inferred emission estimate would be 5.65 ± 1.13 kg CH_4 h^{-1}, which is much lower than the full model estimates because the assumed plume height remains near to the sensor height. Conversely, if plume rise is included but ground reflection is ignored, the estimate would be 12.58 ± 1.69 kg CH_4 h^{-1}, larger than the full model estimate because the plume height is similar to the vertical plume width dimension. As with many leaks from O&G infrastructure that occur near to the ground, we observe that the ground has a significant influence on the plume shape.

	Uncertainty				
Distance (m)	C (µg•m^{-3})	U (m/s)	σy (m)	σz (m)	Z(x)

7.5	8.996354	1.004681	0.503985	0.292311	1.005858
15	0.814611	1.004681	0.223837	0.129826	2.004246
22.5	0.336909	1.004681	0.235387	0.136525	3.004290
47	0.173107	1.004681	0.721669	0.418568	6.292048

Table S1: Uncertainty parameters used in ODR fitting technique. Concentration (C) and plume width (sz) are derived from the gaussian fitting function used on the methane concentration vs wind direction plot (Figure 3a).

	peak wind direction (degrees from north)	STD (wind direction)	methane enhancement (ppm)	sigma y (m)	sigma z (m)	w (vertical wind component)	Height of plume (m)
7.5	246.6405	18.809641	37.437686	2.554617	1.481678	0.508337	1.802396
15	250.1949	11.851	18.010369	3.1476	1.825608	0.508337	2.404793
22.5	251.5541	9.669316	7.915679	3.833595	2.223485	0.508337	3.007189
47	248.918	8.106828	2.769036	6.694805	3.882987	0.508337	4.975017

Table S2: Gaussian plume model inputs used to estimate the Q methane emissions flux in (kg h^{-1}) used to create Figure 5.

S3: Comparison of Anemometer Data

Two TriSonica Sphere sonic anemometers (Anemoment LLC) were deployed to measure wind speed and direction. They were located 7.5 m and 15 m downwind of Foster 1S at 1.65 m above ground (center of sensor). Both sensors were aligned with true north using a GPS. Figure S2 shows the timeseries of wind speed and direction as recorded by the two anemometers. Both anemometers agree very well with a near constant offset of 5.7^{o} and 0.30 m/s (4.5% relative error). The difference in wind direction is likely related to sensor alignment and not differences in wind direction at the different sensor locations. The uncertainty in selecting a reference anemometer for wind speed and direction is minimal. Only the anemometer data collected at 7.5 m was used for the analysis.

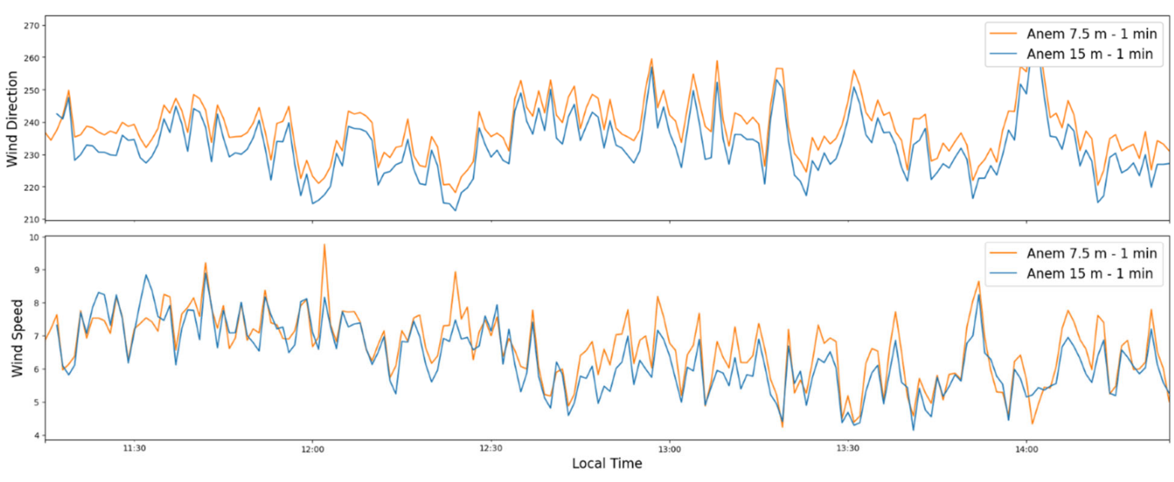

Figure S2: Comparison of wind data measured at 7.5 m and 15 m downwind of Foster 1S

S4: Estimates of vertical plume dispersion

While estimates of horizontal plume width (σ_y) could be made from the methane concentration and wind direction data, it was not possible to use the same strategy to estimate the vertical plume thickness (σ_z). Instead, we parameterize σ_z as a constant factor equal to 58% of σ_y. This value is the typical value of σ_z/σ_y derived from the different atmospheric stability classes parameterized by Pasquill-Gifford (P-G, Turner 1969). For distances relevant to our sampling setup, 5-50 m, this ratio converged to 58% with a maximum error of 10% for stability classes B-E (moderately unstable to slightly stable) and 16% for stability class F (moderately stable). That uncertainty decreased to 10% for stability class F at distances greater than 8 m.

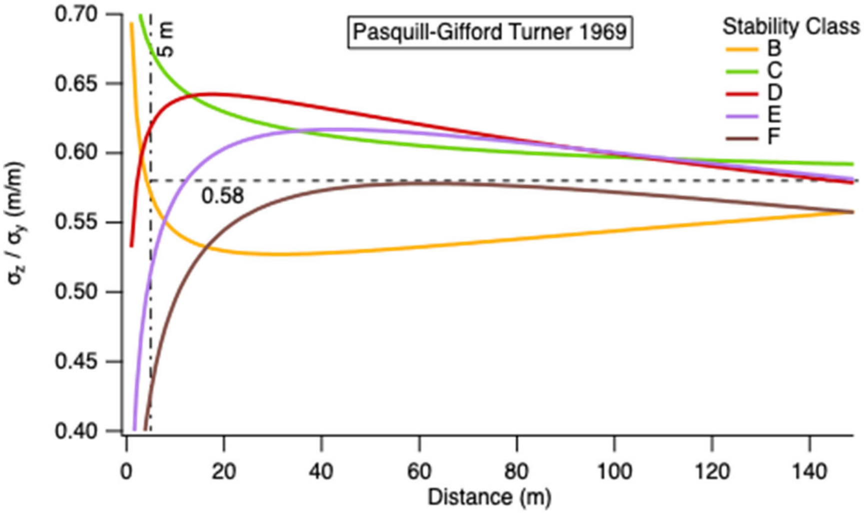

Figure S3: The ratio σ_z/σ_y for plumes parameterized using the estimates from Pasquill-Gifford (P-G 1969).

S5: Ethane-Methane signatures from an orphan well:

Ethane co-production with methane is a signature that distinguishes some methane sources, including oil and gas emissions, from biogenic methane sources, including emissions from ruminant animals. However, the emission ratio (C_2H_6/CH_4) varies between wells. For wells monitored by WDF, the ethane-methane emission ratio is measured offline by gas chromatography. The ethane-methane emission ratio for Foster 1S on 19 Apr 2023 was 0.124 mol/mol. This known signature can be used to determine if other sources contribute to the observed methane plumes and are convolved with the estimates of our time varying background methane concentration.

The ethane mixing ratio was measured by the Aeris MIRA Pico Ethane-Methane sensor at 15 m and 47 m downwind of Foster 1S. The Aeris MIRA Ultra Propane-Ethane-Methane sensor was not calibrated for ethane concentrations at this time. We process the ethane data following the same methods as processing the methane data. Specifically, the raw data is calibrated and averaged to 1-minute intervals. A background value was calculated using the average of the running minimum values. The excess ethane was then calculated as the difference between the smoothed ethane concentration and the background concentration.

Figure S5 shows the excess ethane data plotted against the excess methane data for each 1-minute interval from the Aeris MIRA Pico ethane-methane sensors at 15 m and at 47 m during venting of the well. Both instruments agree extremely well, despite the significantly lower signal observed at 47 m downwind. The Aeris Pico instrument at 15 m estimated an ethane-methane mole ratio of 0.121, which is agrees to the gas chromatography result of 0.124.

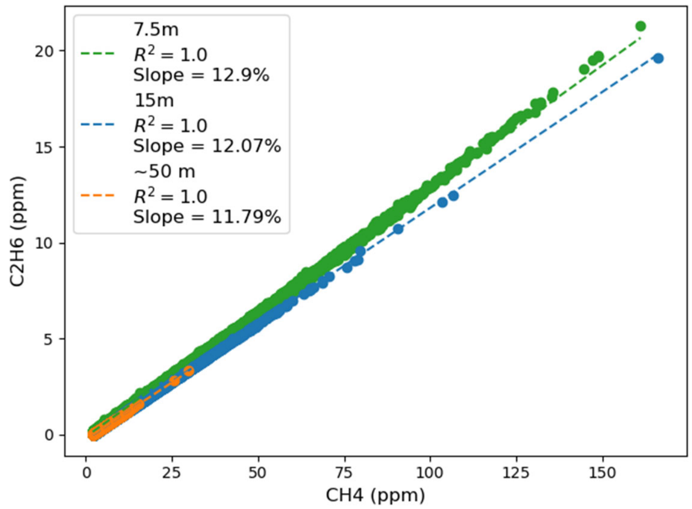

Figure S4: Cross-plot of CH_4 and C_2H_6 15 m downwind of Foster 1S during venting of the production tubing. Emission ratios are estimated as the slopes of the data and are compared to the ratio of 0.124 as measured by gas chromatography.

S6: Reported emissions by NM of plugged orphan wells

New Mexico has plugged over 148 orphan wells (including Foster 1S) with BIL funding. NM has also reported emissions rates from these pre-plug wells, many of them performed by Well Done Foundation. Analysis of these fugitive emissions reveals a very skewed emissions distribution shown in Figure S3. We note that NM reported the April 2022 for Foster 1S leak rate, partly due to our work that showed that steady state may not have been reached during our sampling and may highly bias the reported emissions.

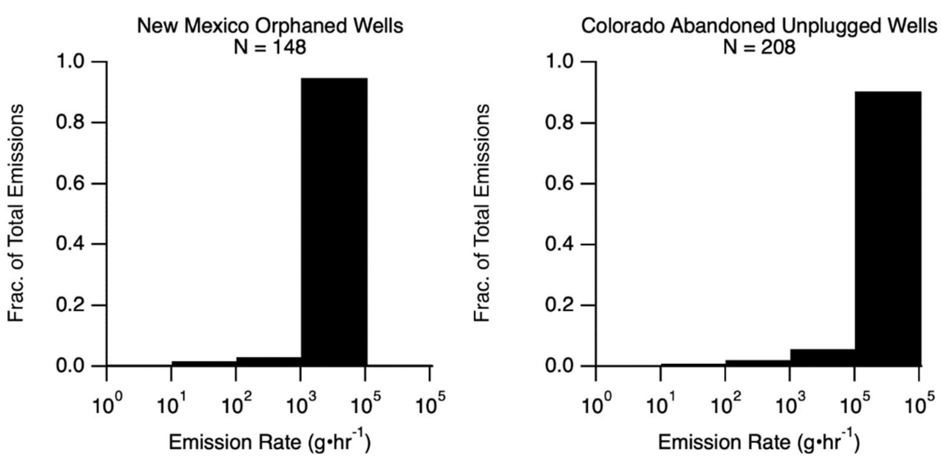

Figure S5: Distribution of unplugged orphan wells as fraction of total emissions from wells that have since been plugged in New Mexico, USA (Griswold, 2024) and from abandoned, unplugged wells in Colorado, USA (Riddick et al., 2024). In both cases, super-emitters dominate the total emissions of observed wells.