Rose-Coss, Dylan H, EMNRD

From:	Rose-Coss, Dylan H, EMNRD
Sent:	Friday, April 22, 2022 12:09 PM
To:	Janacek, Stephen C
Cc:	Goetze, Phillip, EMNRD; Thompson, Joseph, EMNRD; Powell, Brandon, EMNRD; travis.mcbain@intrepidpotash.com; smallory@blm.gov
Subject:	RE: OXY C-108 Application for the Federal 12 No. 1 Well _ SWD-2476 (Admin appl No. pJZT2209855768)
Attachments:	Intrepid Protest.pdf; Letter to Sheila Mallory at BLM re Supplemental Comments on Applications for Permit to Drill 4.8.2022.pdf

Stephen Janacek,

The OCD was notified by Intrepid Potash-New Mexico LLC., that they are protesting this application. This party has been identified as an affected person for the location being considered. Because of the protest, the application can no longer be reviewed administratively. You are being notified that for this application to be considered, Oxy USA INC currently has two options; the first is to go to hearing, the second is to negotiate a resolution with the protesting party. If the protest is withdrawn, then the application can be reviewed administratively. In the meantime, the application will be retained pending a hearing or other resolution. Please continue to provide OCD with information regarding the standing of this application and feel free to call me with any questions.

Contact for Intrepid:

Travis McBain, CPL
Director of Land/Buisness Development
INTREPID
707 17th Street, Suite 4200
Denver, CO 80202
405.938.5411 (mobile)
travis.mcbain@intrepidpotash.com

Regards,

Dylan Rose-Coss

Petroleum Specialist
Oil Conservation Division
1220 South St. Francis Drive
Santa Fe, New Mexico 87505

C: (505) 372-8687

Rose-Coss, Dylan H, EMNRD

From: Engineer, OCD, EMNRD
Sent: Thursday, April 21, 2022 8:43 AM
To: Goetze, Phillip, EMNRD; Rose-Coss, Dylan H, EMNRD
Cc: Thompson, Joseph, EMNRD
Subject: FW: [EXTERNAL] Fwd: Intrepid Potash-New Mexico Protest of OXY SWD Application: SWD FED 12 # 001 (30-015-26742)
Attachments: Letter to Sheila Mallory at BLM re Supplemental Comments on Applications for Permit to Drill 4.8.2022.pdf

---

From: Travis McBain <travis.mcbain@intrepidpotash.com>
Sent: Wednesday, April 20, 2022 4:30 PM
To: Engineer, OCD, EMNRD <OCD.Engineer@state.nm.us>
Subject: [EXTERNAL] Fwd: Intrepid Potash-New Mexico Protest of OXY SWD Application: SWD FED 12 #001 (30-015-26742)

CAUTION: This email originated outside of our organization. Exercise caution prior to clicking on links or opening attachments.

Travis McBain, CPL
Director of Land/Business Development
INTREPID
707 17th Street, Suite 4200
Denver, CO 80202
C. 405.938.5411
travis.mcbain@intrepidpotash.com

Begin forwarded message:

> **From:** Travis McBain <travis.mcbain@intrepidpotash.com>
> **Date:** April 19, 2022 at 4:48:00 PM MDT
> **To:** occ.hearings@state.nm.us, ocd.engineer@state.nm.us
> **Cc:** Brian Stone <Brian.Stone@intrepidpotash.com>, Bob Jornayvaz <bobj@intrepidpotash.com>, Will Fenley <will.fenley@intrepidpotash.com>, Greg Bruce <Greg.Bruce@intrepidpotash.com>, Roy Torres <Roy.Torres@intrepidpotash.com>, Christina Sheehan <christina.sheehan@intrepidpotash.com>, Kyle Smith <kyle.smith@intrepidpotash.com>, Dan Tschopp <daniel.tschopp@intrepidpotash.com>
> **Subject: Intrepid Potash-New Mexico Protest of OXY SWD Application: SWD FED 12 #001 (30-015-26742)**
>
> Dear Whom it May Concern :
>
> Pursuant to Rule19.15.26.8 (1)(C) NMAC and 19.15.26.8 (2)(B), Intrepid Potash – New Mexico, LLC ("Intrepid") hereby protests OXY USA Inc.'s application for authority to inject ("Application"), as specifically identified below, and respectfully requests a hearing on the Application. Intrepid requests a

hearing on the Application during which it expects the presentation and consideration of unbiased evidence based on the best available science, so as to ensure that any proposed injection, in its current location and under the pressures indicated, does not have any potential to adversely affect potash mining activity or access to potash resources. Recent seismic activity near the proposed injection area , which may have been caused by injections similar to those proposed in the below-referenced application, as well as the well's (SWD Federal 12) proximity, both in depth and lateral distance, to Intrepid's current potash mining activities provide a distinct safety hazard to underground miners and the economic viability of potash resources within the Secretary's Potash Area ("SPA"). It is in the public's best interest to protect against undue waste and keep underground miners safe from risks. Intrepid's concerns are more specifically set forth in the attached letter sent to Shelia Mallory, Deputy Sate Director, Minerals of BLM on April 8, 2022.

APPLICATION FOR AUTHORITY TO INJECT for OXY USA Inc., 5 Greenway Plaza, Suite 110, Houston, Texas 77046, is requesting that the New Mexico Oil Conservation Division administratively approve the APPLICATION FOR AUTHORITY TO INJECT as follow: PURPOSE: The intended purpose of the injection well is to dispose of salt water produced from permitted oil and gas wells. WELL NAME AND LOCATION: SWD Federal 12 #001 30-015-26742 located 600' FSL and 660' FWL, Unit Letter M, Section 12, Township 22 South, Range 31 East, NMPM, Eddy County, New Mexico.NAME AND DEPTH OF DISPOSAL ZONE: Delaware-Bell Canyon formation, that was plugged back from the Bone Springs formation and will be injecting at a depth of 4,672 feet to 4,962 feet. Expected maximum injection rates are 2,500 BWPD at a maximum injection pressure of 934 psi.

Protestant: Intrepid Potash-New Mexico LLC.

Best Regards,

Travis McBain, CPL
Director of Land/Buisness Development
INTREPID
707 17th Street, Suite 4200
Denver, CO 80202
405.938.5411 (mobile)
travis.mcbain@intrepidpotash.com

707 17th Street, Suite 4200
Denver, CO 80202
303.296.3006 main
303.298.7502 fax
intrepidpotash.com

April 8, 2022

<u>Via Electronic Mail and Federal Express Overnight Delivery</u>

Sheila Mallory
Deputy State Director, Minerals
Bureau of Land Management
New Mexico State Office
301 Dinosaur Trail
Santa Fe, NM 87508
smallory@blm.gov

Re: Intrepid Potash, Inc. and Intrepid Potash-New Mexico, LLC's Supplemental Comments on the Applications for Permit to Drill for Proposed Wells in the Centennial Resources Parmesan, EOG Resources Capella Moran, and Titus Oil Egg Roll Development Areas in the Secretary's Designated Potash Area

Dear Ms. Mallory:

Intrepid Potash, Inc. and its subsidiary Intrepid Potash-New Mexico, LLC (collectively, "Intrepid"), respectfully submit the following supplemental comments on the applications for permit to drill ("APDs") that the Bureau of Land Management ("BLM") is currently reviewing for proposed drilling in the following Development Areas in the Secretary's Designated Potash Area ("DPA"): (i) Centennial Resources Parmesan, (ii) EOG Resources Capella Moran, and (iii) Titus Oil Egg Roll. These comments supplement Intrepid's initial comments, dated March 22, 2022. Intrepid appreciates the BLM considering and reviewing these supplemental comments as it continues to carefully analyze the underlying issues associated with the proposed APDs, included the issues raised herein. Intrepid further appreciates the BLM's time and dedication to studying the interests of potash miners, potash mining, and oil and gas development.

As explained in detail in Intrepid's initial comments, dated March 22, 2022, currently, the BLM lacks the necessary scientific studies and other information to support an approval of the APDs. Further, as indicated in the March 22, 2022 comments, Intrepid is concerned that BLM's approval of the APDs under current circumstances would not only violate Department of the Interior ("DOI") and BLM policies as well as the National Environmental Policy Act ("NEPA"), 42 U.S.C. §§ 4321, et seq., but also could create serious risks to the health and safety of miners, including miners who work in Intrepid's mines. Significant developments since March 22, 2022 further substantiate the comments set forth in Intrepid's March 22, 2022 correspondence, and evidence why BLM should deny the APDs.

I. NEW DEVELOPMENTS FURTHER SUBSTANTIATE THAT THE BLM LACKS THE NECESSARY STUDIES TO APPROVE THE APDS, AND THAT THE APDS SHOULD BE DENIED.

The supplemental information contained in this letter raise two new issues the BLM should consider and evaluate when reviewing the APDs. First, since Intrepid submitted its initial comments on the APDs, two seismic events have occurred northwest of Carlsbad, New Mexico in an unusual area for seismicity based on recent trends. Intrepid does not know what caused these seismic events, including whether they were triggered by previous or ongoing activity related to oil and gas extraction. Regardless of the cause, the seismic events require the BLM's careful investigation to determine: (i) their cause, likelihood of reoccurrence, and the projected intensity and locations of any such reoccurrence, (ii) whether these events are part of an increasing trend in seismic activity that will interact adversely with high-pressure oil and gas wells in the DPA to the detriment of Intrepid's miners and Life of Mine Reserves, and (iii) the severity and impact of such interaction. Further, the BLM must consider the testing, maintenance, and operations burden that the seismic events impose on Intrepid's underground mine and brine dike/dam facilities.

Second, since Intrepid submitted its initial comments on the APDs, scientists affiliated with Stanford University and other research institutions have published an important study showing that oil and gas operations in New Mexico's Permian Basin may emit substantially more methane than previously thought. *See* Yuanlei Chen, et al. ("Chen"), "Quantifying Regional Methane Emissions in the New Mexico Permian Basin with a Comprehensive Aerial Survey," Environmental Science & Technology (published March 23, 2022)("Chen Study"). A copy of the Chen Study is enclosed herewith and marked as Attachment A. The Chen Study emphasizes the need for an additional, thorough investigation to determine whether methane leaks from oil and gas activity in the DPA pose an increased risk to potash miners, including miners employed by Intrepid, and whether such leaks may sterilize potash reserves for future development.

Collectively, these developments substantiate that significant, additional studies are required before BLM can consider approval of the APDs. Only after such additional studies are completed can the BLM adequately evaluate the APDs and the risk that the proposed wells would present to potash miners, including the miners employed by Intrepid.

A. NEW INFORMATION ON SEISMIC EVENTS NEAR CARLSBAD, NEW MEXICO NECESSITATE REVIEW AND MUST BE CONSIDERED IN EVALUATING THE APDS

The United States Geological Survey ("USGS") recently reported information on two seismic events occurring northwest of Carlsbad, New Mexico in relatively close proximity to the DPA. The first seismic event occurred on the morning of March 25, 2022, approximately 13.6 miles WNW of La Huerta, New Mexico. The event registered 2.6 in magnitude, occurred at a depth of approximately 3.1 miles, and was detected near injection wells that are listed as "active." The wells are operated by Silverback II, Mewbourne, and David H. Arrington Oil and Gas. The seismic event occurred in an unusual area for seismicity based on recent trends. The event occurred outside the Seismic Response Areas established by the State of New Mexico. To Intrepid's knowledge, this seismic event was the first such event occurring this year west of Jal, New Mexico.

Soon thereafter, the USGS reported on April 2, 2022, a second seismic event occurring northwest of Carlsbad, New Mexico. This second seismic event registered 2.8 in magnitude, occurred less than 2.5 miles from the first event, described above, and was detected at a depth of approximately 1.1 miles. This earthquake centered around Brantley Dam and required that Intrepid inspect its underground works and test its dams.

Under the Seismicity Response Protocol established by the New Mexico Oil Conservation Division, this second seismic event will likely cause the OCD to implement a Category 1 response. A Category 1 response requires operators of all salt water disposal ("SWD") wells within a 10-mile radius of the seismic events to submit more detailed and frequent reporting to that agency. Implementation of a Category 1 response will affect 33 wells, most of which are owned by Spur Energy (11 wells), and will affect approximately 2.5 million barrels per day of injection, based on the previous 6-month injection average.

B. NEW INFORMATION ON METHANE EMISSIONS FROM THE NEW MEXICO PERMIAN BASIN NECESSITATE REVIEW AND MUST BE CONSIDERED IN EVALUATING THE APDS

As summarized in the Chen Study published March 23, 2022, Chen recently conducted a site-level, basin-wide field survey of methane emissions in the New Mexico Permian Basin. The Chen Study reports that the Permian Basin produces more oil than all but five countries in the world, underscoring the importance of the study and evaluation of methane in the Permian Basin. Chen, at 4317. The Chen Study emphasizes that circumstances involving oil and gas production in the Permian Basin have changed dramatically over the past decade, a point that Intrepid has advanced repeatedly in its discussions with the BLM. The Chen Study reports that, over the past decade, oil production in the Permian Basin has quadrupled and gas production has tripled, making the Permian Basin "one of the most active oil-producing regions in the world." *Id.*, at 4317, 4322.The Chen Study also reflects that the dramatic increase in oil and gas production from the Permian Basin over the past decade has surprisingly not witnessed corresponding regulatory actions limiting methane emissions from such production. According to Chen, regulations have been slow to catch up to the pace of development – "New Mexico in particular has never before had large-scale oil production, and is only now implementing state-level regulations on venting and flaring." *Id.*, at 4317.

With respect to the Chen Study's methodology, from October 2018 to January 2020, Chen deployed a basin-wide airborne survey of oil and gas extraction and transportation activities in the New Mexico Permian Basin, spanning 35,923 square kilometers, 26,292 active wells, and over 15,000 kilometers of natural gas pipelines using an independently validated hyperspectral methane point source detection and quantification system. *Id.*, at 4317. Chen estimates methane emissions from the New Mexico Permian Basin to be 9.4% (+3.5%/-3.3%) of the gross gas production for the region, much higher than found in previous studies with overlapping, although not identical domains. *Id.*, at 4322. According to the Chen Study, previous studies rarely observed emissions larger than 10 kg/h at a single site, yet Chen's basin-wide survey of over 30,000 assets uncovered 1,958 methane plumes above this size. *Id.* This total includes many emissions over 100 and 1,000 kg/h, with emissions above 308 kg/h accounting for half of measured emissions for the region. *Id.* Chen further concludes that the "clear impact of large emissions found by this study suggests that estimates from ground-based methane surveys may be underestimating total emissions by missing low-frequency, high impact large emissions." *Id.*

C. THE SIGNIFICANCE OF THE RECENT SIESMIC EVENTS AND METHANE STUDY MUST BE STUDIED AND EVALUATED BY THE BLM AND MUST BE CONSIDERED BY THE BLM IN ITS REVIEW OF THE APDS

The recent seismic event and methane study summarized in Section I. A and B, *infra,* provide additional compelling evidence that the BLM must study the safety impacts of oil and gas drilling in the DPA under *current* conditions. Given the dramatic changes in the oil and gas development landscape over the course of the last decade, the BLM cannot approve the APDs until the BLM completes, at a minimum, the additional studies requested herein, and fully analyzes the results of the additional studies. As set forth in Intrepid's initial comments, dated March 22, 2022, the BLM's review of the APDs must be based on the "best science available," as specified in the U.S. Secretary of the Interior's Order No. 3324, dated December 3, 2012, titled "Oil, Gas, and Potash Leasing and Development within the Designated Potash Area of Eddy and Lea Counties, New Mexico," 77 Fed. Reg. 71814, 71817 (Dec. 4, 2012) ("2012 Secretarial Order") and as further described in the DOI, Departmental Manual chapters 305 DM 2 and 305 DM 3 referenced in those comments. Furthermore, the BLM must identify the science on which its review of the APDs is based.

BLM's mandate to develop and utilize the "best science available" is further confirmed by the BLM's website, which states: "*Scientific and technological information, data and evidence are central to developing sound policies, delivering equitable programs, and continually improving them.* For the BLM, this means using science and science-based tools to support decisions about public land uses." https://www.blm.gov/learn/science-in-the-blm (last checked April 6, 2022) (emphasis added). The BLM's website confirms further: "First among this action is *listening to the science*, whether the decision involves *energy development*, recreation, livestock grazing, <u>mining</u>, timber harvest or another use of public lands. *Using the highest-quality information relevant to the issue or decision being addressed*, acknowledging and documenting assumptions and uncertainties, and considering diverse perspectives ensures the integrity and durability of decisions." *Id.* (emphasis added). Moreover, the BLM's website states: "Being a science-informed agency means *striving to consistently apply the latest, best-available science and scientific information to assessments, monitoring, planning, permitting and implementation*. Science-informed decisions are durable, and they increase confidence in the outcomes projected in *land use planning*. In this way science is foundational to transparency and trust." https://www.blm.gov/learn/science-in-the-blm/about-science (last checked April 6, 2022) (emphasis added).

The issues raised in this letter reveal that the BLM cannot currently satisfy these mandates, as the BLM is not using the best available science in evaluating the APDs. It is indisputable that there has not yet been sufficient scientific study of current conditions in the DPA to adequately identify the impacts the proposed wells will have on the health and safety of potash miners, including the miners who work in Intrepid's mines, and on Intrepid's Life of Mine Reserves in the DPA.

As indicated in Section I.A, *infra*, Intrepid does not know if the recent seismic events described herein were triggered by past or ongoing oil and gas drilling. If the seismic events were caused by such activities, the BLM's approval of the APDs could not only exacerbate seismic activity in the DPA, but increase the risk of harm resulting from that activity. Even if the recent seismic activity is unrelated to oil and gas operations, reoccurring earthquakes could still increase the risk of methane leaks from oil and gas infrastructure covered by the APDs. What is clear is that the recent seismic events require careful and complete investigation to determine the cause of these events, the likelihood of their reoccurrence, the projected intensity and locations of any such reoccurrence(s), whether these events are part of an increasing trend in seismic activity. The effect of increased seismic activity needs to be understood and evaluated, as it could directly impact high-pressure oil and gas wells in the DPA to the detriment of the health and safety of miners, including Intrepid's miners, as well as Intrepid's Life of Mine Reserves.

Further, the BLM must consider the significant testing, maintenance, and operations burden that seismic events impose on Intrepid's underground mine and brine dike/dam facilities. Once Intrepid learns of a seismic event that was close to or detected at its sites, its operations personnel must inspect the Intrepid's underground mineworks, West and East tailings dikes and HB ponds and, depending on the severity of a seismic event, structures need to be inspected as well. It takes up to 15 man-hours to conduct inspections of Intrepid's sites after a small event with the accompanying stoppage of normal work. If the seismic event impacts underground mineworks and structure, surface structure and dikes, the repair costs and costs associated with loss of production will escalate. That number could quickly hit tens of thousands of dollars.

Intrepid understands that the additional studies requested herein have not been conducted or even proposed. Approving the APDs without these essential studies would violate the BLM's obligation to base its decisions on the "best science available." Moreover, as we have indicated in our initial comments, such approval would violate the BLM's obligations under NEPA to take a "hard look" at the environmental impacts of its decisions and to conduct such review at "the earliest possible time." *New Mexico ex rel. Richardson v. BLM*, 565 F.3d 683, 704, 707 (10th Cir. 2009) (finding the BLM violated NEPA when it based its decisions on "unanalyzed, conclusory" assertions).

Itis incumbent on the BLM to thoroughly study the frequency, location, and severity of methane leaks from oil and gas wells in the DPA, and methods to mitigate those leaks. The Chen Study establishes that such leaks have recently occurred and at a magnitude substantially higher than previously known. Only by conducting such studies can the BLM identify and accurately assess the potential risks and impacts associated with its approval of the APDs. Such studies are especially important given BLM's findings that if potash mining breaches a well casing, or if a well casing near a potash mine fails for other reasons, gas could enter the mine workings, thus endangering the miners. Notice of Availability of the Draft Order of the Secretary on Oil and Gas and Potash Development within the Designated Potash Area, Eddy and Lea Counties, NM, 77 Fed. Reg. 41442, 41443 (July 13, 2012). Additionally, such a breach would raise the costs of potash mining due to the need for enhanced ventilation techniques and specialized equipment needed to mine in a gassy environment. *Id.* The BLM has therefore found, "[g]iven these safety risks, while potash and oil and gas are found in the same area, they cannot readily be produced at the same time." *Id.*

II. CONCLUSION

For all of the reasons identified in Intrepid's comments, both the initial comments dated March 22, 2022 letter as well as for the reasons set forth above, the BLM lacks the necessary scientific studies and other critical information it is required to evaluate in order to approve the APDs. Intrepid has grave concerns that BLM's approval of the APDs will violate DOI and BLM policies, as well as NEPA, and potentially create serious risks to the health and safety of the men and women who work in Intrepid's mines. Finally, approval of the APDs could negatively impact Intrepid's Life of Mine Reserves and thereby injure Intrepid and its shareholders. Intrepid therefore opposes the BLM's approval of the APDs, and strongly urges the BLM to deny them. Intrepid reserves rights to supplement this letter, as it first learned of the APDs on Monday, March 7, 2022 and as relevant information continues to surface related to BLM's evaluation of the APDs.

Thank you again for providing the opportunity to submit comments on the BLM's review of the APDs. Should you have any questions or require additional information regarding these comments please do not hesitate to contact me.

Respectfully,

Kyle R. Smith

Kyle R. Smith
Vice President, General Counsel & Secretary
Intrepid Potash, Inc.
Intrepid Potash-New Mexico, LLC

Environmental Science & Technology

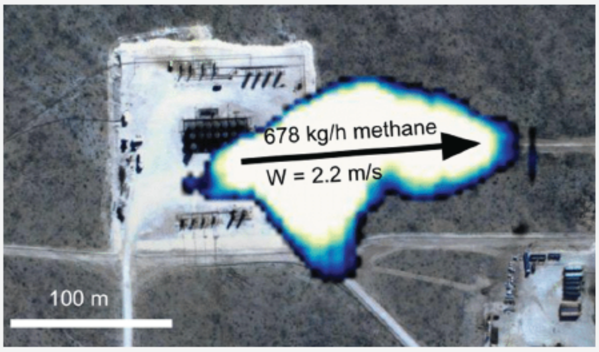
pubs.acs.org/est Article

Quantifying Regional Methane Emissions in the New Mexico Permian Basin with a Comprehensive Aerial Survey

Yuanlei Chen,*,[‖] Evan D. Sherwin,[‖] Elena S.F. Berman, Brian B. Jones, Matthew P. Gordon, Erin B. Wetherley, Eric A. Kort, and Adam R. Brandt

Cite This: Environ. Sci. Technol. 2022, 56, 4317−4323 Read Online

ABSTRACT: Limiting emissions of climate warming methane from oil and gas (O&G) is a major opportunity for short term climate benefits. We deploy a basin wide airborne survey of O&G extraction and transportation activities in the New Mexico Permian Basin, spanning 35 923 km^2, 26 292 active wells, and over 15 000 km of natural gas pipelines using an independently validated hyperspectral methane point source detection and quantification system. The airborne survey repeatedly visited over 90% of the active wells in the survey region throughout October 2018 to January 2020, totaling approximately 98 000 well site visits. We estimate total O&G methane emissions in this area at 194 (+72/−68, 95% CI) metric tonnes per hour (t/h), or 9.4% (+3.5%/−3.3%) of gross gas production. 50% of observed emissions come from large emission sources with persistence averaged emission rates over 308 kg/h. The fact that a large sample size is required to characterize the heavy tail of the distribution emphasizes the importance of capturing low probability, high consequence events through basin wide surveys when estimating regional O&G methane emissions.



KEYWORDS: *methane emissions, oil and gas, leakage, hyperspectral imaging, remote sensing, airborne survey*

■ INTRODUCTION

Methane, the primary constituent of natural gas (NG), is a potent greenhouse gas (GHG) with a global warming potential 28−36 times larger than carbon dioxide over a 100 year time horizon and 84−87 times larger over 20 years.[1] Despite the accelerating transition to renewable energy, NG continues to account for 34% of U.S. primary energy consumption as of 2020.[2] Therefore, reducing the GHG intensity of oil and gas (O&G) through preventing methane emissions is an important mitigation opportunity.

The Permian Basin in Texas and New Mexico produces more oil than all but five countries in the world.[3] Over the past decade, Permian oil production has quadrupled and gas production has tripled.[3] However, as production from this oil rich basin has increased, incentives to limit the resulting emissions of climate warming methane have been lacking. Economically, operators view oil as the primary product,[4] because natural gas prices in the region have remained low, or sometimes even negative, due in part to a lack of gas takeaway capacity.[5] Regulations have also been slow to catch up to the pace of development New Mexico in particular has never before had large scale oil production, and is only now implementing state level regulations on venting and flaring.[6] Taken together, the lack of economic and regulatory incentives to reduce methane emissions has likely contributed to high methane emissions in the Permian Basin.[7−9]

A number of studies have found abnormally high methane emissions from O&G operations in the Permian Basin. With aircraft and tower based methane concentration measure ments, Lyon et al. estimated the NG production loss at 3.3% in a subdomain of the Permian.[8] Zhang et al. apply inversion methods based on satellite measurements by the TROPO spheric Monitoring Instrument (TROPOMI), finding a NG production loss rate of roughly 3.7% for the full Texas and New Mexico Permian.[7] Schneising et al. used 2018/2019 TROPOMI data and a mass estimation framework to reach a similar loss rate estimate of 3.7% in the full Permian Basin.[10] Irakulis Loitxate et al. found 37 extreme methane point sources in the Delaware sub basin with satellites.[11] These extreme sources account for 34% of regional emissions estimated by the Zhang et al. inversion method and TROPOMI measurements, revealing the heavy tailed nature of O&G methane emissions.

Received: September 23, 2021
Revised: February 11, 2022
Accepted: February 15, 2022
Published: March 23, 2022

https://doi.org/10.1021/acs.est.1c06458
Environ. Sci. Technol. 2022, 56, 4317−4323

ATTACHMENT A

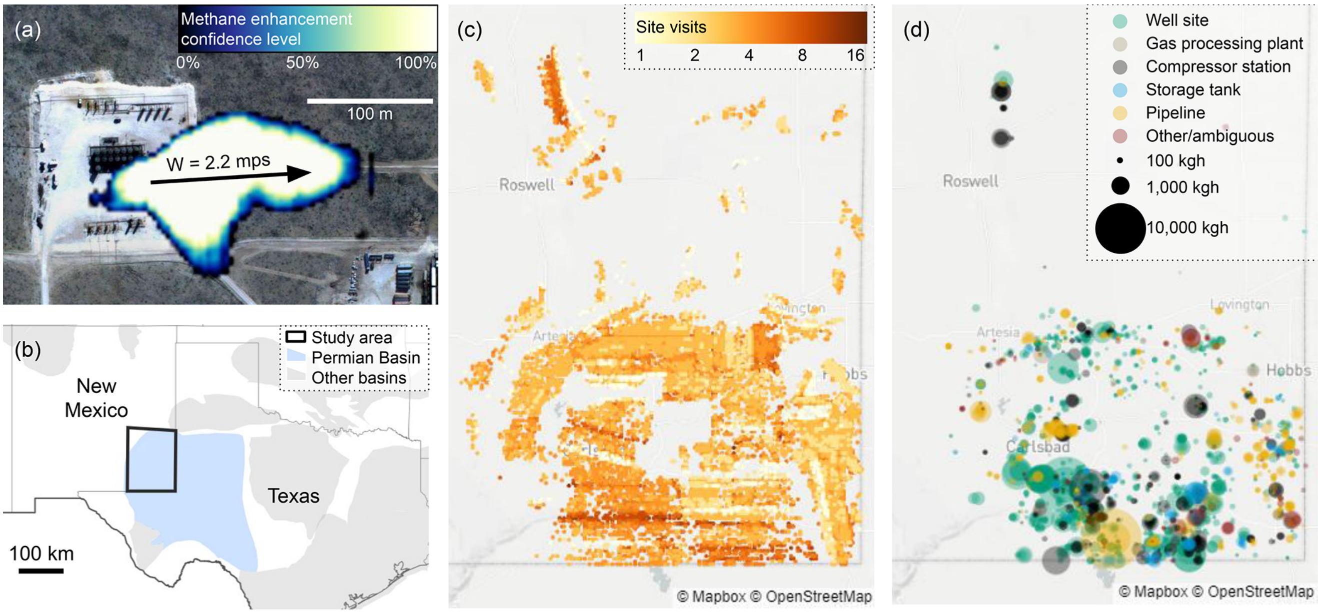


Figure 1. (a) Methane plume from an O&G site. White pixels indicate a high probability of excess methane. (b) Permian Basin map with the survey area outlined in black. Other sedimentary basins are colored gray.[21] (c) Number of measurements of each point asset (pipelines not included). The colorbar is on a logarithmic scale. (d) 1985 detected methane plumes colored by asset type and scaled by plume size. (c,d) map area extends from 102.8°W to 105°W and 31.4°N to 34.2°N, and encloses the study area shown in (b).

More recently, a hyperspectral airborne survey by Cusworth et al. characterizes the very heavy tail of site level methane emissions in the Permian Basin, finding 2874 methane plumes above 100 kg/h and 457 above 1000 kg/h, larger than any observation previously found in ground based methane surveys.[12] Because of the different methods and coverage areas of these studies, direct comparison of their results is challenging and uncertainty remains about the emission rates in the Permian Basin.

However, these studies consistently find emissions significantly in excess of government estimates. The U.S. Environmental Protection Agency (EPA) Greenhouse Gas Inventory (GHGI) estimates a national NG production loss rate of 1.5%,[13,14] but the GHGI has been identified as a conservative estimate of methane emissions,[13,15,16] and a recent alternative estimate finds a U.S. national average NG production loss rate of 2.3% based on a synthesis of measurements from across the O&G supply chain.[13] Note that the Permian findings are even higher than this adjusted national average. One possible driver of larger emissions in the Permian might be the large point sources found by Cusworth et al.: infrequent large emissions (so called "super emitters") are thought to play an important role in driving total emissions. Across many studies, the top 5% of sources contribute over 50% of emissions.[17]

How are these figures still so uncertain? In short: field measurements are noisy and the high expense of surveys means that most studies to date have been very data limited. For example: the largest multipaper synthesis data set of ground based site level methane measurements includes measurements from ~1000 well sites across nine different studies.[15] Given that there are over one million active O&G wells in the U.S., this is a relatively small sample size. Especially given the importance of infrequent superemitters in driving total emissions, such sample sizes are difficult to extrapolate.

We bridge this gap using a novel approach: A basin wide aerial survey capable of measuring emissions from nearly every asset in an O&G producing region with an instrument capable of quantifying and attributing medium to large point source emissions. This work allows us to identify emissions larger than any documented in ground based surveys, and to obtain sample sizes orders of magnitude larger than prior approaches.

MATERIALS AND METHODS

Repeated Comprehensive Airborne Survey. We use a basin wide data set from aerial surveys performed by Kairos Aerospace (henceforth "Kairos") to evaluate medium to large point source emissions in the New Mexico Permian Basin. Kairos' technology consists of an integrated infrared imaging spectrometer, optical camera, global positioning system (GPS), and inertial motion unit.[18] The instrument is flown on an airborne platform at ~900 m above ground, and generates methane plume images superimposed over concurrent optical images (see example in Figure 1a). More information about this sensing technology is available in Kairos' technical white paper and sensing systems patent.[18,19] Note that the methane plume colors indicate confidence levels of methane enhancement.[20] Supporting Information (SI) Figure S1 compares this methane confidence representation with a methane concentration enhancement representation.

Sherwin, Chen et al. evaluated the Kairos technology by conducting an independent, single blind test of the system including 234 total measurements.[22] The test found (1) no false positives among the 21 negative controls; (2) a minimum detection level of 5 kg of methane per hour per meter per second of wind (kgh/mps) and a partial detection range of 5–15 kgh/mps; and (3) an R^2 value of 0.84 between the measured and actual release volumes across a wide range of release sizes tested (18–1025 kg/h) above the technology's detection limit. This study showed the technology's ability to quantify superemitters in the field.[22] See the SI Section S1 for detailed controlled release results.

https://doi.org/10.1021/acs.est.1c06458
Environ. Sci. Technol. 2022, 56, 4317–4323

ATTACHMENT A

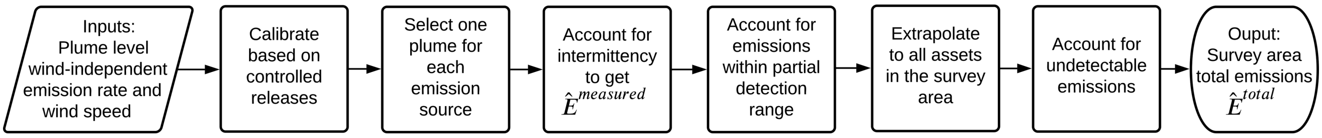


Figure 2. Analysis workflow for estimating survey area total emissions based on methane plume observations.

The Kairos survey of the New Mexico Permian was conducted over 115 flight days from October 2018 to January 2020 (Figure 1b). The campaign surveyed 35 923 km^2 (13 870 sq. mi.) and 26 292 active wells, or 91.2% of all active wells in the covered region. All data were anonymized using procedures described in SI Section S2.2.

Each surveyed nonpipeline facility was observed an average of four times. Accounting for these repeated measurements, the Kairos survey performed a total of 117 658 visits to wells, or approximately 98 000 well site visits based on 1.2 wells per well site in the New Mexico Permian Basin found by a 2018 ground survey.[9]

Figure 1c shows the number of measurements of each point asset (nonpipeline). Multiple overflights also allowed for more frequent sampling in the temporal dimension and provided insights into emission intermittency. The SI Section S2 details the flight plans and SI Section S3 presents an analysis of intermittency.

Basin-Wide Emissions Quantification. A methane survey will detect some number of plumes, each of which is associated with an emission source. An emission source is defined as a point coordinate with one or more methane plumes observed during the campaign. SI Section S4.2 describes the plume source association process.

Figure 2 illustrates the analysis workflow to derive survey area total emissions. SI Section S5.1 describes each step in detail. For each plume, Kairos reports a wind independent emission rate in kgh/mps, and we multiply this rate with the National Oceanographic and Atmospheric Administration's High Resolution Rapid Refresh (HRRR) wind speed estimate at the imaging time and plume coordinates to calculate emission rate in kg/h for each plume using the method described in Duren et al.[23]

We then refer to the single blind test of the instrument by Sherwin, Chen et al. to determine the instrument's detection limit and quantification accuracy and precision (see SI Section S1). Data from the single blind test show an apparent overestimation tendency when simply multiplying HRRR wind with the reported wind independent emission rates for larger releases, possibly due to an underlying nonlinearity or a boundary bias for calibration (see SI Section S1.6). Using a power law correlation from the single blind test, we calibrate the plume level emission rates in kg/h. This correlation (detailed in SI Section S1.5) corrects for the apparent overestimation tendency for large releases when using HRRR wind. The single blind test also quantified the measurement uncertainties, which are modeled as a fixed percent error distribution at all emission levels, indicating that the modeled absolute error scales linearly with emission magnitude (see SI Section S1.5). To account for the measurement error in the New Mexico Permian Basin study, we assume that the percent error follows a normal distribution and apply this error to the plume level emission rates with 1000 Monte Carlo realizations.

For each realization of the Monte Carlo approach, we then select one plume for each emission source if multiple plumes were observed during repeated overflights. Then we multiply the selected plume quantification with a binary term to account for intermittency. Each emission source has a probability, p, of emitting in a given Monte Carlo iteration, with p equal to the fraction of overflights that observed emissions at each emission source.

Basin wide directly measured emissions ($\hat{E}^{\text{measured}}$) is the sum of all emission source level emissions after accounting for intermittency. Note that we include all emission observations, including those from emission sources that were covered only once in the campaign for basin wide emission quantification. Although one observation is not sufficient to characterize the time averaged emission rate of a single source, a basin wide survey measuring a large number of sources one time (or multiple times in the case of this study) is sufficient to give an unbiased estimate of the whole basin. See SI Section S3 for further detail.

For simplicity, we assume that the distribution of methane emissions is stationary over time, although we observe some evidence of seasonal and intraday variation in the frequency of aerially visible methane emissions. The direction of the effect of this variation on our estimate is unclear. SI Section S3.6 explains why $\hat{E}^{\text{measured}}$ is an unbiased estimate of total measured emissions.

To account for undetected emissions in the partial detection range of Kairos' technology, we add to $\hat{E}^{\text{measured}}$ the expected amount of emissions undetected within the partial detection range based on both the detection probabilities and what was observed in the partial detection range during the New Mexico Permian campaign (see SI Sections S1 and S5.1). We then scale up the estimate to the full study area, the black polygon in Figure 1b, assuming that emissions in uncovered areas scale with the number of O&G wells in the area.

Below Kairos' minimum detection threshold, we assume that emissions are described by a combination of the fractional loss rate from Alvarez et al. of 2.2% for production and midstream as well as the emission size distribution from Omara et al.[13,15] Assuming winds from the New Mexico Permian, Kairos would be able to detect 63% of emissions from Omara et al. 2018, translating to a fractional loss rate of 0.8% for emissions below the detection threshold in this study. See SI Sections S1.4 and S5.1 for partial detection definition and detailed steps to account for undetected emissions. We denote the total emissions after incorporating undetected emissions as $\hat{E}^{\text{total}}$.

■ RESULTS AND DISCUSSION

Large Basin-Wide Methane Emissions Quantified. The campaign detected 1985 methane plume observations from 958 distinct emission sources, indicating that for the average emissions source, approximately two different over flights observed a plume. Using the approach described in the Materials and Methods, our estimate for measured emissions ($\hat{E}^{\text{measured}}$) from the New Mexico Permian is 153 (+71/−70, 95% CI) metric tonnes per hour (t/h), shown as the left bar in

ATTACHMENT A

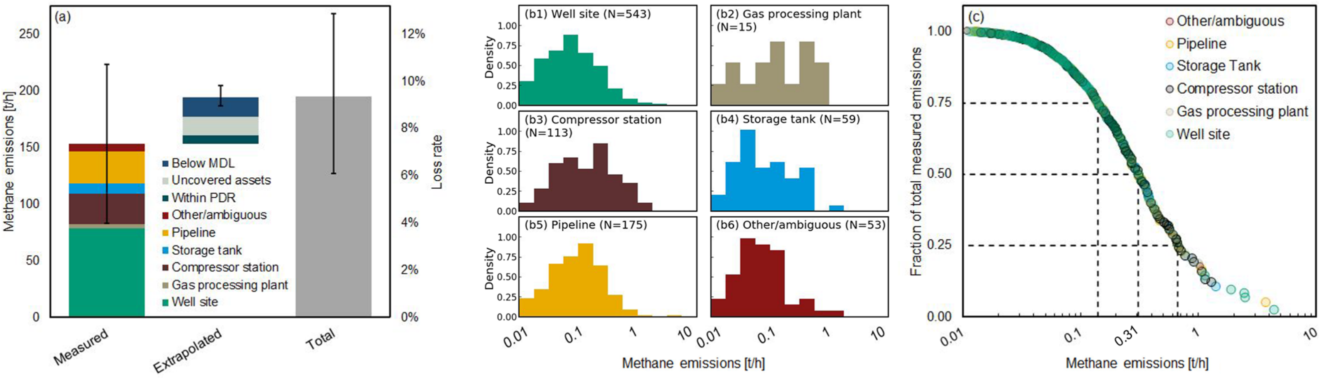


Figure 3. Persistence averaged emissions. (a) The left bar shows directly measured methane emissions ($\hat{E}^{\text{measured}}$) broken down by asset type. The error bars indicate 95% confidence intervals. The middle bar breaks down extrapolated emissions into undetected emissions within the partial detection range (PDR), emissions from assets not measured in the survey area, and emissions that are below minimum detection limit (MDL). The right bar shows that the estimate of total methane emissions in the survey area from upstream and midstream O&G operations is 194 (+72/−68) t/h, 9.4% (+3.5%/−3.3%) of gross gas production. (b) The distribution of asset type specific persistence averaged emission source sizes, which follow heavy tailed distributions. (c) Cumulative emission fraction as a function of persistence averaged emission source sizes.

Figure 3a. This corresponds to 7.4% ± 3.4% of gross gas production in the full survey area.

Accounting for partial detection, emissions below minimum detection limit, and scaling up to assets not covered in this aerial campaign, the total survey area emission estimate ($\hat{E}^{\text{total}}$) is 194 (+72/−68) t/h, equivalent to 9.4% (+3.5%/−3.3%) of gross gas production.

A breakdown of $\hat{E}^{\text{measured}}$ by emission source asset type reveals that 79 ± 46 of the 153 t/h of measured emissions comes from well sites. A "well site" is defined here as the ensemble of all assets (including wells, gathering lines, storage tanks, and compressor stations) found on a congruent gravel or concrete area containing at least one well. Midstream assets were also a significant source, with 29 ± 20 t/h emitted from pipelines (including underground gas gathering pipelines) and 26 ± 16 t/h emitted from compressor stations without a well on site. The remainder was emitted from stand alone storage tank sites (9 ± 6 t/h), gas processing plants (4 ± 2 t/h), and other or ambiguous sources (7 ± 4 t/h). See SI Section S4.2 for definitions of each asset type and the asset attribution method.

Figure 3b shows the distribution of persistence averaged emission source sizes and indicates heavy tailed distributions of emission sizes across asset types. As displayed in Figure 3c, 50% of measured emissions are from 118 (~12%) of the 958 sources, those larger than 308 kg/h. The heavy tail gets even heavier for the largest emissions and contains a disproportionate number of midstream assets. The largest persistence averaged emission source emits at 4.3 t/h. The persistence of the heavy tail for distributions of large emissions demonstrates the significant potential for mitigating methane by detecting and fixing these high consequence sources.

Sensitivity tests show robust support for a mean natural gas fractional loss rate of at least 8.1% of gas produced. As listed in Table 1, switching from a power law fit to a linear fit for the calibration step, described in SI Section S7, brings the loss rate estimate up to 10.2% (+4.1%/−3.6%). A linear fit forced through the origin leads to an estimate of 11.0% (+5.0%/−4.6%). In the calibration fitting process, leaving out large controlled releases improves the statistical validity of the fit due to the underlying asymmetric error distribution at high emission rates, and also increases the total emission estimate,

Table 1. Survey Area Total Methane Emission Rate and Loss Rate Estimates Presented As a Fraction of Total Methane Production for the Base Case and Seven Sensitivity Cases

	$\hat{E}^{\text{total}}$ (t/h)			%NG production loss		
cases	mean	5th%	95th%	mean	5th%	95th%
base case	194	126	266	9.4%	6.1%	12.9%
linear fit for calibration	212	136	296	10.2%	6.6%	14.3%
linear fit forced through origin for calibration	228	131	335	11.0%	6.4%	16.0%
cutoff at 1σ below max controlled release	216	137	301	10.4%	6.9%	14.6%
dark sky wind high time resolution	181	124	244	8.7%	6.1%	11.8%
dark sky wind low time resolution	217	142	301	10.4%	6.8%	14.3%
disable extrapolation	167	119	220	8.1%	5.7%	10.6%
exclude top 20 plumes	173	117	233	8.3%	5.5%	11.2%
no emissions below minimum detection	177	109	249	8.5%	5.2%	12.0%

as described in the SI Section S1.5. Using an alternative wind data set (the commercial Dark Sky wind reanalysis product) results in comparable emissions estimates both for low and high time resolution versions of the data.[24]

To provide a conservative estimate for the loss rate, we apply three additional sensitivity scenarios: (1) disallow extrapolation and assume that emission rates cannot exceed the largest controlled release rate (1025 kg/h); (2) exclude the top 20 largest plumes (~1% of the data set); and (3) assume that there are no emissions from plumes below the Kairos minimum detection limit. These conservative approaches still result in mean loss rate estimates over 8% with a 5th percentile estimate never falling below 5.2%.

These sensitivity cases show that even the lower bound estimates of the conservative scenarios based on our basin wide data are larger than estimates from other Permian studies: 3.7% by the Zhang et al. and Schneising et al. satellite based top down studies and 3.3% by the Lyon et al. tower and airplane based top down study, although these studies include

https://doi.org/10.1021/acs.est.1c06458
Environ. Sci. Technol. 2022, 56, 4317−4323

ATTACHMENT A

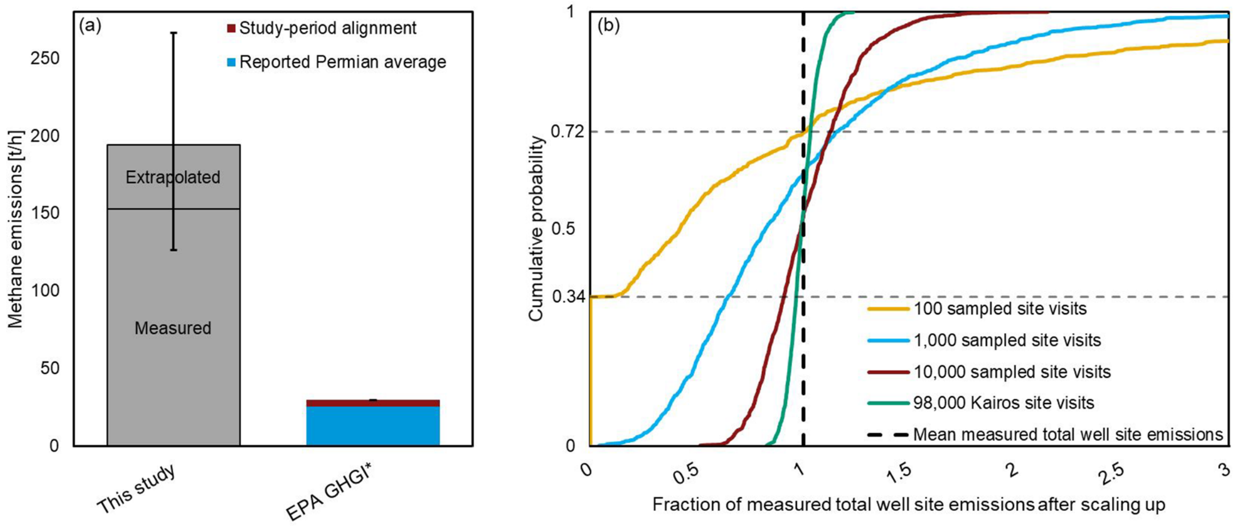


Figure 4. (a) Estimated methane emissions from the New Mexico Permian from this study and EPA GHGI. *Note that the EPA GHGI presented here is based on the 2012 gridded GHGI spatially aligned to this study's area and accounts for production growth.[14] (b) Simulations showing the probability of under or overestimating total emissions if only a subset of the 98 000 well site visits in this study were conducted. Surveying 100 well sites generates a 72% chance of underestimating survey area total emissions, while visiting 1000, 10 000, and 98 000 well sites generates a 63%, 56%, and 50% chance of underestimation, respectively. The computed ratios of simulated emissions detection over mean Kairos measured well site emissions are plotted on the *x* axis.

both Texas and New Mexico.[7,8,10] Applying our basin wide quantification method to data from Cusworth et al. in the overlapping region of New Mexico, we find a fractional loss rate of 4.4% for directly measured emissions.[12] This rises to 5.9% after accounting for an evidently higher effective minimum detection threshold compared to the Kairos survey (see SI Section S8).

The reasons for these discrepancies are currently unknown. Increasing evidence suggests that strong time trends exist in Permian flaring and emissions,[8] and that 2019 was a period of rapid production growth, large amounts of flaring, and presumably poor gas management in general. If this is the case, then our study period could have higher actual loss rates than other study periods.

More work will be required to understand why our results do not align with satellite based top down studies. It is important to note that our study is based upon blind validated methods using hundreds of third party validation measure ments (as seen in SI Section S1). We believe that comprehensive regional aerial surveys with single blind validated instruments could provide an empirical basis for calibrating such top down models, which has historically been difficult due to the large modeling scale.

Importance of Large Sample Size and Direct Measurement. Compared to an EPA GHGI estimate aligned to our study area and time period (Figure 4a), this study suggests total methane emissions from upstream and mid stream O&G activities in the New Mexico Permian to be 6.5 (+2.4/−2.3) times larger. It is important to explore further a key strength of our method compared to prior bottom up studies: very large study sample size. We explore this by simulating the impact of small sample sizes on total emissions estimates (Figure 4b).

Suppose that we only visited 100 well sites, a typical sample size for ground based campaigns. Based on a random subsample of 100 well site visits from our full data set of 98 000 effective well site visits, and using the same minimum detection limit as Kairos, this hypothetical 100 well site survey would detect no emissions 34% of the time and would find average emissions lower than the basin wide survey 72% of the time (based on 1000 Monte Carlo realizations). Median emissions would be 34% of our full survey estimate. In a small number of Monte Carlo realizations (12%), scaling up the 100 sampled visits results in overestimates by a factor of 2 or more. Over many Monte Carlo realizations, a sample size of 100 will ultimately converge on the larger survey results, but this does not reflect the reality of field campaigns: there are usually no more than a few such campaigns for a given basin in a given decade and averaging over 1000 hypothetical surveys does not apply.

Figure 4b shows that increasing the sample size per simulated survey to 1000 well site visits generates an underestimate of total emissions 63% of the time, while a size of 10 000 effectively captures large scale behavior. The extremely non normal distribution of emission sizes plays a large role here and intuition developed with normally distributed phenomena may be deceiving. In normally distributed phenomena, small sample sizes cause variance but not bias, and increasing sample size reduces the variance in the estimated emissions. But with our observed contribution of superemitters, the median estimate of a simulated survey shifts strongly to the right as our sample size increases: at 100 well site visits the median estimate is 42% of our estimate, at 1000 visits this increases to 82%, and at 10 000 visits it increases to 99% of our estimate.

Airplane-Detectable Emitters Drive Total Emissions. While aerial detection technologies have been critiqued for their relatively high minimum detection limit, our results suggest an alternative interpretation: the error introduced from the small sample sizes feasible with ground campaigns may overwhelm any benefits they get from a lower detection threshold. For example, below minimum detection limit emis sions account for 9% (+4%/−3%) of our study total, suggesting that higher sensitivity would lead to only a modest

ATTACHMENT A

increase in total estimated emissions relative to simulated levels.

In conclusion, we conducted a site level, basin wide field survey of methane emissions in one of the most active oil producing regions in the world. We estimate emissions to be 9.4% (+3.5%/−3.3%) of the gross gas production for the region, much higher than found in previous studies with overlapping, although not identical, domains. The increase is partly because our method allows us to inspect the entire O&G producing population using an independently verified instrument capable of detecting large methane emissions. This allows us to identify the largest emissions from all assets surveyed, sidestepping the statistical uncertainties of scaling up small samples of ground based field measurements.

Previous studies rarely observed emissions larger than 10 kg/h at a single site, yet our basin wide survey of over 30 000 assets uncovered 1958 methane plumes above this size.[9,15] This includes many emissions over 100 and 1000 kg/h, with emissions above 308 kg/h accounting for half of measured emissions for the region. While it is possible that the New Mexico Permian was an anomaly during this study period, the clear impact of large emissions found by this study suggests that estimates from ground based methane surveys may be underestimating total emissions by missing low frequency, high impact large emissions.

■ ASSOCIATED CONTENT

● Supporting Information

The Supporting Information is available free of charge at https://pubs.acs.org/doi/10.1021/acs.est.1c06458.

Details of the technology, the New Mexico Permian survey, intermittency analysis, emission attribution, quantification method, sensitivity cases, and comparison with other Permian studies (PDF)

■ AUTHOR INFORMATION

Corresponding Author

Yuanlei Chen − *Energy Resources Engineering, Stanford University, Stanford, California 94305, United States;* orcid.org/0000 0002 4341 2414; Email: yuliac@stanford.edu

Authors

Evan D. Sherwin − *Energy Resources Engineering, Stanford University, Stanford, California 94305, United States;* orcid.org/0000 0003 2180 4297

Elena S.F. Berman − *Kairos Aerospace, Mountain View, California 94040, United States*

Brian B. Jones − *Kairos Aerospace, Mountain View, California 94040, United States*

Matthew P. Gordon − *Kairos Aerospace, Mountain View, California 94040, United States*

Erin B. Wetherley − *Kairos Aerospace, Mountain View, California 94040, United States*

Eric A. Kort − *Climate and Space Sciences and Engineering, University of Michigan, Ann Arbor, Michigan 48109, United States*

Adam R. Brandt − *Energy Resources Engineering, Stanford University, Stanford, California 94305, United States;* orcid.org/0000 0002 2528 1473

Complete contact information is available at: https://pubs.acs.org/10.1021/acs.est.1c06458

Author Contributions

[||]Y.C. and E.D.S. contributed equally to this work.

Notes

The authors declare the following competing financial interest(s): E.S.F.B., B.B.J., M.P.G., and E.B.W. are employees of Kairos Aerospace. The remaining authors have no competing interests to declare.

■ ACKNOWLEDGMENTS

We thank the Kairos Aerospace team for collecting and preparing the data for this study. We gratefully acknowledge the help from Ritesh Gautam, Ben Hmiel, David Lyon, and Mark Omara at the Environmental Defense Fund, Yuzhong Zhang currently at Westlake University, Anna Robertson and Shane Murphy at the University of Wyoming, and Daniel Cusworth and Riley Duren at Carbon Mapper, and Andrew Thorpe at NASA's Jet Propulsion Lab for assisting in comparing this aerial survey with their methane studies. We thank Jeffrey Rutherford at Stanford University for providing comments on the study. This study was funded by the Stanford Natural Gas Initiative, an industry consortium that supports independent research at Stanford University. Analysis was supported in part by the Alfred P. Sloan Foundation Grant G 2019 12451 in support of the Flaring and Fossil Fuels: Uncovering Emissions and Losses (F3UEL) project.

■ REFERENCES

(1) U.S. Environmental Protection Agency (EPA), Understanding Global Warming Potentials. https://www.epa.gov/ghgemissions/understanding global warming potentials (accessed 2021/2/9).

(2) U.S. Energy Information Administration (EIA), US energy facts explained. https://www.eia.gov/energyexplained/us energy facts/, 2020 (accessed 2021/2/9).

(3) U.S. Energy Information Administration (EIA), Permian region drilling productivity report. https://www.eia.gov/petroleum/drilling/pdf/permian.pdf, 2020 (accessed 2020/9/29).

(4) U.S. Energy Information Administration (EIA), Natural gas spot and futures prices (NYMEX). https://www.eia.gov/dnav/ng/ng pri fut s1 d.htm (accessed 2020/9/29).

(5) U.S. Energy Information Administration (EIA), Permian Basin natural gas prices up as a new pipeline nears completion. https://www.eia.gov/naturalgas/weekly/archivenew ngwu/2020/03 19/#tabs rigs 1, 2019 (accessed 2020/5/10).

(6) U.SDepartment of Energy (DOE), New Mexico natural gas flaring and venting regulations. https://www.energy.gov/sites/prod/files/2019/08/f66/New%20Mexico.pdf, 2019, (accessed 2021/5/9).

(7) Zhang, Y.; Gautam, R.; Pandey, S.; Omara, M.; Maasakkers, J. D.; Sadavarte, P.; Lyon, D.; Nesser, H.; Sulprizio, M. P.; Varon, D. J.; Zhang, R.; Houweling, S.; Zavala Araiza, D.; Alvarez, R. A.; Lorente, A.; Hamburg, S. P.; Aben, I.; Jacob, D. J. Quantifying methane emissions from the largest oil producing basin in the United States from space. *Science advances* **2020**, *6*, eaaz5120.

(8) Lyon, D. R.; Hmiel, B.; Gautam, R.; Omara, M.; Roberts, K. A.; Barkley, Z. R.; Davis, K. J.; Miles, N. L.; Monteiro, V. C.; Richardson, S. J.; Conley, S.; Smith, M. L.; Jacob, D. J.; Shen, L.; Varon, D. J.; Deng, A.; Rudelis, X.; Sharma, N.; Story, K. T.; Brandt, A. R.; Kang, M.; Kort, E. A.; Marchese, A. J.; Hamburg, S. P. Concurrent variation in oil and gas methane emissions and oil price during the COVID 19 pandemic. *Atmospheric Chemistry and Physics* **2021**, *21*, 6605−6626.

(9) Robertson, A. M.; Edie, R.; Field, R. A.; Lyon, D.; McVay, R.; Omara, M.; Zavala Araiza, D.; Murphy, S. M. New Mexico Permian Basin measured well pad methane emissions are a factor of 5−9 times higher than US EPA estimates. *Environ. Sci. Technol.* **2020**, *54*, 13926−13934.

(10) Schneising, O.; Buchwitz, M.; Reuter, M.; Vanselow, S.; Bovensmann, H.; Burrows, J. P. Remote sensing of methane leakage

ATTACHMENT A

from natural gas and petroleum systems revisited. *Atmospheric Chemistry and Physics* **2020**, *20*, 9169−9182.

(11) Irakulis Loitxate, I.; Guanter, L.; Liu, Y. N.; Varon, D. J.; Maasakkers, J. D.; Zhang, Y.; Chulakadabba, A.; Wofsy, S. C.; Thorpe, A. K.; Duren, R. M.; Frankenberg, C.; Lyon, D. R.; Hmiel, B.; Cusworth, D. H.; Zhang, Y.; Segl, K.; Gorrono, J.; Sanchez Garcia, E.; Sulprizio, M. P.; Cao, K.; Zhu, H.; Liang, J.; Li, X.; Aben, I.; Jacob, D. J. Satellite based survey of extreme methane emissions in the Permian basin. *Science Advances* **2021**, *7*, eabf4507.

(12) 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. *Environ. Sci. Technol. Lett.* **2021***8*, 567−573.

(13) Alvarez, R. A.; Zavala Araiza, D.; Lyon, D. R.; Allen, D. T.; Barkley, Z. R.; Brandt, A. R.; Davis, K. J.; Herndon, S. C.; Jacob, D. J.; Karion, A.; Kort, E. A.; Lamb, B. K.; Lauvaux, T.; Maasakkers, J. D.; Marchese, A. J.; Omara, M.; Pacala, S. W.; Peischl, J.; Robinson, A. L.; Shepson, P. B.; Sweeney, C.; Townsend Small, A.; Wofsy, S. C.; Hamburg, S. P. Assessment of methane emissions from the US oil and gas supply chain. *Science* **2018**, *361*, 186−188.

(14) Maasakkers, J. D.; Jacob, D. J.; Sulprizio, M. P.; Turner, A. J.; Weitz, M.; Wirth, T.; Hight, C.; DeFigueiredo, M.; Desai, M.; Schmeltz, R.; Hockstad, L.; Bloom, A. A.; Bowman, K. W.; Jeong, S.; Fischer, M. L. Gridded national inventory of US methane emissions. *Environ. Sci. Technol.* **2016**, *50*, 13123−13133.

(15) Omara, M.; Zimmerman, N.; Sullivan, M. R.; Li, X.; Ellis, A.; Cesa, R.; Subramanian, R.; Presto, A. A.; Robinson, A. L. Methane emissions from natural gas production sites in the United States: Data synthesis and national estimate. *Environ. Sci. Technol.* **2018**, *52*, 12915−12925.

(16) Rutherford, J. S.; Sherwin, E. D.; Ravikumar, A. P.; Heath, G. A.; Englander, J.; Cooley, D.; Lyon, D.; Omara, M.; Langfitt, Q.; Brandt, A. R. Closing the methane gap in US oil and natural gas production emissions inventories. *Nat. Commun.* **2021**, *12*, 1−12.

(17) Brandt, A. R.; Heath, G.; Kort, E.; O'Sullivan, F.; Pétron, G.; Jordaan, S. M.; Tans, P.; Wilcox, J.; Gopstein, A.; Arent, D.; Wofsy, S.; Brown, N.; Bradley, R.; Stucky, G.; Eardley, D.; Harriss, R. Methane leaks from North American natural gas systems. *Science* **2014**, *343*, 733−735.

(18) Kairos Aerospace *Technical White Paper: Methane Detection*. https://osf.io/7njpv/, 2019.

(19) Jones, B. B.; Dieker, S. W. Systems and methods for detecting gas leaks. 2019; https://patft.uspto.gov/netacgi/nph Parser?Sect2=PTO1&Sect2=HITOFF&p=1&u=%2Fnetahtml%2FPTO%2Fsearch bool.html&r=1&f=G&l=50&d=PALL&RefSrch=yes&Query=PN%2F10267729.

(20) Kairos Aerospace, Methane Emissions Quantification. https://osf.io/y6w7r/, 2020.

(21) U.S. Energy Information Administration (EIA), Maps: Oil and Gas Exploration, Resources, and Production. https://www.eia.gov/maps/maps.htm (accessed 2021/4/26).

(22) Sherwin, E. D.; Chen, Y.; Ravikumar, A. P.; Brandt, A. R. Single blind test of airplane based hyperspectral methane detection via controlled releases. *Elementa: Science of the Anthropocene* **2021**, *9*. DOI: 10.1525/elementa.2021.00063

(23) Duren, R. M.; Thorpe, A. K.; Foster, K. T.; Rafiq, T.; Hopkins, F. M.; Yadav, V.; Bue, B. D.; Thompson, D. R.; Conley, S.; Colombi, N. K.; Frankenberg, C.; McCubbin, I. B.; Eastwood, M. L.; Falk, M.; Herner, J. D.; Croes, B. E.; Green, R. O.; Miller, C. E. California's methane super emitters. *Nature* **2019**, *575*, 180−184.

(24) Dark Sky by Apple Inc., Dark Sky data attribution. https://darksky.net/attribution (accessed 2021/7/16).

■ EDITOR'S NOTE

The data required to reproduce key results in this article are available at https://github.com/KairosAerospace/stanford nm data 2021. While the remaining data from this study are not available for open release due to confidentiality concerns, Kairos Aerospace is committed to working with research groups studying methane emissions. Access may be granted, but must be done directly through Kairos Aerospace. Interested researchers should contact research collaborations@kairosaerospace.com.

https://doi.org/10.1021/acs.est.1c06458
Environ. Sci. Technol. 2022, 56, 4317−4323

ATTACHMENT A