Unaddressed Uncertainties When Scaling Regional Aircraft Emissions Surveys to Basin Emission Estimates

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Abstract

Wide-area aerial methods provide comprehensive screening of methane emissions from oil and gas (O&G) facilities in production basins. Emissions detections ('plumes') from these studies are also frequently scaled to basin level. However, little information exists to determine if plumes detected fugitive emissions or known, reported, maintenance activities. This study analyzed an aircraft field study in the Denver-Julesberg basin to quantify how often plumes identified maintenance events, using a geospatial inventory of 12,629 O&G facilities with facility outlines. Study partners (7 midstream and production operators) provided timing and location of 5910 maintenance events that occurred in a 6-week period. Results indicated three substantial uncertainties with potential bias unaddressed by current prior studies. First, plumes often detect maintenance events, which short-duration, large, and poorly estimated by aircraft methods:

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9.2% to 48% [35% to 62%] of plumes on production were likely due to known maintenance events. Second, data indicated that plumes on midstream facilities were both infrequent and unpredictable, calling into question whether these estimates were representative of midstream emissions. Finally, 4 plumes attributed to O&G, representing 19% of all emissions, were not aligned with any location that would logically create emissions. While it is unclear how frequently this occurs, in this study it had material impact on emissions estimates and was detectable only with complete geospatial information. While aircraft emissions detection remains a powerful tool for identifying methane emissions on oil and gas facilities, this study indicates that additional data inputs, such as detailed GIS data, a more nuanced analysis of emission persistence and frequency, and improved sampling strategies are required to accurately scale plume estimates to basin emissions.

Introduction

Methane is the second most common greenhouse gas (GHG), increasing interest in the quantification and mitigation of anthropogenic methane emissions. Additionally, as a short-lived atmospheric species with a global warming potential (GWP) 86 times that of CO_2 over a 20-year time horizon, control of methane emissions could produce a substantial reduction in climate forcing.[1,2] In the U.S., methane emissions from the oil and gas (O&G) supply chain accounts for approximately one third of anthropogenic methane emissions,[3] with the natural gas production, transport, use and export accounting for the majority of those emissions. Recent legislative initiatives,[4,5] and subsequent regulatory moves, have increased interest in accurate assessment of O&G methane emissions. Additionally, O&G operators have publicly committed to report and reduce methane as part of voluntary programs for measurement[6] and reporting standards.[7–9]

The natural gas supply chain is traditionally divided into several sectors, including exploration and production, gas processing, distribution, and 'midstream' transport operations including gathering and boosting (G&B), transmission and storage (T&S), and liquified natural gas (LNG). While the supply chain is trans-national, production through midstream sectors occur in every production basin.

In all sectors, methane emissions are classified into three categories. *Fugitive* emissions refer to unplanned emissions, typically from leaks, abnormal process conditions, or degradation of operational components. *Vented* emissions refer to the planned release of uncombusted gas from maintenance operations (e.g. depressurization of equipment (blowdowns), well liquid unloadings, etc.) or the non-combustion use of pressurized gas in process control (e.g. gas-driven pneumatic controllers and pumps). *Combustion* emissions, or 'combustion slip,' refers to unburned fuel gas in the exhaust from combustion processes, such as gas-fueled engines or turbines, heaters, flares, and thermal oxidizers.

Fugitive emissions, including excess emissions from poorly operating vented or combustion sources, are (by definition) unknown and must be detected before they can be quantified, reported, and mitigated. In contrast, properly operating vented and combustion sources are generally known to operators, and are typically estimated and reported to regulatory or voluntary programs. Most maintenance events are short, episodic, emission sources. Operators typically log the time and nature of the event and estimate emissions for reporting via a variety of engineering methods.[10] A typical production operation in one basin may have hundreds of events per workweek.

Methane emissions have traditionally been assessed using on-site emissions measurements,[11–16] occasionally coupled with simultaneous, full-facility estimates using downwind methods.[17–21] A key aspect of these on-site studies was the presence of on-site staff who could observe and log the operational state of the facility during measurement. Maintenance events that occurred during measurement were typically logged, and measurements were adjusted for the maintenance activity or treated separately in data sets. As a result, on-site studies generally control for emissions from maintenance activities.

More recently, anonymous top-down (TD) sampling of facility-scale emissions has become more common. These methods have been exceptionally useful for rapidly estimating emissions from large numbers of facilities in short periods, and identifying patterns in the frequency and magnitude of large emitters. With the exception of a 2016 study,[22] most of these studies utilize facility-scale aerial methods[23–28] or, less commonly, anonymous deployment of downwind methods[29,30] without observers on the facility. Studies of this design lack coordinated on-site observations, making it difficult to differentiate maintenance venting or combustion slip emissions, which are typically known and reported, from fugitive emissions, which are reported only if independently discovered (*Reported* values vary in accuracy and may not always reflect actual emissions). Recent campaigns have attempted to account for maintenance emissions by estimating emitter persistence.[24] However, questions remain, namely: What fraction of emitters discovered by anonymous, TD surveys are due to known maintenance events?

The data used here was collected as part of the *Colorado Coordinated Campaign* (C3).[31] Field work was conducted in July and September 2021 in the Denver-Julesberg (DJ) basin in northeastern Colorado. The boundary of the study is shown in Figure S-1. C3 included aerial sampling coordinated with on-site measurement and extensive operational data collection. During the measurement period, partner operators were asked to record and report all maintenance events to the study team. The first stage of reporting was done double-blind: Measurement teams did not know what events were reported, and operators did not know where aerial or ground teams identified emitters (SI section S-2). A second stage allowed operators to assess the timing of detected emissions to identify potential explanations for the emissions. This second stage resulted in identification of additional known maintenance and pre-production events.

The coordinated sampling in this study provides the first controlled, in-depth, analysis of how often an anonymous aerial sampling method detects known emissions. Additionally, the event dataset profiles when, where, and what type of venting occurs during maintenance, providing unique insight into weekly and diurnal patterns.

Methods

Data utilized for this analysis includes three data sources. First, aerial screening anonymously sampled a defined subset of the DJ basin (hereafter the 'study area'). Each detection (a 'plume') was also quantified by the aerial team and assigned a location category - agriculture ('Ag'), waste management ('Waste') and O&G. Second, partner production and midstream operators in the basin provided lists of maintenance events including location (latitude and longitude), type of event, and when the event occurred. Finally, a variety of public data sources were integrated to identify the location and operator(s) of O&G facilities in the study area. Each data source is discussed in the following subsections.

Aerial Sampling

Aerial sampling was conducted by a team from the University of Arizona and Carbonmapper, and all data collected during the aerial campaign was later released on the Carbonmapper data portal.[32] Initial work utilized data provided directly by Carbonmapper shortly after the flights. These data were updated in July 2023 from the Carbonmapper data portal.

Flights covered a subset of the more active portion of the DJ basin (Figure S-1). Flights covered approximately half of the study area each flight day; most areas were revisited approximately every second flight day. Figure 1 provides an example of two such consecutive flights in September 2021; animations in the SI illustrate all flights overlaid with maintenance events. Each flight leg overlapped the previous leg, providing full coverage of the overflown area (Figure S-2). Due to the overlap, some facilities were overflown twice on one day within 15-20 minutes.

With crew rest and weather restrictions, aircraft flight operations occurred on 18 days during the four weeks planned for coordinated sampling. The duration of flights ranged from 0.94 to 5.1 hours, for a total of 76 hours during the field campaign. Since the aircraft cannot observe emissions during turns and other maneuvers, flight coverage was divided into

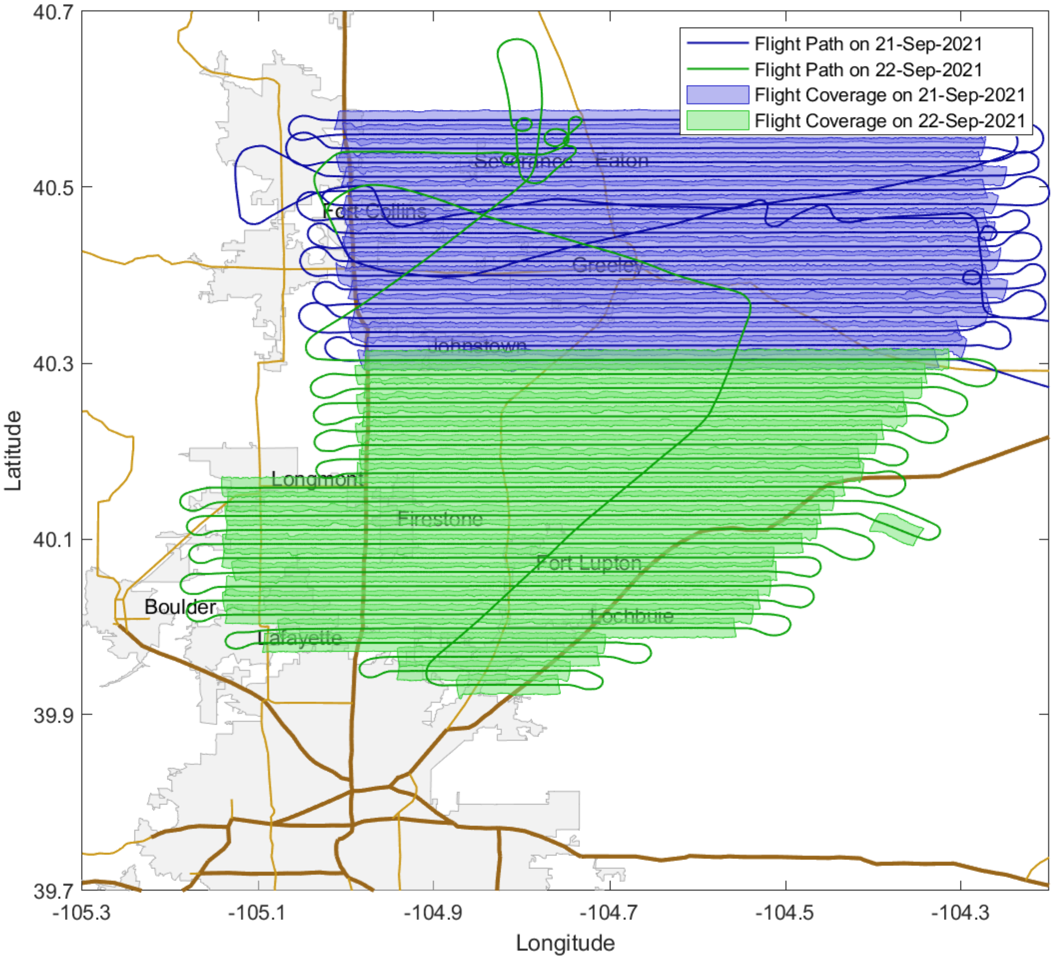


Figure 1: Example showing two consecutive flight days. Flights were structured to allow approximately half of the study area to be covered on each flight day. Lines represent path followed by the aircraft, taken from FlightRadar24.com. Shaded areas represent land area covered by the imaging system; effective sampling does not occur while the aircraft is turning at the end of each flight leg. While exact flight coverage varies by day, shaded area is approximates the study boundary on all days (see Figure S-1);

355 segments where observations met quality control requirements, resulting 49.8 hours of aircraft observation time. Flight coverage segments ranged from 0.46 to 13 minutes in length.

Flight start times varied from 09:12:17 to 13:50:00, and finished in the early afternoon.

Observation times occurred on both weekdays (33.5 hours), and weekends (16.3 hours). The resulting fraction of weekday time – 67% – is representative of the ratio of weekdays to total days.

Various sources provide different estimates of the detection sensitivity for the Carbonmapper method, ranging from a popularly quoted '10-20 kg/h' to 32 kg/h in a 3 m/s wind by Conrad et al.[33] to a 'full detection limit' of 280 kg/h by Kunkel et al.[34]. In this study, the mean estimated plume emission rate was 283 kg/h, with 95% of all estimates above 30 kg/h.

Event Data

The study was assisted by 7 companies ('partner operators') with major operations in the DJ basin. For all but one partner, the study was double-blind: The operators did not know where the aircraft had detected plumes, and the aircraft team did not know where events had been reported. These partners also supported onsite measurements of emissions by the ground teams (not covered in this paper). The remaining operator was engaged in merger activities during the field campaign, but provided event data approximately 6 months after the last field period, prior to being informed of any aerial results (SI Section S-2).

Maintenance event data was not available for non-partner facilities. Fortunately, partners operate a majority of the facilities in the study area: Of the approximately 89 operators in the study area, partner operators collectively operate 69% of midstream facilities and 85% of production facilities, which produce 93% of the natural gas in the basin.

Partners provided maintenance event data for two periods, July 1 through July 31, 2021 and September 19 through October 1, 2021. Except for three long-duration pipeline leaks, the 5031 reported maintenance events represent episodic venting – i.e. short-duration, vented, emissions. Events provided to the study team were later aggregated by the operators and included in regulatory reporting. Partners reported events from their internal tracking systems, which varied between partners in both classification of events and which events were recorded. To provide consistent treatment, the study team worked with the partners to classify events into 10 categories, some with sub-categories: Blowdown, Bradenhead, Compression, Hot Oiling Flowline, Pigging, Pipeline Leak, Swab, Tank, Unloading and Well. See SI Section S-2 for more complete descriptions. While many logged and reported events likely produced peak emission rates below the method detection limit (MDL) of the aircraft method,[34] all events were considered as potential matches to aircraft plumes.

Clustering events to those falling within 20 m of each other, 89% of locations (1680 of 1893 locations) had only one type of episodic event, but up to 5 event types occurred at a few locations.

While partners provided latitude and longitude where each event occurred, the location where emissions are released to the atmosphere may differ by 10s of meters from the reported maintenance event location. For example, a well unloading may be reported by the wellhead location, while the venting of gas may occur at tanks on the wellpad. It was therefore important that all facilities had geospatial outlines, particularly for large well pads and midstream facilities. Events and plumes were both matched to facilities; any plume on a facility matches any event on the same facility if overflight and event timing aligned.

For this analysis, the primary question is whether the aircraft was overhead when the event was occurring. Event timing was reported with varying specificity, depending upon what operator personnel had logged, resulting in three classifications:

1. Events identified only by the day of the event (2,639 events, 43%).
2. Events with specified start time, but no end time (744 events, 12%).
3. Events with both start and end times (2,692 events, 44%).

To simulate the probability that an aircraft *may* see an event, it is necessary to estimate (a) when the event started, (b) the duration of the event, and (c) when emissions occurred during the event. Monte Carlo (MC) simulation methods were utilized to deal with this uncertainty.

Start times: If only a date was provided (classification 1, above), start time was simulated by drawing a start times from events of the same category – i.e. events in classifications 2 and 3, above.

Durations: When an end time was not provided (classifications 1 and 2, above), duration was simulated by drawing the duration from events of the same category (i.e. events in classification 3).

Additionally, since most events were logged by personnel, recorded timing may have errors. Therefore, MC detection simulations included a time buffer before (5 minutes) and after (15 minutes) the emission period to account for uncertainty in operator logs, clock errors and dispersion time of the emission plume.

Active emission periods: Reported event durations reflect the entire duration of a maintenance operation, and are not necessarily indicative of the duration of emissions. Active emission periods were simulated as described in SI Section S-4. These simulations were used in all cases to estimate the practical duration of an event. In a few cases (e.g. Table S-7), the probability of detecting *within* the duration of the event was also simulated.

Facility Data

A step-by-step discussion of the facility list development is provided in SI Section S-3 and Table S-5; a brief description follows.

The primary data source for facility location and facility metadata were facilities reported to the Colorado Department of Public Health and Enviroment (CDPHE) greenhouse gas reporting program[35] for reporting year 2021. These data were submitted to the state by June 30, 2022, with updates occurring into late 2022. A final facility list was compiled cooperatively by CDPHE and the study team in May 2023. The GHG data included facility locations (longitude and latitude), operator identifier, and basic information about facilities. For production, reports connected wellheads identified by API number (a unique identification code assigned to all well bores in the U.S.) to wellpads identified by state reporting numbers (AIRS_ID).[36] Data from CDPHE GHG reports provided metadata for 4,679 facilities (37% of facilities). These data were augmented by additional public midstream data (SI Section S-3).

Wellhead locations and production rates for 2021 were acquired from Colorado Energy and Carbon Management Comission (ECMC) data portal[37] in January 2022. Well locations were clustered by distance, resulting in wellhead clusters ranging from 1-24 wellheads (Figure S-6). The wellpad and wellhead cluster facility types represent a wide range of complexity, from a single wellhead far from any other facility, to integrated wellpads including 1-4 wells, to wellhead clusters of 2-24 wellheads distant from other well pad equipment. Across all facility types, ECMC wellhead reports provided metadata for 7,041 facilities (56%).

Since data sources provided only single point coordinates for each facility, manual and machine recognition of satellite imagery were used to assign outlines to facilities. Outlines were used to identify overlapped facilities, attach events and plumes to facilities, and to identify cases where two operators were co-located.

When no other metadata was available, flowline routing provided by ECMC was used to augment existing metadata. Flowlines are pipelines which connect wellheads to the liquid/gas separation equipment on wellpads. For example, a wellpad report record from CDPHE may have specified a wellhead location, rather than the wellpad location. Assuming the wellpad was detected by satellite recognition *and* a flowline between the two was reported, the flowline routing could be used to assign the misplaced wellpad metadata to the true wellpad location. A mapping example of production facilities is shown in Figure 2. This method recovered metadata for 360 facilities (2.9%).

Since all events reported by partners originated, by definition, from a facility, any event locations not matched to a facility from one of the public sources were added to the facility list (173/1.4% of facilities). These additions include pigging locations where pigging operations occurred and one pipeline leak location detected by the aircraft and verified by the study team.

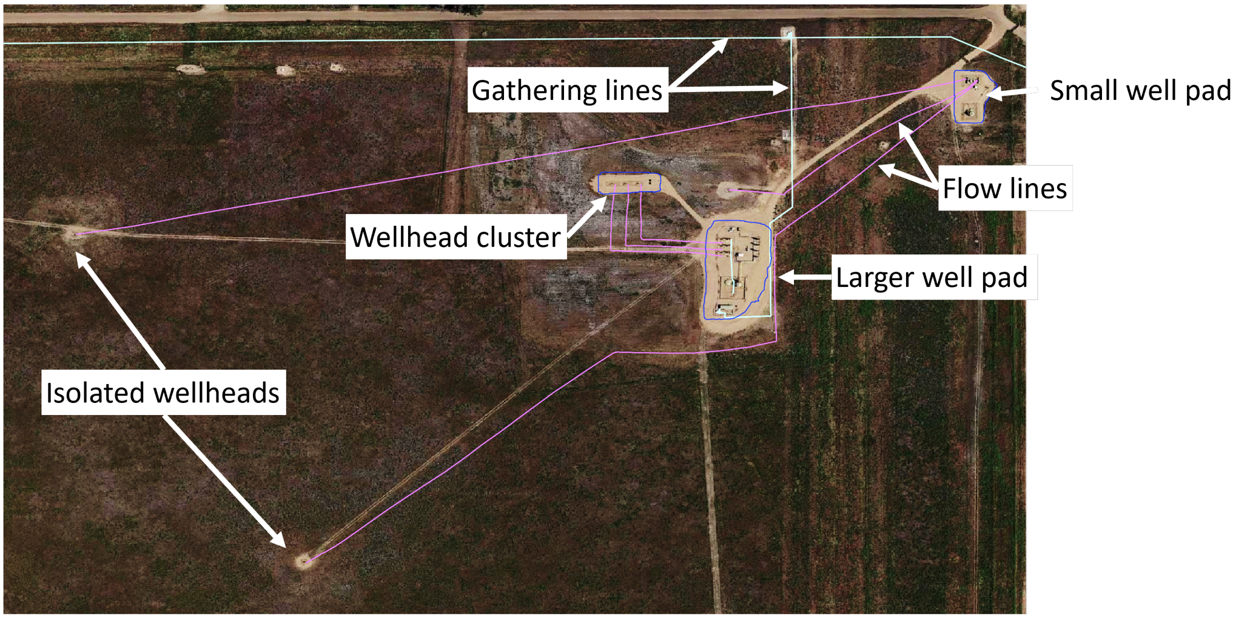


Figure 2: Wellpad facility example. Image shows two well pads, connected wellheads, and the flowlines connecting wellheads to wellpad. Gathering lines are also shown, including the connection originating at the larger wellpad. Satellite imagery from Google Earth™. Image was produced using QGIS™.

Because some facilities are large (spatial dimensions of hundreds of meters), assigning all events and O&G-identified plumes to facilities provides the spatial alignment for the study method. A plume was 'aligned' with an event if (a) the event was on the same facility as the plume, and (b) the event was occurring at the same time as the plume. Uncertainty in facility boundaries is discussed in SI Section S-3, and uncertainty in event and flight timing in SI Section S-4.

Compressor Emissions

In addition to episodic maintenance emissions, many compressor stations have multiple large compressors. In the study area the median midstream station had 5 compressors totaling 12,100 HP (9.02 MW) (Figure S-11). Often vented and combusted (combustion slip) methane emissions from these units may be larger than fugitive emissions at the facility.[18,21,38] The majority of units utilized gas-fueled drivers (51% reciprocating engines and 18% turbines). Engine exhaust contains significant methane from unburned fuel ('combustion slip') and emission rates vary over two orders of magnitude depending upon the type of engine.[39] Since combustion slip is both hot and dilute (1000-2500 ppm_v is typical[39]), it often does not form the well-defined plumes characteristics of cold point sources like vent stacks or leaks.[40] Combustion slip also occurs in heaters of gas upgrading equipment. Compressors also include large (2-5 kg/h) vented sources such as rod packing and shaft seals vents that are co-located with compressor driver emissions.

Midstream facilities may also include substantial fugitive emissions, such as blowdown, starter, and isolation valve leaks, which may be dispersed throughout the facility or combined into a few vent locations.

To compare with plume estimates, known compression and processing emissions for midstream facilities were estimated with common simulation methods[13,39,40] using an emission simulator.[41]

Finally, little information was available for compressors on production facilities, the largest of which could have emissions detectable emissions by the aircraft method. Aircraft detections of these sources could not be assessed.

Event-Plume Matching

In simulation all events were assigned to a facility and either had reported or modeled start, end, and emitting times. These emission periods were compared to the timing of aircraft overflights, with uncertainty. In all cases, location was fixed and timing varied on each iteration, resulting in a probabilistic comparison between the events and the flights. Figure S-9 illustrates the result of an example event simulation, and Figure S-10 illustrates combined event and overflight simulations.

All confidence intervals in this paper are 95% empirical confidence intervals, unless otherwise stated.

Results and Discussion

Facility Model

Table 1 summarizes the facility list. If a facility was detected in satellite photography, the outline of the facility represents the area of disturbed ground around the facility's equipment; if not detected, a default size was utilized. Partners operate 85% of production facilities and 69% of midstream facilities, providing an excellent basis for matching maintenance events with aircraft detections. While most midstream facilities were operating, 59% of production facilities were in an operating state, if wellhead clusters were counted as facilities. Since shut-in facilities generally have lower emissions and fewer maintenance activities, the approximately 5,000 shut-in facilities were unlikely to have either plumes or maintenance events.

Table 1: Known Facilities in Study Area

	Operator Information						Operating Status				
Facility Type[1]	Multiple[2]	Other Known[3]	Partner	Unknown[4]	Total	Fraction Partner	Operating	Shut In	Mixed Status[5]	Unknown	Fraction Operating
Wellhead Cluster	0	1,258	5,784	4	7,046	82%	3,457	3,184	400	5	55%
Production	76	472	4,341	179	5,068	89%	2,879	1,572	164	192	66%
Pigging	2	5	139	128	274	95%	146	0	0	128	100%
PreAndProduction	1	17	64	0	82	78%	74	1	0	5	99%
Gathering	1	20	47	0	68	69%	57	8	2	1	88%
Pre-Production	5	5	25	0	35	71%	0	0	0	35	
Other	0	0	2	16	18	100%	2	0	0	16	100%
Processing	0	5	11	0	16	69%	14	1	0	1	93%
Pipeline	0	0	15	0	15	100%	15	0	0	0	100%
Oil Handling	0	6	1	0	7	14%	7	0	0	0	100%
Total	85	1,788	10,429	327	12,629	85%	6,651	4,766	566	383	60%

[1] See SI for for complete facility type definitions. Note that wellpads are divided into three categories reflecting how the facilities were reported to the Colorado GHG reporting program: 'Pre-Production' indicates well development activities with no regular production, 'PreAndProduction' indicates the wellpad transitioned from pre-production to production during the reporting year, and 'Production' indicates active production with no pre-production activities. Any of the above may be operating or shut in.

[2] Indicates that metadata from two operators was geospatially coincident, such that a specific operator could not be identified. For example, wellheads co-located on a newer wellpad run by a different company.

[3] Operator is known, but is not a study partner.

[4] Indicates the facility location had no spatially co-located metadata from public data sources; see text.

[5] Meta data indicated a combination of operating and non-operating status. For example, a wellhead cluster with a combination of operating and shut-in wellheads.

Event Timing

Partners reported events for approximately 44 days, compared to 18 days of aircraft flights; these extra days provided more robust characterization of event timing for simulation purposes. Reported events occurred on all days of the week, but since most were maintenance activities that required on-site personnel, significantly more events occurred on weekdays – 113 [1 to 182] events per day – than on weekends and holidays (July 5) – 50.6 [1 to 85] events per day (Figure S-4). Most events occur during working hours, with a slight bias toward starting prior to noon (67% of events). Start time data are summarized in Figure 3, overlaid with the start time of flight legs. Since flights are temporally aligned with maintenance events, a reasonable hypothesis is that some fraction of the plumes detected by aircraft would be maintenance events.

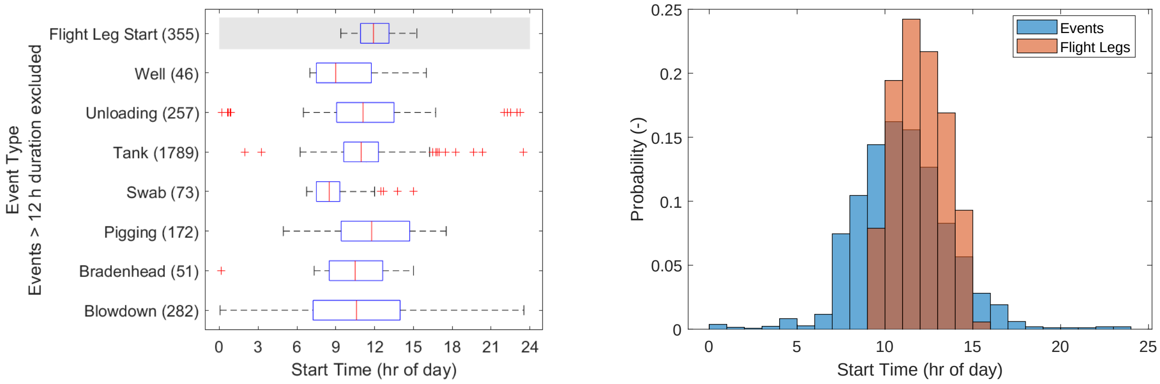


Figure 3: Summary of start times for events where the start time was specified. Left panel shows start times by event type. Boxes show inner quartile and median, whiskers 1.5x inner quartile, and points are outliers. For reference, the start of every flight leg in the study is also shown, shaded gray. Right panel overlays histograms of start times for all events and for flight legs. Since flight legs are 8.4 [0.86 to 12] minutes long, the histogram of flight leg starts is indicative of when the aircraft overflies facilities. In contrast, emitting periods for events may occur minutes to hours after the start of the event. Therefore, active emission periods for events are shifted right from start times shown in right panel.

Plumes Discovery Rate

Methane detection plumes from the aerial survey were classified by the aerial team as O&G, agricultural, or waste management, all of which were landfills. Excluding pigging locations, 0.898 plumes were detected per 1000 facilities overflown (R^2=0.766, Figure 4). On weekdays, the plume discovery rate was 0.988 $\frac{plumes}{1000sites}$ (R^2=0.867), while the weekend discovery rate was substantially lower at 0.702 $\frac{plumes}{1000sites}$ (R^2=0.133), or 71% of weekday rate. These data suggest that some emission process or processes differ between weekends and weekdays for emission types large enough to be detected by the aircraft method; a logical hypothesis is that these are due to human intervention on the facilities.

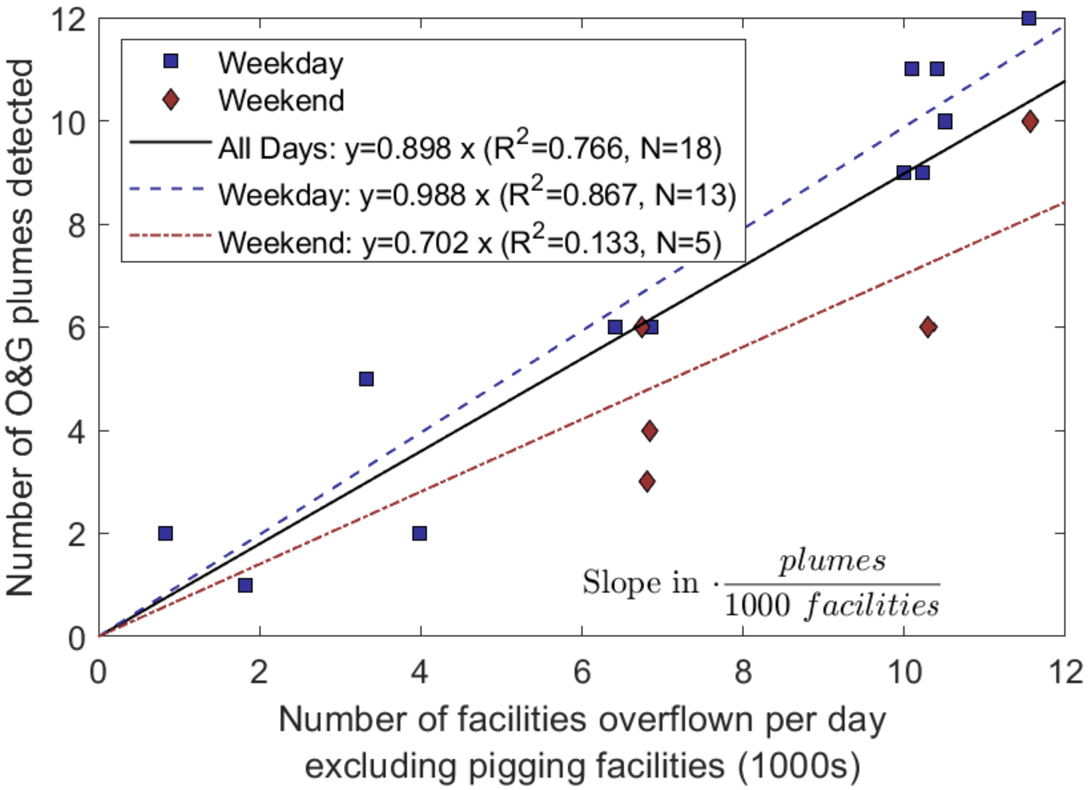


Figure 4: Across all flight time, there is a strong relationship between the number of O&G plumes identified per day and the number of O&G facilities overflown. While there are few points and low R^2 for weekends and holidays, data indicate weekend detections were 71% of detections on weekdays.

Plumes Detecting Events

Matching is shown in Table 2, grouping plumes by the type of plume-facility-event match. The table should be read as a 'decomposition' of the emissions detected by aircraft, starting at the top (Group A) with the most general subdivision, to the most specific at the bottom (Group C). Only Group A considers non-O&G plumes.

Since the aircraft may overfly a facility on two sequential passes, a few minutes apart, columns distinguish between individual plumes and revisits during one day; in all cases the revisits are within $\frac{1}{2}$ hour. Plume counts eliminating same-day revisits are called 'detections' in this discussion.

Group A considers all plumes as classified by the aerial team into O&G and non-O&G (waste and agricultural) locations. Qualitative examination of the single non-O&G plume location spatially matched to O&G facilities indicated that the emissions likely did not originate with O&G operations, but with surrounding agricultural operations. O&G accounted for two thirds of emissions estimated from plumes. Group B splits the O&G plumes based upon spatial matching to midstream and production facilities. Approximately two thirds of O&G plumes and estimated emissions were coincident with production facilities.

Group C divides the O&G plumes into categories suitable for discussing plume attribution in detail. First, we consider plumes which could not be assigned to a known facility. These fall into two categories:

- *Leak found during study:* (6.5% of plumes, 1.9% [1.3% to 2.5%] of O&G by emissions) This classification includes one pipeline leak discovered by overflights and confirmed by the study team and operator personnel during field work. The leak represented a persistent emitter, detected 8 times in 4 flights during July 2021. Due to the repeated detections, the fraction of plumes exceeds the fraction of emissions attributed to the leak.

- *Not on any known facility:* (3.3% of plumes, 19% [13% to 25%] of O&G by emissions)

Table 2: Plume-Event Matching Results

	Number of Plumes						
Description	Total plumes	*Detections* (plumes without revisits)[1]	Matched to facilities[2]	Matched to known event[3]	Total aerial estimated emissions (Mg CH_4/hr)[4]	Fraction of plumes[5]	Fraction of estimated emissions
(A) All Plumes							
Non oil and gas	65	57	1	0	16.6 ±2.35	35%	34% ±5.5%
Oil and gas	123	113	111	22	31.7 ±2.9	65%	66% ±8%
(B) Breakdown of oil and gas plumes:							
On no known facility	12	8	0	1	6.63 ±1.75	9.8%	21% ±5.9%
On midstream facilities	29	27	29	12	4.89 ±0.871	24%	15% ±3.1%
On production facilities	82	78	82	9	20.2 ±2.19	67%	64% ±9.1%
Total oil and gas	**123**	**113**	**111**	22	**31.7 ±2.94**	**100%**	**100% ±13%**
(C) Summary by sector and availability of event information:							
Plumes on no known facility:							
Confirmed pipeline leak	8	4	0	1	0.595 ±0.182	67%	9% ±3.9%
No known facility	4	4	0	0	6.04 ±1.72	33%	91% ±37%
Total (no facility/total O&G)	**12**	**8**	**0**	1	**6.63 ±1.75**	**9.8%**	**21% ±5.9%**
Plumes on non-partner production facilities (no event info):							
Total (non-partner prod/total O&G)	**17**	**16**	**17**	0	**5.01 ±1.11**	**14%**	**16% ±3.8%**
Plumes on partner production facilities:							
Matched to event (Stage 1)	6	6	6	9	1.08 ±0.575	9.2%	7.1% ±3.9%
Matched to event (Stage 2)		23.7 ± 4.17			6.2 ±1.87	37% ±6.5%	41% ±13%
Unmatched to event (Stage 2)		24.2 ± 4.18			5.02 ±1.75	37% ±6.4%	33% ±12%
No Stage 2 Info	11	11	11	0	2.9 ±0.881	17%	19% ±6.3%
Total (partner prod/total O&G)	**65**	**62**	**65**	9	**15.2 ±1.91**	**53%**	**48% ±7.5%**
Plumes on midstream facilities:							
Partner, known cause	9	7	9	3	0.699 ±0.178	31%	14% ±4.6%
Partner, unknown cause	14	14	14	6	2.87 ±0.608	48%	59% ±17%
Non-partner	6	6	6	4	1.32 ±0.619	21%	27% ±14%
Total (midstream/total O&G)	**29**	**27**	**29**	12	**4.89 ±0.874**	**24%**	**15% ±3.1%**

[1] Counts cases where the aircraft overflew, and detected, the same location twice in one day as one overflight.

[2] Plumes were with 60 m of a known facility. One plume may be within that distance of multiple known facilities.

[3] A reported event was occurring at the facility during the time of overflight.

[4] In cases where the aircraft detected emissions at the same facility on the same day, the average emission estimates for that location is used.

[5] Fractions are computed relative to the total number of plumes or total emissions in the lettered grouping in the table. May not sum to 100% due to category rounding.

Each detection had a single plume detected more than 60 m from the edge of any known facility. SI Section S-7 discusses each plume and provides satellite imagery.

One plume (C-4) was clipped by the field-of-view of the aircraft instrument, and may have originated on a facility.

The remaining three plumes (C-1 to C3) were near visible linear scars which possibly indicated pipeline rights-of-way, but no pipelines reported to ECMC were near these features. Emission estimates for these plumes were approximately 310, 500, and 3,900 kg CH_4/h, and included the largest plume estimate in the study.

Two hypotheses may explain these plumes.

1. The plumes were caused by pipeline leaks. This hypothesis is unlikely, as each detection occurred only once in many overflights, and since pipeline leaks are typically continuous emitters, at least the two larger plumes should have been detected on every overflight.
2. The plumes were due to a short, high-rate, event (e.g. a blowdown), that had detached from its source location while moving downwind, but were not dispersing into background methane concentrations as expected. This hypothesis raises concerns about the emission rate estimate: Plume emission rate calculations make assumptions about transport of emissions assuming a stationary emission point. If the plume moved *en masse* with the wind, it is unclear if the emission rate estimation method would adapt to this unusual condition.

Since these three plumes represented ≈15% of all emissions estimated by aircraft for this study, uncertainty about cause and estimated rate is material to basin-scale emission estimates derived from aircraft plume estimates. More broadly, most aerial studies do not have the complete facility list utilized here and therefore would struggle identifying plumes unattached to a likely emitter; no such analysis was conducted in any study known to the authors. This type of plume classification therefore represents an uncertainty of unknown size in emission studies using plume estimates.

Next, we consider plumes spatially aligned to production facilities. Since no event data was available for non-partner facilities, no matching simulation was possible for the 17 plumes on these facilities.

The remaining matches – about half of all plumes (53% of O&G plumes and 48% [41% to 56%] of O&G emissions) – answer for production the key question posed earlier: What fraction of aircraft detections are known emission events? This analysis has four steps:

- *Matched Stage 1:* (4.9% of plumes, 3.4% [1.7% to 5.3%] of O&G emissions). Double-blind matching of plumes to reported maintenance events resulted in 6 matches to 9 possible events, see Section S-8 for images and analysis.

  In 5 of 6 cases, the plume location aligns well with the event's characteristics (Confidence='Yes' in Table S-7). Additionally, the matched events for all five are known to have instantaneous emission rates which would likely be detectable by the aircraft method. The final case is unclear primarily due to the lack of transport of the plume (low winds). For this analysis it was considered a valid plume-event match.

  Therefore, at a minimum 9.2% of plumes and 7.1% [3.5% to 11%] of production emissions were due to known events. In this case, all events were due to maintenance operations.

- *Matched Stage 2:* (19% [15% to 23%] of plumes, 20% [13% to 26%] of O&G emissions). Substantially more plumes were matched during the Stage 2 unblinded matching. Partners were sent a formatted document, including information about all production plumes unmatched in Stage 1, and GIS files for plumes and the context camera image. Partners responded back to the study team with possible operational explanations for 39 of the 51 plumes, summarized in Table 3, including both maintenance operations and other known emission events. Analysis of each response is listed in SI Section S-9.

  The three largest categories provide insight into possible explanations for plumes. First, when Stage 1 events were transmitted to the study team, pre-production operations were excluded from reporting at the request of the partners (likely due to ongoing regulatory discussions). During Stage 2 analysis, ≈20% of plumes on partner production facilities were aligned with pre-production operations, some of which are known to have periodic emissions large enough to be detected from aircraft. All of these are

Table 3: New Information from Partners During Stage 2 Matching

	Assigned Probability[1] Plume Matched Event					
New Information Type	0%	10%	50%	90%	Total Plumes	Weighted Plumes[2]
Pre-Production	0	0	0	11	11	9.9
Omitted from Stage 1 Reports	0	4	9	5	18	9.4
Timing	0	0	0	5	5	4.5
Spatial Matching Issue	0	0	0	1	1	0.9
No Information	4	0	0	0	4	0
Unmatched	12	0	0	0	12	0
Total	16	4	9	22	51	24.7

[1] Each Stage 2 plume match was assigned a probability that the described event was matched by a plume; see text for additional details.

[2] Plume count weighted by *Probability of Match*.

likely detections of known pre-production operations. Note that while *reported* implies that emissions were included in regulatory reporting, this study had insufficient data to analyze whether total reported emissions were accurate.

An additional third of proposed matches were due to data omitted from Stage 1 reports for a variety of reasons (see SI). Each of these was assigned a probability depending upon how well the explanation matched observed plume location and behavior. The third category, *Timing*, were due to relatively small differences between reported time and aircraft overflight times.

Given given plume weightings in Table 3, Stage 2 results indicate that an additional 37% [29% to 43%] of plumes and 41% [28% to 55%] of production emissions may have been related to known emission events for partner facilities where event data was available.

- *Unmatched Stage 2:* (20% [16% to 24%] of plumes, 16% [11% to 22%] of O&G emissions) These plumes and facilities had stage 2 data, but remained unmatched, considering both lack of any likely operational cause and probability weighting when a possible operational cause was provided.

- *No Stage 2 info:* (20% [16% to 24%] of plumes, 16% [11% to 22%] of O&G emissions) Due to delays in acquiring CDPHE data to finalize the facility list, Stage 2 matching was performed on a partial facility list, and these 11 plumes were later matched to the improved facility list in June 2023, illustrating the importance of a complete facility list for this type of analysis. To minimize possible confirmation bias, Stage 2 matching was not repeated with these plumes. Lack of analysis for these plumes indicates that some valid plume-event matches may have been omitted from the totals.

Combining Stage 1 and 2 matches provides a reasonable high (but not upper) bound on the fraction of plumes matched to known emission events: 46% [38% to 52%] of plumes, and 48% [35% to 62%] of emissions, on production facilities. It is reasonable to assume that, had operational and event data been available for non-partner production, a similar fraction of plumes could be matched to events.

The final subdivision in Table 2/Group C considers plumes on gathering compressor stations and gas processing plants; no plumes were spatially aligned with remote pigging locations.

As noted earlier, midstream facilities often include equipment with significant combusted and/or vented emissions, including combustion slip from compressor drivers and gas upgrading equipment, and venting from centrifugal compressor seals and reciprocating compressor rod packing when those units are pressurized.[13,39] All above sources tend to be concentrated near compressor units or upgrading equipment, which in the DJ basin are typically housed in large buildings that disturb winds and may cause pooling of emissions.[40] Major equipment on midstream facilities operates most of the time (Figures S-11 to S-13); many large units operate more than 95% of the time, and few midstream facilities have long periods with no compression or processing in operation. Therefore, on these facilities, the emissions should be detectable by aircraft on nearly all overflights, or, alternatively, may be too diffuse and seldom/never detected. In the latter case, aircraft estimates would be lacking and would need to be replaced using non-aircraft estimates to calculate basin emissions.

However, data from this study suggest that many, if not the majority, of plumes on midstream facilities represented detections of known vented and combusted sources, and that the probability of detecting these emissions on any given overflight was unpredictable. We cover these two points in turn:

- *Most plumes detected combusted and vented emissions:* Approximately 20% of midstream plumes show visible transport where the origin of the plume can be clearly identified on the facility (Table S-8). The remainder of plumes show little transport; the plume indicates a general methane enhancement, typically over the main equipment at the facility. Figure 5 and Table 4 illustrates that facilities with multiple detections generally have higher estimated emissions, and that in the majority of cases when a facility had more than one plume, the plume was located on the same location on each detection, over the compressor building (Table S-8). Figure S-26 shows plume location for the facility with 7 plumes co-located over a compressor building housing 4 large two-stroke lean burn engines, which have high methane emissions from combustion slip.

  However, not all midstream plumes are consistent with compressor or processing emissions. Midstream facilities may also have large fugitive emissions, notably from isolation and blowdown valves, valves on liquid separation equipment, or combustion issues with flares.[13,21,40,42] These fugitive sources tend to be located away from compressors or processing equipment, and are typically concentrated point sources. Figure S-27 shows an example for a facility with 2 plumes co-located over the compressor building, and two plumes possibly indicative of fugitive emissions.

  These data suggest that the majority of midstream plumes may be explained by detections of known compression and processing emissions.

- *Unpredictable detections:* Figure 5 also illustrates that (a) even facilities with multiple plumes were detected on less than half of overflights, and (b) many facilities with similar modeled emissions were never detected. The nature of midstream facilities make both of these results unsurprising. Location of exhaust stacks from compressor drivers, or compressor vents interconnections, differ between facilities. These differences may concentrate or disperse emissions, raising or lowering the probability of that emissions will be concentrated enough to form a detectable plume. The size and shape of buildings, interacting with changing wind direction and speed, likely change emissions transport and plume visibility.

Data indicate that the probability that a given midstream facility will be detected appears low, is somewhat dependent on the size of compression and processing emissions, and is unpredictable between overflights.

Table 4: Plumes spatially aligned with midstream facilities

	Number of Plumes[1]					
Facility Type	No Plumes	One Plume	Multiple Plumes	Total By Facility Type	Fraction Multiple Plumes	Fraction At Least One Plume
Gathering	42	5	2	49	4.1%	14%
Oil Handling	6	0	0	6	0%	0%
Processing	8	1	4	13	31%	38%
Total	56	6	6	68	8.8%	18%
Median Emissions (kg/h)	11.4	16.8	33.4			

[1] Number of plumes spatially aligned with midstream facilities; see text.

Combined, these two results indicate that midstream plumes were unlikely to be representative of known combustion and vented emissions at facilities, and it is highly unlikely that aircraft plumes primarily detected only fugitive emission sources that are additive to known combustion and processing emissions.

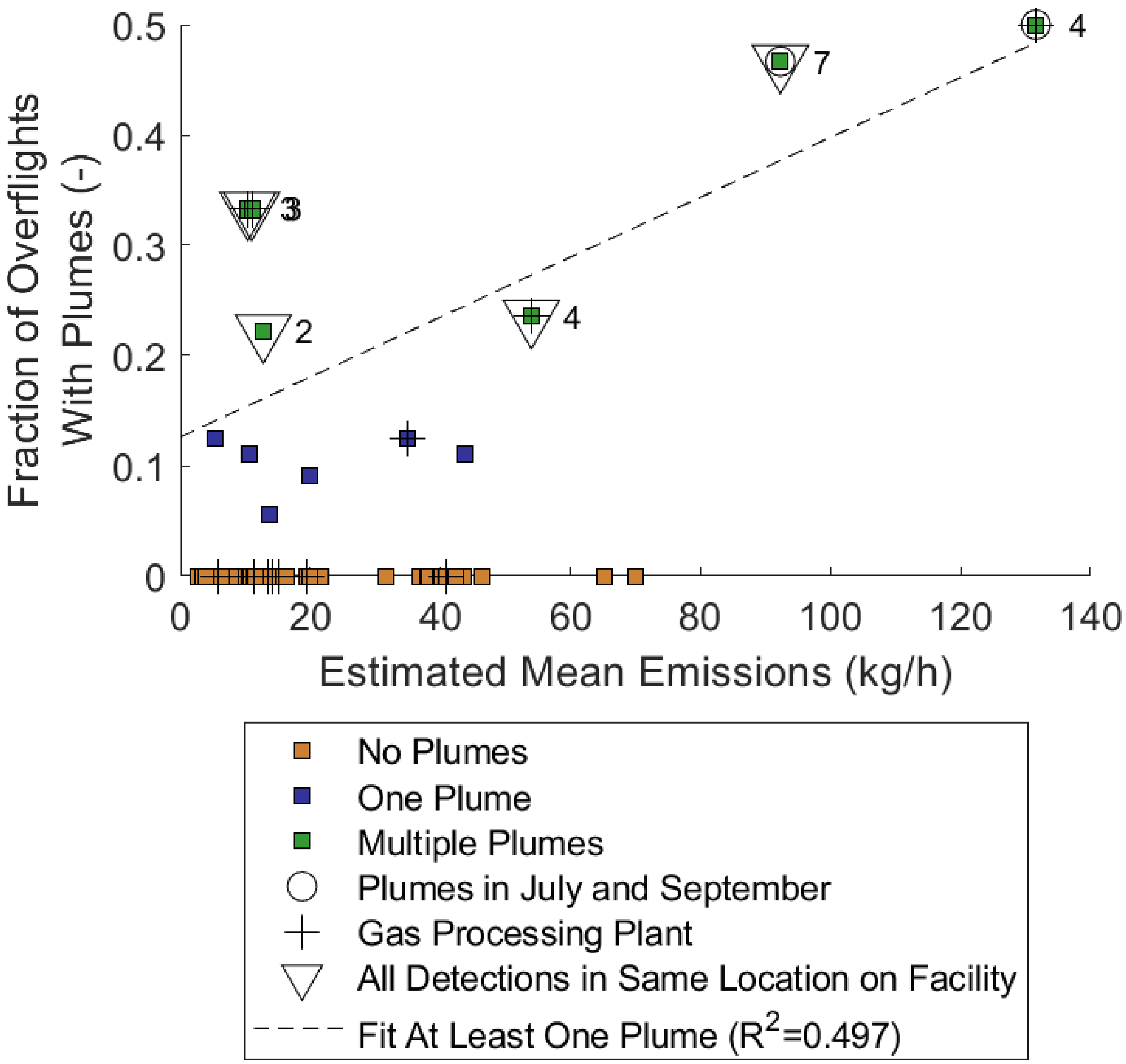


Figure 5: Characteristics of midstream detections. Each midstream facility in the study area is represented by one point, colored by whether multiple, one or no plumes were detected on the facility. Overlays indicate processing plants and whether a facility was detected in both July and September flights. For facilities with multiple plumes, a triangle indicates if all plumes were on the same location at the facility; in all cases the location was over the compressor house.

Implications

Typically aerial plume detections are scaled to basin emissions by adding plume totals, potentially weighted by a 'persistence' estimate based upon what fraction of overflights resulted in a plume at a particular location.[24,28] There are two implicit assumptions in this scaling method: (a) that the probability of detecting a plume is representative of all time, i.e. 24 hours per day, 7 days per week, and (b) that detections are equally probable for the same source on all overflights. Data from this study indicates that both assumptions are not wholly correct, and that scaling from aerial detections to basin emissions requires more analysis and conditioning than is currently applied.

Data from this study indicate that flight timing preferentially identifies maintenance emission sources, as indicated by both plume-event matching and weekday-weekend analysis. Given the number of facilities and maintenance events, these detections are also more prevalent on production facilities; between 7.1% [3.5% to 11%] and 48% [35% to 62%] of emissions attributed to production were likely due to detecting known pre-production sources or episodic maintenance events. Since these emitters are typically short duration and highly variable, the estimated size of each emitter will be highly uncertain, and scaling to basin estimates would need to account for both this uncertainty and emission durations substantially below 24 hours per day. Neither of these issues is currently included in recent studies when scaling aerial emissions to basin scale. Insufficient data was available to assess the net impact of this issue, which is impacted by fraction of maintenance events seen, the accuracy of plume estimates for highly variable and transient events, and the duration of known emission events.

In contrast, plume detections on midstream facilities indicate that major, known, emission sources are infrequently and unpredictably identified. Many midstream facilities with known large emissions were never detected by aircraft methods, and no midstream facility, even those detected multiple times, was detected in more than half of overflights. These data indicate that midstream emissions - even known, reported, large emission sources - are not detected in a representative fashion by the aircraft method used in this study. The impact of this issue is difficult to assess, but data suggest that midstream emissions estimated by plumes may be significantly low; detection frequencies below 50% alone suggest midstream emissions estimated this way could be half actual emissions, assuming individual plume estimates are correct and unbiased.

Plumes from this study attribute one fifth of detected emissions to midstream and two thirds to production. In contrast, state greenhouse gas reports for reporting year 2021 indicate include 14,400 metric tons of methane emissions from midstream and 8,000 metric tons from production - two thirds midstream, predominantly due to known compression and processing emissions. Results from this study illuminate this disagreement. Data developed here indicate that maintenance and other known, short-duration, emitters are likely over-represented in aerial detections on production facilities, while unpredictable detection of known, long-duration, emission sources at midstream facilities are likely under-represented in aerial detections.

It is unclear how the issues identified here would translate to other production basins or to other aircraft methods that utilize plume detection; additional study is warranted. However, it is unlikely that the issues identified here are totally absent from other basins. Aerial emissions surveys remain highly useful for assessing production basin emissions. However, results from this study suggest that additional data inputs (particularly correct and complete facility GIS data), a more nuanced analysis of emission persistence and frequency, and improved sampling strategies are required to accurately scale plume estimates to basin emissions.

References

(1) Team, I. C. W.; Pachauri, RK.; Meyer, LA. IPCC, 2014: Climate Change 2014: Synthesis Report. Contribution of Working Groups I. *II and III to the Fifth Assessment Report of the intergovernmental panel on Climate Change. IPCC, Geneva, Switzerland* **2014**, *151*.

(2) Alvarez, R. A.; Pacala, S. W.; Winebrake, J. J.; Chameides, W. L.; Hamburg, S. P. Greater Focus Needed on Methane Leakage from Natural Gas Infrastructure. *Proceedings of the National Academy of Sciences* **2012**, *109*, 6435–6440.

(3) US EPA *Inventory of U.S. Greenhouse Gas Emissions and Sinks 1990-2020*; Greenhouse Gas Invetory EPA 430-R-22-003.

(4) Yarmuth, J. A. H.R.5376 - 117th Congress (2021-2022): Inflation Reduction Act of 2022. 2022.

(5) Proposal for a REGULATION OF THE EUROPEAN PARLIAMENT AND OF THE COUNCIL on Methane Emissions Reduction in the Energy Sector and Amending Regulation (EU) 2019/942. 2021.

(6) Veritas. https://www.gti.energy/veritas-a-gti-methane-emissions-measurement-and-verification-initiative/, 2021.

(7) Oil and Gas Methane Partnership (OGMP) *Guidance Document: Reconciliation and Uncertainty (U&R) in Methane Emissions Estimates for OGMP2.0*; Guidance Document, 2022.

(8) MIQ. https://miq.org/.

(9) Trustwell Standards. https://www.projectcanary.com/private/trustwell-and-rsg-definitional-document/.

(10) US EPA Mandatory Reporting of Greenhouse Gases: Petroleum and Natural Gas Systems.

(11) Allen, D. T.; Torres, V. M.; Thomas, J.; Sullivan, D. W.; Harrison, M.; Hendler, A.; Herndon, S. C.; Kolb, C. E.; Fraser, M. P.; Hill, A. D.; Lamb, B. K.; Miskimins, J.; Sawyer, R. F.; Seinfeld, J. H. Measurements of Methane Emissions at Natural Gas Production Sites in the United States. *Proceedings of the National Academy of Sciences* **2013**, *110*, 17768–17773.

(12) Allen, D. T.; Sullivan, D. W.; Zavala-Araiza, D.; Pacsi, A. P.; Harrison, M.; Keen, K.; Fraser, M. P.; Daniel Hill, A.; Lamb, B. K.; Sawyer, R. F.; Seinfeld, J. H. Methane Emissions from Process Equipment at Natural Gas Production Sites in the United States: Liquid Unloadings. *Environmental Science & Technology* **2015**, *49*, 641–648.

(13) Zimmerle, D.; Vaughn, T.; Luck, B.; Lauderdale, T.; Keen, K.; Harrison, M.; Marchese, A.; Williams, L.; Allen, D. Methane Emissions from Gathering Compressor Stations in the U.S. *Environmental Science & Technology* **2020**, *54*, 7552–7561.

(14) Group, P. *Final Report For Determining Bleed Rates for Pneumatic Devices in British Columbia*; 2013.

(15) Pacsi, A. P.; Ferrara, T.; Schwan, K.; Tupper, P.; Lev-On, M.; Smith, R.; Ritter, K. Equipment Leak Detection and Quantification at 67 Oil and Gas Sites in the Western United States. *Elem Sci Anth* **2019**, *7*, 29.

(16) GSI Environmental *Draft Final Report: Quantification of Methane Emissions from Marginal (Small Producing) Oil and Gas Wells*; 21.

(17) Bell, C.; Vaughn, T.; Zimmerle, D.; Herndon, S.; Yacovitch, T.; Heath, G.; Pétron, G.; Edie, R.; Field, R.; Murphy, S.; Robertson, A.; Soltis, J. Comparison of Methane Emission Estimates from Multiple Measurement Techniques at Natural Gas Production Pads. *Elem Sci Anth* **2017**, *5*.

(18) Vaughn, T. L.; Bell, C. S.; Yacovitch, T. I.; Roscioli, J. R.; Herndon, S. C.; Conley, S.; Schwietzke, S.; Heath, G. A.; Pétron, G.; Zimmerle, D. Comparing Facility-Level Methane Emission Rate Estimates at Natural Gas Gathering and Boosting Stations. *Elem Sci Anth* **2017**, *5*.

(19) Marchese, A. J.; Vaughn, T. L.; Zimmerle, D. J.; Martinez, D. M.; Williams, L. L.; Robinson, A. L.; Mitchell, A. L.; Subramanian, R.; Tkacik, D. S.; Roscioli, J. R.; Herndon, S. C. Methane Emissions from United States Natural Gas Gathering and Processing. *Environmental Science & Technology* **2015**, *49*, 10718–10727.

(20) Subramanian, R.; Williams, L. L.; Vaughn, T. L.; Zimmerle, D.; Roscioli, J. R.; Herndon, S. C.; Yacovitch, T. I.; Floerchinger, C.; Tkacik, D. S.; Mitchell, A. L.; Sullivan, M. R.; Dallmann, T. R.; Robinson, A. L. Methane Emissions from Natural Gas Compressor Stations in the Transmission and Storage Sector: Measurements and Comparisons with the EPA Greenhouse Gas Reporting Program Protocol. *Environmental Science & Technology* **2015**, *49*, 3252–3261.

(21) Zimmerle, D. J.; Williams, L. L.; Vaughn, T. L.; Quinn, C.; Subramanian, R.; Duggan, G. P.; Willson, B.; Opsomer, J. D.; Marchese, A. J.; Martinez, D. M.; Robinson, A. L. Methane Emissions from the Natural Gas Transmission and Storage System in the United States. *Environmental Science & Technology* **2015**, *49*, 9374–9383.

(22) Vaughn, T. L.; Bell, C. S.; Pickering, C. K.; Schwietzke, S.; Heath, G. A.; Pétron, G.; Zimmerle, D. J.; Schnell, R. C.; Nummedal, D. Temporal Variability Largely Explains Top-down/Bottom-up Difference in Methane Emission Estimates from a Natural Gas Production Region. *Proceedings of the National Academy of Sciences* **2018**, 201805687.

(23) Cusworth, D. H.; Thorpe, A. K.; Ayasse, A. K.; Stepp, D.; Heckler, J.; Asner, G. P.; Miller, C. E.; Yadav, V.; Chapman, J. W.; Eastwood, M. L.; Green, R. O.; Hmiel, B.; Lyon, D. R.; Duren, R. M. Strong Methane Point Sources Contribute a Disproportionate

Fraction of Total Emissions across Multiple Basins in the United States. *Proceedings of the National Academy of Sciences* **2022**, *119*, e2202338119.

(24) Cusworth, D. H.; Duren, R. M.; Thorpe, A. K.; Olson-Duvall, W.; Heckler, J.; Chapman, J. W.; Eastwood, M. L.; Helmlinger, M. C.; Green, R. O.; Asner, G. P.; Dennison, P. E.; Miller, C. E. Intermittency of Large Methane Emitters in the Permian Basin. *Environmental Science & Technology Letters* **2021**, *8*, 567–573.

(25) Thorpe, A. K. et al. Mapping Methane Concentrations from a Controlled Release Experiment Using the next Generation Airborne Visible/Infrared Imaging Spectrometer (AVIRIS-NG). *Remote Sensing of Environment* **2016**, *179*, 104–115.

(26) Frankenberg, C.; Thorpe, A. K.; Thompson, D. R.; Hulley, G.; Kort, E. A.; Vance, N.; Borchardt, J.; Krings, T.; Gerilowski, K.; Sweeney, C.; Conley, S.; Bue, B. D.; Aubrey, A. D.; Hook, S.; Green, R. O. Airborne Methane Remote Measurements Reveal Heavy-Tail Flux Distribution in Four Corners Region. *Proceedings of the National Academy of Sciences* **2016**, *113*, 9734–9739.

(27) Duren, R. M. et al. California's Methane Super-Emitters. *Nature* **2019**, *575*, 180–184.

(28) Sherwin, E.; Rutherford, J. S.; Zhang, Z.; Wetherly, E.; Yakovlev, P.; Berman, E.; Jones, B.; Thorpe, A. K.; Ayasse, A. K.; Duren, R.; Brandt, A.; Cusworth, D. H. Quantifying Oil and Natural Gas System Emissions Using One Million Aerial Site Measurements. 2023.

(29) Yacovitch, T. I.; Herndon, S. C.; Pétron, G.; Kofler, J.; Lyon, D.; Zahniser, M. S.; Kolb, C. E. Mobile Laboratory Observations of Methane Emissions in the Barnett Shale Region. *Environmental Science & Technology* **2015**, *49*, 7889–7895.

(30) Omara, M.; Sullivan, M. R.; Li, X.; Subramanian, R.; Robinson, A. L.; Presto, A. A. Methane Emissions from Conventional and Unconventional Natural Gas Production

Sites in the Marcellus Shale Basin. *Environmental Science & Technology* **2016**, *50*, 2099–2107.

(31) C3: Colorado Coordinated Campaign. https://energy.colostate.edu/metec/c3/.

(32) CarbonMapper Methane, CO2 Data l Global Open Portal l Carbon Mapper. https://carbonmapper.org/data/.

(33) Conrad, B. M.; Tyner, D. R.; Johnson, M. R. Robust Probabilities of Detection and Quantification Uncertainty for Aerial Methane Detection: Examples for Three Airborne Technologies. *Remote Sensing of Environment* **2023**, *288*, 113499.

(34) Kunkel, W. M.; Carre-Burritt, A. E.; Aivazian, G. S.; Snow, N. C.; Harris, J. T.; Mueller, T. S.; Roos, P. A.; Thorpe, M. J. Extension of Methane Emission Rate Distribution for Permian Basin Oil and Gas Production Infrastructure by Aerial LiDAR. *Environmental Science & Technology* **2023**,

(35) Oil & Gas Compliance and Recordkeeping | Department of Public Health & Environment. https://cdphe.colorado.gov/oil-and-gas-and-your-health/oil-gas-compliance-and-recordkeeping.

(36) Colorado Department of Public Health and Environment Air Pollution Control Division Records | Department of Public Health & Environment. https://cdphe.colorado.gov/public-information/air-pollution-control-division-records.

(37) Colorado Energy and Carbon Management Comission Data Portal. https://ecmc.state.co.us/data2.html#/downloads, 22.

(38) Vaughn, T.; Luck, B.; Zimmerle, D.; Marchese, A.; Keen, K.; Lauderdale, T.; Harrison, M.; Allen, D. *Methane Emissions from Gathering and Boosting Compressor Stations in the U.S. Supporting Volume 2: Compressor Engine Exhaust Measurements*; 2019; p 23.

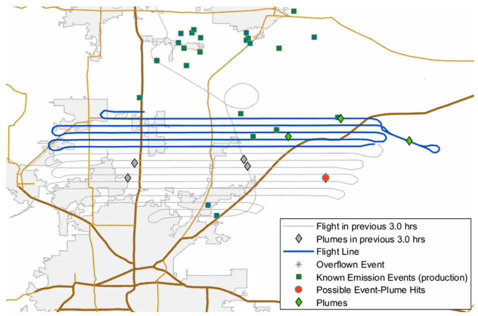
(39) Vaughn, T. L.; Luck, B.; Williams, L.; Marchese, A. J.; Zimmerle, D. Methane Exhaust Measurements at Gathering Compressor Stations in the United States. *Environmental Science & Technology* **2021**,

(40) Brown, J. A.; Harrison, M. R.; Rufael, T.; Roman-White, S. A.; Ross, G. B.; George, F. C.; Zimmerle, D. Informing Methane Emissions Inventories Using Facility Aerial Measurements at Midstream Natural Gas Facilities. *Environmental Science & Technology* **2023**,

(41) Zimmerle, D.; Duggan, G.; Vaughn, T.; Bell, C.; Lute, C.; Bennett, K.; Kimura, Y.; Cardoso-Saldaña, F. J.; Allen, D. T. Modeling Air Emissions from Complex Facilities at Detailed Temporal and Spatial Resolution: The Methane Emission Estimation Tool (MEET). *Science of The Total Environment* **2022**, *824*, 153653.

(42) Plant, G.; Kort, E. A.; Brandt, A. R.; Chen, Y.; Fordice, G.; Gorchov Negron, A. M.; Schwietzke, S.; Smith, M.; Zavala-Araiza, D. Inefficient and Unlit Natural Gas Flares Both Emit Large Quantities of Methane. *Science* **2022**, *377*, 1566–1571.

TOC Graphic



Partial flight lines and events on July 15, 2021.