Contextualizing Quantitative Optical Gas Imaging Samples of Methane Emissions from Oil and Gas Activities in Colorado, New Mexico and Texas

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Authors

Lee Ann L. Hill, MPH[1]

Zoya Banan, PhD, MS[1]

Seth B.C. Shonkoff, PhD, MPH[1,2]

[1] PSE Healthy Energy, Oakland, CA

[2] Department of Environmental Science, Policy and Management, University of California, Berkeley

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PSE Healthy Energy
1440 Broadway, Suite 750
Oakland, CA 94612
510-330-5550
www.psehealthyenergy.org
info@psehealthyenergy.org

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1.0 Executive Summary

In the United States, oil and gas development is a significant anthropogenic source of atmospheric methane, a potent greenhouse gas, that is 86-times as climate forcing as carbon dioxide over a 20-year timeframe. Quantitative optical gas imaging (QOGI) is a method of atmospheric methane and hydrocarbon detection that can help to quantify methane emissions. From 2018 to 2019, Earthworks conducted a field sampling effort to measure methane emissions from upstream oil and gas sources in several states, including three oil and gas basins: Denver-Julesburg (Colorado), San Juan (Colorado and New Mexico), and Permian (New Mexico and Texas). This report aims to contextualize methane emission measurements collected by Earthworks using QOGI technology across these three select basins in 2018 and 2019 using methane emission estimates and measurements from the peer-reviewed literature and emissions inventories.

In this report we (1) review and summarize the peer-reviewed literature, government reports, and emissions inventories on methane emission measurements and estimates from the fields, equipment and facilities where Earthworks collected their QOGI-based methane emission measurements; (2) discuss oil and gas production trends over time in these select basins; and (3) contextualize methane emissions measurements collected by Earthworks with QOGI technology using basin-level annual production, basin-level methane emissions estimates, and additional equipment-level methane emission measurements and estimates. Key limitations regarding data availability and quality and challenges comparing methane emission rates from various data sources are also discussed. Key findings from this assessment are summarized below:

- Overall, basin-level methane emission rates — reported in the peer-reviewed literature and emissions inventories — generally appear to increase proportionally with oil and gas production trends in the San Juan Basin, Denver-Julesburg Basin, and Permian Basin over time.
- The majority of methane emission measurements collected by Earthworks fell within the range of methane emission estimates provided in the literature and emissions inventories for corresponding sources in the select basins, particularly for tanks and unlit flares.
    - **Tanks:** Earthworks' methane emission measurements from tanks were lower than average values reported from tanks in the San Juan Basin and in the Permian Basin, but higher than average values reported from tanks in the Denver-Julesburg Basin.

    - **Unlit flares:** Methane emission rates from unlit flares detected by Earthworks also fell within the ranges presented in the literature. Earthworks' average methane emission rates detected from unlit flares were above the average of values available in the literature in both the San Juan Basin and Permian Basin. In the San Juan Basin, Earthworks' maximum detected emissions from unlit flares exceeded the maximum value reported in the literature for this basin. However, the maximum methane emission rate associated with unlit flares in the Permian Basin was far less (approximately half of) the maximum value reported in the literature and emissions inventories in the Permian Basin, indicating that in certain cases Earthworks' measurements may underestimate methane emission rates from specific sources, such as unlit flares in this particular basin.
- Earthworks detected methane emission rates from pipe fittings and pneumatic controllers in the San Juan Basin that exceeded rates presented in the literature and emissions inventories.
    - **Pipe fittings and pneumatic controllers:** Earthworks' methane emission rates for pipe fittings and pneumatic controllers in the SJB were expanded over a wider range of values as compared to the reported estimates in the literature, often exceeding the maximum emission rate reported from these sources in the literature.

The limitations of this assessment are discussed in detail in the report. The key limitations include:

- Limitations of data availability and uncertain representativeness of both the Earthworks' dataset and the data presented in the peer-reviewed literature and emissions inventories
- Challenges presented during Earthworks' field sampling, including lack of site access and pad-level operational information, limited proximity to observed emission sources and lack of gas composition data for specific sources
- Uncertainty regarding comparable source categories related to upstream oil and gas activities and equipment to enable accurate comparison of methane emission measurements across data sources.

Despite these limitations, this report contributes to the current literature by assessing methane leakage associated with oil and natural gas development by situating equipment-level emission rates in the Denver-Julesburg, San Juan, and Permian Basins, measured by Earthworks using QOGI technology, within the methane emission estimates published in the peer-reviewed literature and methane emissions inventories. Additionally, this assessment contextualizes methane emissions observed during Earthworks data collection efforts with respect to trends of crude oil and natural gas production and basin-level methane emission estimates in previous years. Earthworks' field sampling provides additional methane emission measurements to improve understanding about methane leakage associated with oil and gas development and to help to inform efforts aimed to reduce methane emissions from this sector.

Future projections of hydrocarbon production in the San Juan, Denver-Julesburg and Permian Basins indicate that methane emissions are anticipated to remain a matter of climate concern. Our assessment indicates that future research in this area should include detailed categorizations of methane emission sources, an increase in sample size per emission source collected over a longer time-horizons, and an examination of methane emissions sources in additional oil and gas basins.

2.0 Introduction

Oil and natural gas systems are significant sources of anthropogenic methane emissions, contributing approximately one-third of methane emitted to the atmosphere in the United States (U.S. EPA, 2020a). In 2018, petroleum and natural gas production alone accounted for the majority of methane emissions from petroleum and natural gas systems nationally (96% and 58%, respectively) (U.S. EPA, 2020a). Methane, the primary component of natural gas, is a potent greenhouse gas (GHG) with a global warming potential (GWP) 86-times higher than the carbon dioxide (CO_2) over the 20-year time-horizon (U.S. EPA, 2017). During oil and gas development, methane may be emitted into the atmosphere intentionally from venting during maintenance or off-normal operations, or unintentionally from leaking connections, valves or other infrastructural components. Understanding and addressing methane leakage from oil and gas operations requires ongoing monitoring to detect and repair leaks. According to the United States Environmental Protection Agency's (U.S. EPA) New Source Performance Standards for oil and natural gas industry, monitoring of methane emissions must be conducted using optical gas imaging (OGI) as part of the leak detection and repair (LDAR) program (40 C.F.R. §63, 2017).

Over the last decade, OGI cameras have served as beneficial tools that allow for visual inspection of otherwise invisible methane emissions from leaking components at oil and gas sites (Log et al., 2019; Ravikumar et al., 2020). An OGI camera detects methane plumes by visualizing the band of infrared (IR) spectrum which methane absorbs. The recent development of quantitative optical gas imaging (QOGI) method has enabled the direct quantitative measurement of leakage rates (Zeng and Morris, 2019). QOGI quantifies the leakage rate through a pixel-by-pixel analysis of IR radiation intensity of the image as a function of temperature difference between the background and the plume (Abdel-Moati et al., 2015).

In this context, each pixel captures a column of methane emission detected between the camera and the background (Abdel-Moati et al., 2015).

2.1 Earthworks' efforts to quantify methane emissions associated with oil and gas development

In recent years, Earthworks joined the effort to quantify methane emissions released during oil and gas production—in part because of a lack of publicly available, site- and equipment level data. This work was undertaken as part of Earthworks' Community Empowerment Project (CEP), which uses OGI to visualize emissions otherwise invisible to the naked eye, provide documentation of pollution to local residents, and leverage OGI videos to secure policies and regulations that are protective of health and the climate. Additionally, Earthworks uses OGI images and other research to inform the filing of formal complaints and to encourage regulators and oil and gas operators to take action to reduce climate forcing and health-damaging air pollution from their operations.

As part of the CEP project, Earthworks quantified methane emissions at select oil and gas sites in the United States using QOGI technology (Earthworks, 2019). Specifically, Earthworks used a Forward Looking Infrared (FLIR) GF320 camera in conjunction with a QL320 manufactured by Providence Photonics. The QL320 can be calibrated only for single gases and the gas selected by the user (e.g., propane, methane, or butane) serves as a "proxy" for the complex mix of gases that oil and gas operations release.[1] This particular limitation of the technology contributes some uncertainty in the actual proportion of the proxy gas in a specific emissions stream, which is difficult to overcome given the lack of publicly available data on gas composition in specific oil and gas-specific infrastructure (e.g., flares and tanks) in specific oil and gas basins. However, emissions inventories indicate that emissions sources similar to those that Earthworks has investigated contain a significant proportion of methane (U.S. EPA, 2020b). For that reason, and based on a direct recommendation from Providence Photonics, Earthworks currently sets the tool to "methane" with the assumption that the documented pollution sources release a high volume of that gas.

Between the years of 2018 and 2019 Earthworks measured equipment-level methane emissions rates using QOGI technology at various upstream oil and gas development sites in several states, including the three oil and gas basins considered in this report: the Denver-Julesburg Basin (DJB) in Colorado; the San Juan Basin (SJB) in Colorado and New Mexico; and the Permian Basin in New Mexico and Texas. Earthworks' sampling sites included oil and gas wells, compressor stations, processing facilities, and oil and gas storage equipment. Field

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[1] https://earthworks.org/publications/fs_oilandgas_airpollution/

sampling was conducted in coordination with the property owners or was undertaken on public lands and free-access roads. Sampling sites were identified by Earthworks by communicating with residents about the potential impacts of air pollution associated with oil and gas development activities and conducting research into the active operations in the area.

This report was undertaken to further contextualize methane emission data collected by Earthworks, given the emerging use of QOGI technology and the general lack of previous quantification efforts. In this report we aim to situate the methane emission measurements collected by Earthworks using QOGI technology across the Denver-Julesburg Basin (DJB), San Juan Basin (SJB) and Permian Basin throughout 2018 and 2019 within the existing body of scientific literature and emission inventories.

3.0 Methodology

Our aim in this report is to contextualize the methane emission observations collected by Earthworks using QOGI technology within available methane emission research and reporting. Our approach consists of three primary components:

(1) Using peer-reviewed literature, government reports, and emissions inventories, we review and summarize methane emission measurements and estimates from select basins, equipment, and facilities where Earthworks collected methane emission measurements using QOGI technology.

(2) To contextualize basin-specific methane emissions over time, we extract oil and gas production data from the Denver-Julesburg Basin (DJB), San Juan Basin (SJB), and the Permian Basin since 2000 and discuss basin-specific production trends and methane emission trends over time.

(3) We then summarize the equipment-level methane emission rates measured by Earthworks using QOGI technology and compare these rates by equipment type, by basin, and over time to available methane emission measurements and estimates in the literature and emissions inventories.

3.1 Review and compilation of methane emission estimates and measurements

To contextualize measurements of equipment-level methane emission rates collected by Earthworks using QOGI technology (herein referred to as 'the Earthworks dataset'), we compiled additional estimates and measurements of methane emissions and emission rates from peer-reviewed studies (published 2012-2020), government reports, and emissions inventories for three major oil and gas basins in the United States: Denver-Julesburg Basin

(DJB) in Colorado, San Juan Basin (SJB) in Colorado and New Mexico, and Permian Basin in New Mexico and Texas. These resources were compiled between December 2019 through February 2020. We considered data sources focused on methane emissions from upstream oil and gas activities at the basin level in the select basins (SJB, DJB, and Permian). Data sources were considered specifically if they included information relevant to allow for further comparison with the Earthworks dataset. For example, studies that provided estimates of methane emissions from specific upstream oil and gas activities (development, production, site-level processing and gathering and boosting, and transmission or distribution), information about site types (with respect to Earthworks' sampling sites) and estimates or direct measurements of methane emission rates for specific equipment or components associated with upstream oil and gas development.

A number of peer-reviewed studies provide information about methane emissions for the select oil and gas basins through direct measurements during field campaigns through top-down or bottom-up methane emissions estimates. Top-down (TD) approaches include measurements of atmospheric methane concentrations using aircraft, satellite, stationary or mobile on-the-ground monitors, which estimate total methane emissions by different activities across broader scales (basin, regional, state, or national) (Alvarez et al., 2018; Balcombe et al., 2016). In contrast, bottom-up (BU) methods either quantify methane emissions at leakage point (e.g., equipment, facility, operations) using direct measurements, or estimate methane emissions by aggregating and extrapolating emission rates reported in emission inventories or through simulation approaches (Alvarez et al., 2018; Balcombe et al., 2016).

Literature search criteria and approach

We used the following search engines to compile relevant peer-reviewed publications: PSE's Repository for Oil and Gas Energy Research (ROGER)[2], ScienceDirect, Web of Science, and Google Scholar. Key search terms used in varying combinations included the following: *methane, emission, rate, leak, leakage, oil, natural gas, gas, production, development, Permian, San Juan, Denver Julesburg*.

We identified twenty-one peer-reviewed studies that estimated methane emissions at different spatial scales (equipment, wellsite, facility, county, basin) in the basins of interest. Methane emission estimates included in the selected literature were primarily generated based on field

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[2] PSE Healthy Energy's Repository for Oil and Gas Energy Research (ROGER) is a near exhaustive database of peer-reviewed studies relevant to assessing the impacts of shale and tight gas development. Available at: https://www.psehealthyenergy.org/our-work/shale-gas-research-library/

measurements between 2003 to 2016 (using either top-down, bottom-up or a combination of top-down and bottom-up approaches), emission inventories (e.g., U.S. EPA Greenhouse Gas Reporting Program), and simulation tools (i.e., Monte Carlo).

We also searched federal and state agency websites for reports and projects focused on estimating or measuring methane emissions from upstream oil and gas development in the select basins. The search included projects focused on methane emissions from oil and gas development conducted or contracted by: the Texas Railroad Commission, Colorado Oil and Gas Conservation Commission, Colorado Department of Public Health and Environment, Department of Energy, the National Energy Technology Laboratory, U.S. Energy Information Administration, Texas Commission on Environmental Quality, New Mexico Oil Conservation Division, and New Mexico Environment Department Air Quality Bureau. Of available data sources from these federal and state agencies, only two reports by National Energy Technology Laboratory (NETL) were relevant for this assessment, as they provided estimates of methane emissions from oil- and natural gas- related sources using a life cycle assessment approach (Skone et al., 2016; Roman-White et al., 2019).

Additionally, we investigated recent work by research teams focused on methane emissions from oil and gas sources, including research efforts by: the Environmental Defense Fund, Collaboratory to Advance Methane Science, Climate and Clean Air Coalition, Howarth-Marino Lab Group at Cornell University, Center for Energy and Environmental Resources at the University of Texas at Austin, ICF International, Rocky Mountain Institute, Environmental Integrity Project, Houston Advanced Research Center, GSI Environmental, Global Methane Initiative, Methane Emissions Technology Evaluation Center at Colorado State University, Gas Technology Institute, Gas Research Institute, and the National Academies of Sciences, Engineering and Medicine. One recent project by the Environmental Defense Fund (EDF) was found to be relevant, as it reported methane estimates from SJB at the state-level for New Mexico in 2017.[3] Resources authored by other research groups were not relevant for this assessment, because they either focused on sources of methane emissions out of the scope of this report (e.g. transmission and distribution), addressed other related questions to methane leakage from oil and gas activities, or had yet to publish the results of research efforts.

We also investigated the U.S. EPA Greenhouse Gas Reporting Program (GHGRP) using the Envirofacts data platform (U.S. EPA, 2020b). Envirofacts is an online platform managed by the U.S. EPA that provides access to reported annual methane emissions collected through the GHGRP for all industry segments. We used Envirofacts' GHG Customized Search tool[4] to extract

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[3] https://www.edf.org/nm-oil-gas/

[4] https://www.epa.gov/enviro/greenhouse-gas-customized-search

methane emissions data associated with onshore petroleum and natural gas production facilities for the select basins (DJB, SJB, and Permian) between 2015 and 2018.

Overall, our search yielded twenty-five relevant data sources (21 peer-reviewed studies, 2 government reports [NETL], 1 research team resource [EDF], and 1 government database/emissions inventory [U.S. EPA GHGRP]), which provided methane emission estimates for the basins of interest at different scales (i.e., basin, region, state, county, and equipment). Table 1 includes detailed information about each data source considered in this assessment. Studies were excluded from further evaluation if the estimates included methane emissions from sources other than oil and natural gas-related activities in the select basins or the scale of estimates were not compatible with Earthworks' data collected via QOGI technology and therefore, could not be used to contextualize the Earthworks dataset. After applying the aforementioned exclusion criteria, eleven data sources (ten peer-reviewed studies and an emission inventory, GHGRP) with relevant methane emission estimates or measurements were included for further evaluation (Table 1).

3.2 Compilation of oil and gas production data for select basins

To investigate trends of methane emissions associated with oil and gas development in the basins where Earthworks collected QOGI measurements, we evaluated oil and natural gas production in SJB, DJB and Permian Basin in recent years. The relationship between methane emissions and production of oil and natural gas in the U.S. have been investigated in previous studies (Brantley et al., 2014; Lyon, et al., 2016; Omara et al., 2016). Numerous studies report a positive correlation between oil and gas production rates and methane emissions sourced from production sites (Brantley et al., 2014; Omara et al., 2016), and daily oil and gas production rates and methane emissions from specific sources, such as tanks (Lyon et al., 2016).

We retrieved oil and natural gas production data in SJB, DJB and Permian Basin from Enverus (formerly DrillingInfo) (Enverus, 2020). Enverus provides monthly production of oil (barrels) and natural gas (thousand cubic feet) for 1951-2019 in SJB, 1950-2019 in DJB and 1933-2019 in the Permian Basin. For the purpose of this report, we analyzed oil and gas production rates in the select basins in recent years (from 2000 to 2019) to be compatible with the time span for which we could derive estimates of methane emissions from previous studies and reports. We summed basin-specific monthly production rates in each year to calculate annual oil and natural gas production for each select basin.

Table 1. Oil and gas methane emission data sources considered for further evaluation, listed in alphabetical order by first author's last name. "X" represents studies that were included for further evaluation. (DJB: Denver-Julesburg Basin; SJB: San Juan Basin; TD: top-down; BU: bottom-up; ER: emission rate; GHGRP: Greenhouse Gas Reporting Program)

Data source	Included	Basin(s)	Approach / Methods	Sources of methane evaluated
Alvarez et al. (2018)	X	DJB SJB	**TD**: Data from TD analysis by other studies. **BU**: Based on reported facility-scale measurements in GHGRP 2015.	Production, gathering, processing, transmission and storage, local distribution, oil refining and transportation.
Brandt et al. (2014)		Permian	**BU**: Sensitivity analysis on the U.S. EPA net emissions rate	Flowback during completion and hydraulic fracturing.
Brantley et al. (2015)		DJB	**TD**: Other Test Method (OTM) 33A. **BU**: Optical Gas Imaging (OGI).	Condensate tank.
Brantley et al. (2014)		DJB	**TD**: 1) Other Test Method (OTM) 33A used either Picarro or Los Gatos gas analyzer, 2) Used a point source Gaussian model.	Short term (i.e., condensate tank flashing) and maintenance-related emissions.
Collett et al. (2016)		DJB	**TD**: Tracer Ratio Method (TRM) and Picarro gas analyzer.	Fracking, flowback, production and liquid loading well pads.
Environmental Defense Fund, New Mexico Oil and Gas Data (2017)		Permian SJB	**TD**: - Permian: Site-level measurements using 1) U.S. EPA Other Test Method 33A (OTM 33A), 2) inverse-Gaussian method. Basin-level emissions were extrapolated from site-level measurements by a statistical bootstrapping approach. - SJB: EFs were calculated with a gas production dependent, log-normal equation. The underlying data are from >400 site-level measurements from six U.S. basins (Barnett, Fayetteville, Marcellus, Uintah, Upper Green River, Denver-Julesburg). **BU**: GHGRP 2017 and previously published measurement studies.	Upstream oil and gas sites in New Mexico, including well pads, gathering stations, and gathering pipelines.
U.S. EPA (2020a)	X	DJB Permian SJB	**BU**: Self-reporting to GHGRP (2015 – 2018).	Multiple sources from oil and natural gas production.

Data source	Included	Basin(s)	Approach / Methods	Sources of methane evaluated
Frankenberg et al. (2016)		SJB	**TD**: NASA/Jet Propulsion Laboratory airborne imaging spectrometers (namely, AVIRIS-NG and HyTES).	Gas processing facilities, storage tanks, pipeline leaks, and well pads, as well as a coal mine venting shaft.
Kort et al. (2014)	X	SJB	**TD**: 1) SCanning Imaging Absorption SpectroMeter for Atmospheric CHartographY (SCIAMACHY) instrument, and 2) Total Carbon Column Observing Network (TCCON). **BU**: EDGAR v4.2 (a bottom-up inventory estimates which has not been validated).	**TD:** Established gas, coal, and coalbed methane mining and processing. **BU:** Natural gas production, processing, and distribution.
Levi (2012)	X	DJB	Data retrieved from Petron et al., 2012: **TD**: 1) NOAA Boulder Atmospheric Observatory tower, 2) Mobile Lab, consisted of a Picarro gas analyzer, a CO gas-filter correlation instrument, an O3 UV-absorption analyzer from 2B Technologies and a Global Positioning System (GPS) unit. **BU**: 1) WRAP Phase III inventory of total volatile organic compound (VOC) emissions from oil and gas exploration, production and processing, 2) Colorado Oil and Gas Conservation Commission composition of 77 samples of raw natural gas collected at different wells in the Greater Wattenberg Area.	Venting and flashing
Marchese et al. (2015)		Permian SJB	**TD**: Downwind tracer flux measurements using two tracer gases (nitrous oxide and acetylene) and a mobile laboratory equipped with Aerodyne QC-TILDAS and/or Picarro. Infrared camera survey performed at 108 gathering facilities to identify emission sources.	Liquid storage tanks (gathering and processing sites)
Mitchell et al. (2015)		Permian SJB	**TD**: Monte Carlo analysis using the same dataset as Marchese et al., 2015.	Liquid storage tanks (gathering and processing sites).
Omara et al. (2018)	X	DJB Permian SJB	**TD**: 1) Direct onsite measurements, 2) Downwind tracer flux, 3) Downwind methane plume measurements combined with inverse Gaussian modeling. **BU**: 1) a robust regression model, and 2) a nonparametric model.	Routine operations (e.g., equipment leaks, venting from pneumatic controllers and storage tanks) or were unplanned (e.g., unintended emissions from malfunctioning equipment). Not including methane emissions from completion flowback or liquids unloading, storage or coalbed methane well sites.

Data source	Included	Basin(s)	Approach / Methods	Sources of methane evaluated
Pacsi et al. (2019)	X	Permian SJB	**BU in Permian**: OGI with a FLIR Model GF-320 infrared (IR) camera. **BU in SJB**: handheld flame ionization detector (FID) conducted with a Thermo Scientific TVA-1000B.	On-site piping and process components, such as valves and flanges.
Peischl et al. (2018)	X	DJB	**TD**: 1) Atmospheric measurements taken aboard a National Oceanic and Atmospheric Administration (NOAA) WP-3D (P-3) aircraft, 2) Methane was measured by Picarro. **BU**: Used a methane emission inventory and cattle and calf data to estimate emissions from sources not related to the oil and natural gas industry, such as livestock and landfills, and attribute the remaining methane emissions to O&NG activity.	Oil and natural gas production operations as a result of routine operations, such as through venting and the use of pneumatic controls, and unintentionally, via leaks and other fugitive emissions.
Petron et al. (2014)	X	DJB	**TD**: Aircraft observation using Picarro. **BU**: EF from literature, inventory data compiled by the State of Colorado, annual facility-level emission estimates reported to U.S. EPA GHGRP in 2012.	**TD:** Oil and gas sources. **BU:** Agricultural operations, landfills, and water treatment plants.
Petron et al. (2012)	X	DJB	**TD**: 1) NOAA Boulder Atmospheric Observatory tower, 2) Mobile Lab, consisted of a Picarro gas analyzer, a CO gas-filter correlation instrument, an O3 UV-absorption analyzer from 2B Technologies and a Global Positioning System (GPS) unit. **BU**: 1) WRAP Phase III inventory of total volatile organic compound (VOC) emissions from oil and gas exploration, production and processing, 2) Colorado Oil and Gas Conservation Commission composition of 77 samples of raw natural gas collected at different wells in the Greater Wattenberg Area.	**TD:** Venting. **BU:** Flashing from condensate storage tanks and venting.
Robertson et al. (2017)		DJB	**TD**: Other Test Method (OTM) 33a.	Well pads in normal operation including episodic events (e.g., flash emissions, automated liquid unloading) and failed components (e.g., thief hatch stuck open, malfunctioning pressure relief valves); not including water unloading truck or sites under maintenance.

Data source	Included	Basin(s)	Approach / Methods	Sources of methane evaluated
Roman-White et al. (2019)		Permian SJB	**BU**: Life cycle analysis (LCA) model using data from GHGRP 2016 and GHGI 2018.	Natural gas production, gathering and boosting.
Skone et al. (2016)	X	Permian	**BU**: Life cycle analysis (LCA) through Monte Carlo analysis using data from: 1) EIA's natural gas database (2015), 2) U.S. EPA's Envirofacts database (2014), and 3) the flaring data provided by a partnership between the National Oceanic and Atmospheric Administration (NOAA) and the World Bank-led Global Gas Flaring Reduction Partnership (GGFRP).	Pneumatic devices, valves, open-ended lines (OELs), connections, flanges during natural gas extraction.
Smith et al. (2017)		SJB	**TD**: Aircraft sampling using Twin Otter (NOAA) Mooney (Scientific Aviation) aircraft. **BU:** U.S. EPA GHGI 2012.	Gas processing plants, compressor stations, reinjection facility, power plant, coal mine vent shaft, and geological seep).
Townsend-Small et al. (2016)		DJB	**TD**: Remote Methane Leak Detector (RMLD). **BU**: Detecto-Pak InfraRed (DPIR).	Abandoned wells.
Willyard and Schade (2019)	X	Permian	**TD**: Satellite imagery radiant heat measurements by the National Oceanic and Atmospheric Administration (NOAA) Visible Infrared Imaging Radiometer Suite (VIIRS) satellite-based radiance sensors. **BU**: TxRRC: data self-reported by companies to the Texas Railroad Commission.	Venting and flaring
Yacovitch et al. (2017)		DJB	**TD**: Dual tracer flux ratio measurements performed with Tunable Infrared Laser Direct Absorption Spectroscopy (TILDAS).	Wellpads, gathering stations, and processing plants (not including any transmission-sector compressor stations).
Zaimes et al. (2019)		DJB Permian SJB	**BU**: Monte Carlo simulation using data from 1) American Petroleum Institute (API), 2) America's Natural Gas Alliance (ANGA) survey, 3) DrillingInfo, 4) GHGRP 2016, and 5) peer-reviewed literature.	Liquids unloading.

3.3 Comparing methane emissions measurements and estimates across data sources

Earthworks reported methane emission measurements in pounds per hour (lbs/hr) and/or cubic feet per hour (scf/hr). To be consistent with the Earthworks' field measurements, we converted reported equipment-level methane emission rates in the literature to pounds per hour (lbs/hr). Results of all calculations (i.e., calculation of mean, median, minimum and maximum methane emission rates) based on the estimates by other studies and sources are rounded to the appropriate number of significant digits. For data sources used to evaluate methane emissions at the basin level, methane emissions are reported either annually (i.e., lbs/yr) or as an hourly rate (i.e., lbs/hr). These estimates were not combined, as to not assume that hourly rates reported in the literature represent constant hourly rates throughout an entire year (normalized over one year).

The Earthworks dataset includes seven categories of equipment- or component-level methane emission sources: unlit flares, tanks, pipes, pipe fittings, vents, separators and pneumatic controllers (herein referred to as 'Earthworks source categories'). To contextualize methane emissions rates observed from Earthworks source categories, we first extracted equipment-specific definitions and descriptions from the peer-reviewed literature and the Code of Federal Regulations (40 C.F.R. §98, 2010). We also reviewed Earthworks field sampling information, including site descriptions, site configurations, and QOGI video footage. Some of the relevant equipment categories retrieved from the literature and emissions inventories were too broad to be accurately compared to the Earthworks source categories. These included oil- and gas-related sources outside the scope of this project, such as natural gas processing, underground natural gas storage, liquid natural gas (LNG) storage, LNG import and export equipment, and natural gas distribution. Detailed descriptions of how Earthworks' source categories were compared across different data sources are included below. Briefly, Earthworks source categories considered for further comparison included unlit flares, tanks, pipe fittings and pneumatic controllers; separators were re-categorized under the pneumatic controllers category based on review of reported emissions data by Earthworks and recorded video footage of emission sources; and vents and pipes were excluded from further evaluation given the lack of source specificity in the Earthworks dataset and the lack of comparable source categories available in the literature.

Unlit flares

In the Earthworks dataset, uncombusted emissions from direct flaring were categorized as ‘unlit flare’.[5] Two identified data sources for the purpose of this evaluation provided methane emissions estimates using categories which could include ‘unlit flare’ emissions: Alvarez et al. (2018) and GHGRP (2015 – 2018). Alvarez et al. (2018) reported methane emissions from each facility in the basins of interest under two separate categories (one for vented [uncombusted] gas and another for flared [combusted] gas), using emissions reported to GHGRP in 2015. On the other hand, GHGRP categorized the emissions from associated gas venting and flaring (both combusted and uncombusted) under one category. Therefore, we included the Alvarez et al. (2018) vented gas category to compare with ‘unlit flare’ emissions in the Earthworks dataset, and excluded the remaining categories and data sources that included combusted gas from further evaluation.

Tanks

We reviewed Earthworks’ field sampling QOGI camera footage to identify any specific labeling on tanks. In the majority of QOGI camera footage available, tank labels were not shown (except for one site, where one tank was labeled as "Crude Oil" and another was labeled as "Condensate"). Therefore, we compared methane emissions from ‘tanks’ in the Earthworks dataset to estimates and measurements from the literature and emissions inventories pertaining to atmospheric storage tanks (i.e. tanks with contents stored at atmospheric pressure) and production storage tanks, as they are likely compatible by definition. These storage tanks are used in upstream oil and gas production, typically located on the well pad or within proximal distance of the well pad, and designed to contain crude oil, condensate, intermediate hydrocarbon liquids, or produced water (40 C.F.R. § 63.761, 2004).

Separators and pneumatic controllers

Upon review of Earthworks’ QOGI camera footage of ‘separators’, the methane emissions primarily originated from pneumatic controllers presumably nearby separators rather than directly from the separators. Review of Earthworks’ data demonstrates comparable ranges of methane emissions from the sources categorized under “pneumatic controller” (0.2 - 2.8 lbs/hr) and ‘separator’ (0.9 - 4.3 lbs/hr). Furthermore, a relevant study (Pacsi et al., 2019) which included direct emission measurements from similar types of components and equipment, identified emissions specific to separator as being from related sub-components (e.g., regulator, valves, flanges, connector, and OELs) rather than from separators as a single

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[5] Personal communication with Earthworks on January 14, 2020.

equipment category. Therefore, we recategorized Earthworks' methane emissions measurements from 'separators' as from 'pneumatic controllers'.

Vent and pipe

Earthworks' source categories 'vent' and 'pipe' are broad categories that did not clearly overlap with equipment or component descriptions in the literature and emissions inventories. Additionally, Earthworks had limited proximity to leakage sites (i.e., measurements were collected at far distances) making leakage sources difficult to discern; consequently, limited information was provided in the documented field observations. Therefore, 'vent' and 'pipe' measurements were omitted from further comparative analysis.

4.0 Results

4.1 Basin-level methane emission estimates

Of the eleven data sources included in this assessment (ten peer-reviewed studies and U.S. EPA GHGRP), eight studies provide basin-level estimates of methane emission rates associated with oil and gas sources, using top-down and bottom-up approaches. Four studies provided annual rates of the basin-level methane emissions (Kort et al., 2014; Levi, 2012; Petron et al., 2012; Willyard and Schade, 2019). The remaining four studies provided basin-level estimates of methane emission rates by hour (Alvarez et al., 2018; Omara et al., 2018; Peischl et al., 2018; Petron et al., 2014). Arithmetic mean and bounds (lower and upper) for the basin-level methane emission rates associated with the oil and gas sources in the DJB, SJB, and Permian Basin for years with available data are shown in Table 2.

While methane emission estimates are not always available for continually consecutive years and in comparable units across all basins, and these estimates may include different upstream sources of emissions associated with oil and gas development, generally, average methane emissions appear to have increased over time in DJB and the Permian Basin (Table 2). Estimated average basin-level methane emissions in the most recent available year (i.e., 2015) appear highest in the Permian Basin (242,508 lbs/hr), and lowest in the DJB (60,627 lbs/hr) (Table 2).

Table 2. Basin-level methane emissions estimates for Denver-Julesburg Basin (DJB), San Juan Basin (SJB) and Permian Basin. Methane emissions reported annually (lbs/yr) and hourly (e.g., lbs/hr) were not combined, to avoid generalizing the hourly rates to represent constant hourly rates throughout an entire year.

Year	Average [1] (Min – Max)	Unit	Source of Emissions	Reference(s) and Approach (TD or BU) [2]
Denver-Julesburg Basin (DJB)				
2008	201,392,037 (80,468,630 – 266,759,020)	lbs/yr	All oil and gas sources	Petron et al. (2012) - TD & BU Levi (2012) - TD & BU
2012	42,549 (27,337 – 57,761)	lbs/hr	Venting and flashing	Petron et al. (2014) - TD & BU
2015	44,092 (12,787 – 72,753)	lbs/hr	All oil and gas sources	Alvarez et al. (2018) - TD & BU
2015	60,627 (37,479 – 82,673)	lbs/hr	Routine operations or unplanned leakages from producing sites	Omara et al. (2018) [3] - BU Peischl et al. (2018) [4] - TD
San Juan Basin (SJB)				
2003-2009	374,785,400[6]	lbs/yr	Natural gas production, processing, and distribution	Kort et al. (2014) - BU
2015	125,663 (9,480 – 242,508)	lbs/hr	All oil and gas sources	Alvarez et al. (2018) - TD & BU
2015	68,343 (44,092 – 90,389)	lbs/hr	Routine operations or unplanned leakages from producing sites	Omara et al. (2018) - BU
Permian Basin				
2012	1,247,626,085 (907,677,637 – 1,587,574,534)	lbs/yr	Venting and flaring	Willyard and Schade (2019) [5] - TD & BU
2013	1,747,144,445 (1,424,642,648 – 2,069,646,242)	lbs/yr	Venting and flaring	Willyard and Schade (2019) - TD & BU
2014	2,206,018,993 (1,476,849,343 – 2,935,188,643)	lbs/yr	Venting and flaring	Willyard and Schade (2019) - TD & BU
2015	3,969,336,694 (3,578,418,413 – 4,360,254,976)	lbs/yr	Venting and flaring	Willyard and Schade (2019) - TD & BU
2015	242,508 (147,710 – 330,693)	lbs/hr	Routine operations or unplanned leakages from producing sites	Omara et al. (2018) - BU

[1] Average value is either the estimate of average basin-level methane emissions reported by a single study or the average of average methane emission rates reported by multiple studies.

[2] TD: Top-Down; BU: Bottom-Up.

[3] Corresponding activities evaluated by Omara et al. (2018) include routine operations (e.g., equipment leaks, venting from pneumatic controllers and storage tanks) or unplanned activities (e.g., unintended emissions from malfunctioning equipment) in producing sites. Omara et al., (2018) did not include methane emissions from completion flowback or liquids unloadings, storage or coalbed methane well sites.

[4] Corresponding activities evaluated by Peischl et al. (2018) include routine oil and natural gas production operations, such as venting and the use of pneumatic controls, and unintentionally, via leaks and other fugitive emissions.

[5] Willyard and Schade (2019) reported estimates of methane emission rates in the unit of standard cubic feet per year (scf/yr). Methane density (0.0418 lb/ft^3) at standard temperature and pressure (60˚F and 14.7 Psi) was used to convert these estimates to the mass unit of pounds per year (lbs/yr).

[6] Only the average value of methane emissions was reported over the period.

4.2 Recent trends in oil and gas production in the select basins

Trends of natural gas and oil production in the select basins (2000-2019) are depicted in Figure 1 and Figure 2, respectively. While natural gas production is directly relevant to assessments of methane emissions, oil production is also relevant, as natural gas is co-produced during oil production (i.e., associated gas). Overall, natural gas production increased in the DJB and Permian Basin between 2000 and 2019 (by 354% and 136%, respectively), but gas production in the SJB showed a decreasing trend over this timeframe (54% decrease). Meanwhile, oil production generally increased across the three basins (by factor of 14, 4 and 2 in DJB, Permian and SJB, respectively) between 2000 and 2019. However, annual decreases in oil production were observed in the DJB and SJB beginning in 2016.

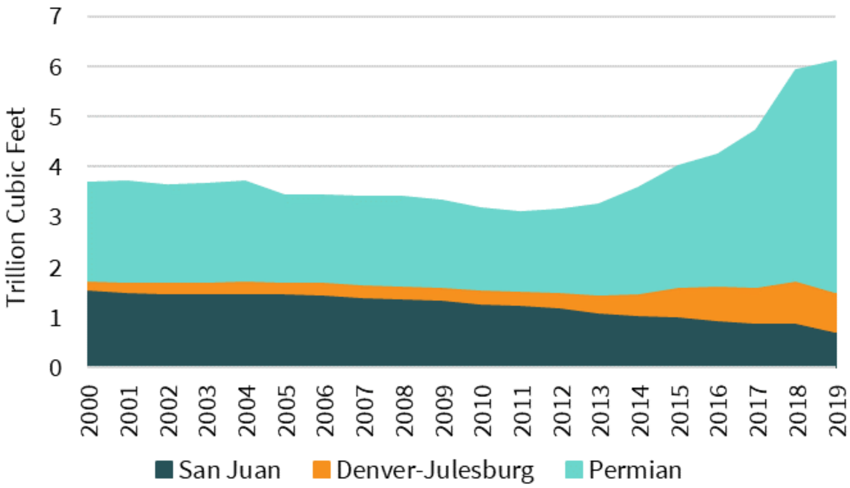

Figure 1. Natural gas production (trillion cubic feet) in the San Juan, Denver-Julesburg and Permian Basins, 2000-2019.

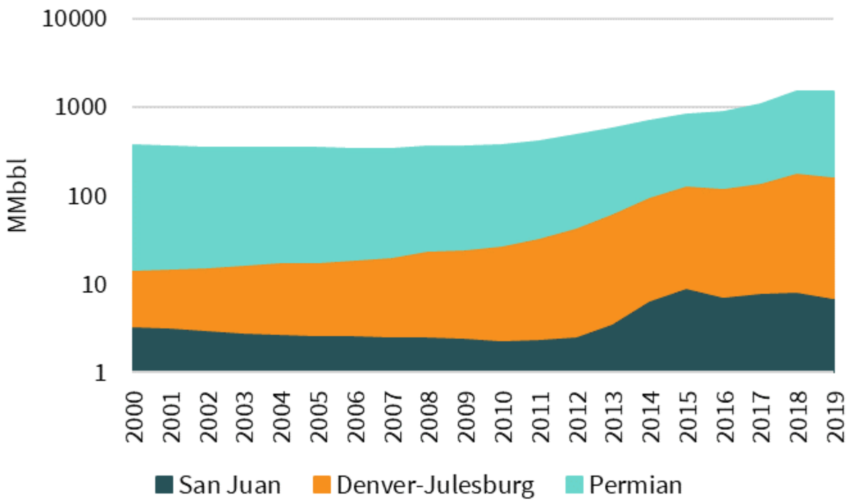

Figure 2. Oil production in the San Juan, Denver-Julesburg and Permian Basins, 2000-2019 (MMbbl - million barrels).

Oil and gas production in the Permian Basin increased consistently from 2011 and 2019. This trend corresponds with increased estimated methane emissions reported to emission inventories and published in the literature for the Permian Basin between 2012 and 2015 (Table 2). Additionally, both oil and gas production in the Permian Basin exceeds that of the other select basins. Omara et al. (2018) estimated average methane emissions from routine operations and unintended leakages (from malfunctioning equipment) to be 2.5% of total natural gas production in the Permian Basin in 2015 (Table A-1). However, while routine operations include equipment leaks, venting from pneumatic controllers and storage tanks, these estimates do not include emissions from other oil and gas sources, such as completion flowback, liquids unloading, and storage and coalbed methane well sites (Omara et al., 2018). Therefore, such an estimate likely does not comprehensively represent basin-level methane emissions as percentage of produced natural gas.

With the exception of a 5.6% decrease in 2016 and 8% decrease in 2019 (as compared to the years directly prior), oil production in the DJB has increased since 2010 (Figure 2). Similar to oil production in this basin, the gas production trend is ascending overall. While annual oil production in the DJB exceeded the SJB across all years (2000-2019), annual gas production in the DJB was less than that of the other select basins, except in 2019 when gas production exceeded that of the SJB. In the literature, average methane emissions from routine operations and unintended leakage from the DJB in 2015 is estimated to be 2.1% (Peischl et al., 2018) and 2.8% (Omara et al., 2018) of total natural gas production (Table A-1). Other studies also provided estimates of methane emissions from oil and gas activities in the DJB for previous years. Petron et al. (2014) estimated the methane emissions from all sources associated with oil and gas activities in the DJB to be 4% of total natural gas production from this basin in 2012 (Table A-1).

Oil production in the SJB increased consistently between 2011 and 2015. Oil production then decreased between 2016 and 2019 with notable drops in 2016 (20%) and 2019 (17%) compared to years prior. Gas production in the SJB has also decreased since 2005. Only a few studies provide basin-level methane emission estimates across years in the SJB, limiting our ability to compare production rates to methane emission estimates across all infrastructure and over time. Nonetheless, according to Omara et al. (2018), the average methane emissions from routine operations and unintended leakages comprises 4.5% of total natural gas production in the SJB in 2015 (Table A-1). However, given that not all oil- and natural gas- related sources are considered in this estimate, this percentage likely does not fully represent basin-level methane emissions as a percentage of produced natural gas.

4.3 Contextualizing Earthworks' equipment-level methane emissions measurements collected using QOGI technology

Earthworks quantified methane emissions from leaking equipment or components at three select basins for different site types (oil well, gas well, oil and gas well, unknown well, compressor station, and gas storage facility). Samples were collected in the DJB (at one site in July 2019); in the SJB (at two sites in May 2018 and ten sites in July and November 2019); and in the Permian Basin (at five sites in June 2018). Locations of Earthworks' field sampling in the SJB, DJB, and Permian Basins are shown in Figure 3. Earthworks field sampling yielded a total of 56 methane emissions measurements across the three select basins (8 in DJB, 28 in SJB, and 20 in the Permian Basin). Number of measurements collected by basin and by equipment- or component- type are listed in Table 3. Seven samples (from pipes and vents in DJB) were excluded from our comparative analysis, as these source categories were too broad to compare to methane emission estimates and measurements in the literature and in emissions inventories.

Figure 3. Map of methane emission sources assessed by Earthworks using QOGI technology.

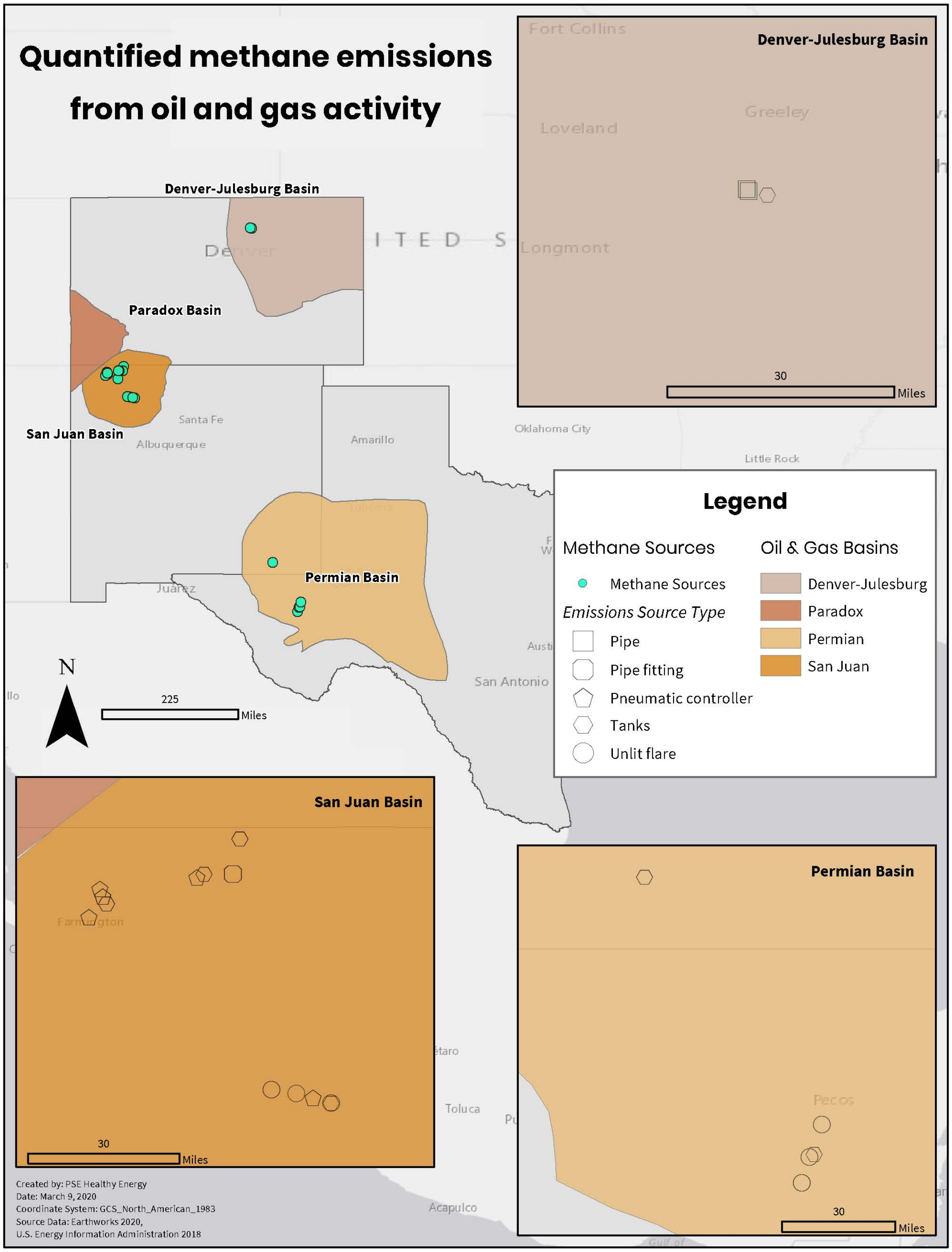

Table 3. Number of methane emission measurements collected by Earthworks using QOGI technology by source category and by basin.

	Oil and Gas Basin			
Source category	**Denver-Julesburg**	**San Juan**	**Permian**	**Total**
Pipes	5	0	0	**5**
Pipe fittings	0	4	0	**4**
Pneumatic controllers	0	11	0	**11**
Tanks	1	9	8	**18**
Unlit flares	0	4	12	**16**
Vents	2	0	0	**2**
Total	**8**	**28**	**20**	**56**

In Table 4, we show the methane emission source categories located at the select oil and gas sites in the SJB, DJB, and Permian Basins for which Earthworks quantified methane emissions using QOGI technology. Data sources used to compare and contextualize methane emission rates associated with each Earthworks source category are also shown in Table 4. We used four data sources that reported equipment-level methane emission measurements or estimates for the three select basins; one based on field sampling (Pacsi et al., 2019), one using reported emissions from U.S. EPA GHGRP (Alvarez et al. 2018), one that relied on Monte Carlo simulation (Skone et al. 2016), and lastly, U.S. EPA GHGRP data directly extracted from the Envirofacts platform.

Table 4. Equipment types that Earthworks quantified methane emissions using QOGI technology.

Earthworks Source Category	Earthworks Site Type	Description	Comparative source(s)
Unlit Flare	Oil and Gas Well; Oil Well	Direct flare emission.	Alvarez et al. (2018)[a] - Associated Gas Venting.
Pipe	Oil and Gas Well; Metering Station	Generally, pipes on well heads.	Broad category; not included in comparative analysis due to lack of specificity.
Pipe Fitting	Oil and Gas Well	Leaks from a pipe fitting (not a valve or other controlling equipment).	Comparative Analysis with methane estimates at Wellsite, Well Production and Central Production sites by: 1) Pacsi et al. (2019) – Compressor Connector; Heat Treater Connector; Wellhead Connector; Meters/Piping Connector; 2) Pacsi et al. (2019)– Separator Connectors; Separator Flange; 3) Skone et al. (2016).
Pneumatic Controller	Gas Well; Well (General)	Depending on the site configuration, a pneumatic controller is defined to be associated with 3/8 inch (roughly) stainless steel/aluminum lines leading to a piece of equipment. Sometimes the ends of these lines emit directly whereas some sites emit from a control box with the 3/8 lines leading to the box.	Comparative Analysis with methane estimates at Wellsite, Well Production and Central Production sites by: 1) Pacsi et al. (2019)– Compressor Regulator; Compressor Valves; Compressor open-ended lines (OELs); Meters/Piping Valves; Meters/Piping Regulator; Wellhead OELs/ Wellhead Valves; Heater Treater Valves; Heater Treater Regulator; Heater Treater OELs; Other OELs; 2) Pacsi et al. (2019)– Separator Regulator; Separator Valves; Separator OELs; Separator Other; 3) Skone et al. (2016).

Earthworks Source Category	Earthworks Site Type	Description	Comparative source(s)
Tanks	Oil and Gas Well; Gas Well; Oil Well; Well (General); Gas Storage Facility; Compressor Station	All types of tanks, including crude oil, condensate tanks, hydrocarbon tanks, and produced water tanks. Recorded images by Earthworks were reviewed and tank labels were considered and used in source type identification when possible.	Comparative Analysis with methane estimates by: 1) GHGRP - Atmospheric Storage Tanks; 2) GHGRP - Production Storage Tanks; 3) Alvarez et al. (2018) - [Production Storage][b] Tanks.
Vent	Gas Storage Tanks	Any vent, sometimes a stand-alone stack, excluding vents from tanks.	Broad category; not included in comparative analysis due to lack of specificity.
Separator	Well (General)	Review of OGI records in this category show pneumatic controllers on separator equipment to be the source of methane leakage.	This Earthworks' category was merged under "Pneumatic Controller".

[a] Data retrieved from GHGRP (2015-2018) and Alvarez et al. (2018) stem from EPA's GHG Reporting Program (GHGRP).

[b] Reported values by Alvarez et al. (2018) for the equipment category of "Tanks" were compared to data from GHGRP 2015. The values matched with the "Production Storage Tanks" category from GHGRP 2015.

To contextualize Earthworks' observed equipment-level methane emissions, we compare Earthworks' measurements to estimates and direct methane measurements reported in the literature and emissions inventories. Table 5 summarizes hourly equipment-level methane emission rates associated with sources in the select basins that allowed for comparison (pipe fittings, pneumatic controllers, tanks, and unlit flares). Mean, median, minimum, and maximum values are shown separately for Earthworks' observed methane emission rates and for estimates and measurements reported in the literature and emissions inventories. Ranges of methane emission rates by equipment and by basin over time are also depicted in Figure 4.

Methane emissions data retrieved from GHGRP (2015-2018) for different sources categorized under 'onshore petroleum and natural gas production' often included zero (0) values. Upon seeking further clarification, a zero in a data table indicates that the operator reported a zero for that data variable.[6] However, Earthworks only reported methane emissions from the components and equipment where methane leakage actually occurred and data do not include the full list of all potential equipment/components. Therefore, in order to appropriately compare values across these datasets, we excluded reported zero values in GHGRP when calculating summary statistics (mean, median, minimum, and maximum) (see Table 5). This approach effectively leads us to compare methane emission rates when they occur across equipment types (Figure 4). Equipment-level methane emission estimates and summary statistics including zero values are presented in Table A-.

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[6] Personal communication with GHGRP help desk on February 13, 2020.

Table 5. Equipment-level methane emission rates collected by Earthworks or reported in the literature and/or emissions inventories. Emission rates are shown in lbs/hr and organized by basin and by year.

	EARTHWORKS			LITERATURE / EMISSIONS INVENTORY			
SOURCE CATEGORY (Year)	**ER[1] Mean (Min – Max)**	**ER Median**	**Sample Count**	**ER Mean (Min – Max)[2]**	**ER Median**	**Sample Count**	**Reference(s)**
DENVER-JULESBURG BASIN (DJB)							
Pipe Fitting	-	-	-	-	-	-	-
Pneumatic Controller	-	-	-	-	-	-	-
Tank							
2015	-	-	-	8 (0.003 – 42)	4	31	GHGRP; Alvarez et al. (2018)
2016	-	-	-	11 (0.03 – 28)	8	14	GHGRP
2017	-	-	-	13 (0.02 – 68)	6	16	GHGRP
2018	-	-	-	9 (0.07 – 37)	3	18	GHGRP
2019	21[3]	-	1	-	-	-	-
Unlit Flare							
-	-	-	-	-	-	-	-
SAN JUAN BASIN (SJB)							
Pipe Fitting							
2015	-	-	-	0.21 (0.0005 – 2)	0.02	36[4]	Pacsi et al. (2019)
2018	10 (7 – 13)	11	4	-	-	-	-
Pneumatic Controller							
2015	-	-	-	0.24 (0.00025 – 1)	0.02	9[4]	Pacsi et al. (2019)
2019	2 (0.20 – 4)	2	11	-	-	-	-
Tank							
2015	-	-	-	48 (0.18 – 459)	9	27	GHGRP; Alvarez et al. (2018)
2016	-	-	-	68 (5 – 459)	17	12	GHGRP
2017	-	-	-	88 (0.19 – 813)	12	12	GHGRP

	EARTHWORKS			LITERATURE / EMISSIONS INVENTORY			
SOURCE CATEGORY (Year)	**ER[1] Mean (Min – Max)**	**ER Median**	**Sample Count**	**ER Mean (Min – Max)[2]**	**ER Median**	**Sample Count**	**Reference(s)**
2018	1 (0.02 – 3)	1	4	168 (7 – 1070)	21	9	GHGRP
2019	26 (1 – 92)	9	5	-	-	-	-
Unlit Flare							
2015	-	-	-	32 (3 – 68)	26	3	Alvarez et al. (2018)
2019	50 (12 – 120)	33	4	-	-	-	-
PERMIAN BASIN							
Pipe Fitting							
2012	-	-	-	0.0007 (0.0005 – 0.0009)	0.0007	2 [4]	Skone et al. (2016)
2015	-	-	-	0.05 (0.001 – 1)	0.01	21 [4]	Pacsi et al. (2019)
Pneumatic Controller							
2012	-	-	-	0.007 (0.005 – 0.01)	0.007	2 [4]	Skone et al. (2016)
2015	-	-	-	0.14 (0.001 – 1)	0.01	25 [4]	Pacsi et al. (2019)
Tank							
2015	-	-	-	84 (0.01 – 2119)	13	103	GHGRP; Alvarez et al. (2018)
2016	-	-	-	132 (0.02 – 2887)	18	62	GHGRP
2017	-	-	-	96 (0.01 – 1878)	21	62	GHGRP
2018	30 (8 – 52)	30	8	123 (0.01 – 4613)	15	68	GHGRP
Unlit Flare							
2015	-	-	-	67 (1 – 291)	58	13	Alvarez et al. (2018)
2018	82 (39 – 151)	73	12	-	-	-	-

[1] ER: Emissions rate in pounds per hour (lbs/hr).

[2] Numbers smaller than 0.5 were not rounded to the appropriate number of significant digits in order to be distinguished from zero (i.e 0.0). Such numbers included mainly minimum values, but also average and maximum values presented for pipe fittings and pneumatic controllers in the SJB and Permian Basin.

[3] Single value was recorded by Earthworks using QOGI technology.

[4] To standardize this table by unit, emission rates reported in the literature by volumetric flow rate (scf/hr) were converted to mass flow rate (lbs/hr) using pure methane density (0.0418 lb/ft^3) at standard temperature and pressure (60˚F and 14.7 PSI).

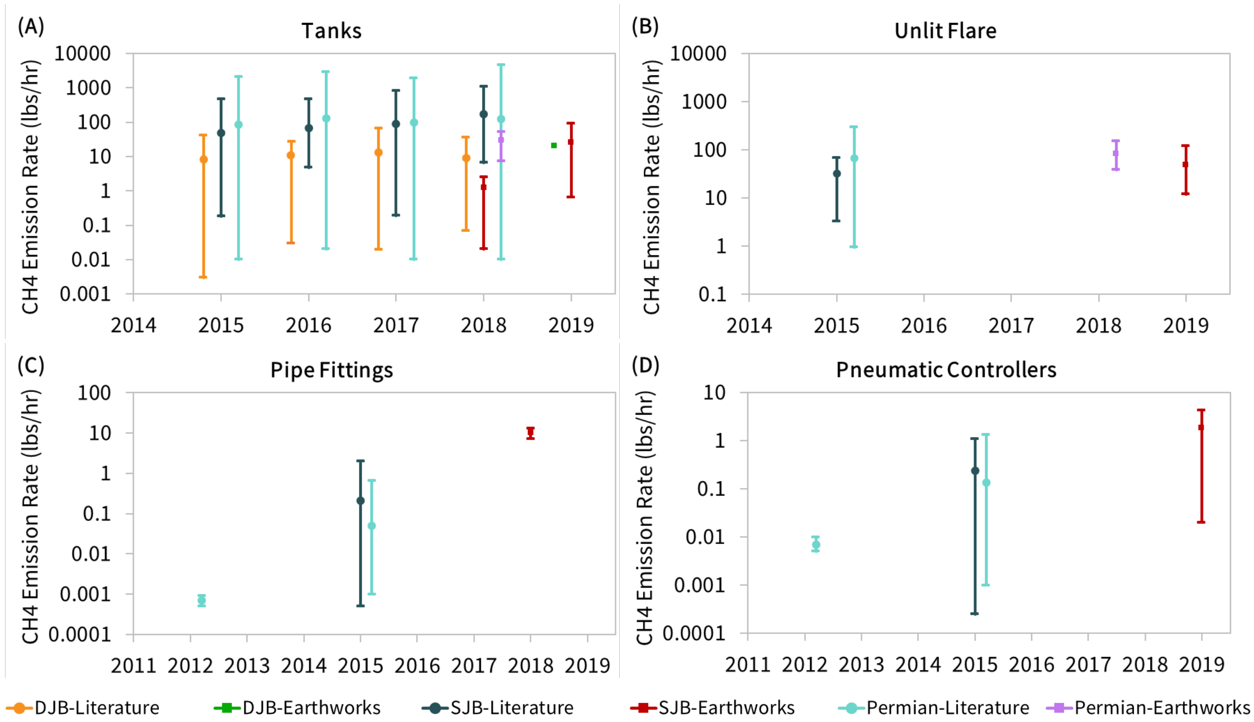

Figure 4. Methane emission rates recorded by Earthworks or reported in the literature and/or emissions inventories for various equipment and component sources. **(A)** Tanks, top left; **(B)** Unlit flares, top right; **(C)** Pipe fittings, bottom left; **(D)** Pneumatic controllers, bottom right.

Table 5 and Figure 4 show that methane emission measurements collected by Earthworks in the DJB and Permian Basin fall within the range of values observed in the literature for these basins. Overall, the data do not demonstrate constant increase in methane emissions from each equipment type in the three basins over time, which could be related to different production activities being responsible for the methane emissions at different times and the overall representativeness of available estimates. However, combined methane emission rates from all types of equipment (tanks, unlit flares, pipe fittings and pneumatic controllers) in each basin show an increasing trend over the depicted time. In the Permian Basin, Earthworks collected methane measurements for tanks and unlit flares. Methane emission rates measured from tanks in this basin are lower than average estimates and measurements included in the literature for the same year (2018), as well as years prior (Figure 4-A). Earthworks' methane emissions measurements from unlit flares in the Permian Basin in 2018 (39 – 151 lbs/hr) fall within the range of reported values in the literature for a prior year (2015) (1 - 291 lbs/hr)(Figure 4-B). Notably, Earthworks' maximum recorded methane emissions rate from an unlit flare in the Permian Basin (151 lbs/hr) is approximately half the value of reported maximum for unlit flares in literature and emission inventories (Table 5).

In the DJB, there is only a single comparable measurement collected by Earthworks from a tank in 2019. However, estimates of methane emission rates from tanks in the literature are provided for 2018 and the years prior. Earthworks' single comparable measurement (21 lbs/hr, tank) was higher than all average values but lower than the maximum values reported for tanks across all years in the literature and emissions inventories (28 - 68 lbs/hr) (Table 5; Figure 4-A).

In the SJB, methane emission rates for comparable sources are not available in the literature during the same year of data collection, except for tanks (Table 5). Earthworks methane emissions measurements from tanks in this basin in 2018 are lower (mean, minimum and maximum are 1, 0.02 and 3 lbs/hr, respectively) than the minimum emission rate reported in the literature for the same year (7 lbs/hr) (Figure 4-A). In SJB, Earthworks measurements from tanks in 2019 fall within the range of emission rates presented in the literature for 2018. However, similar to the case of tanks in the Permian Basin, Earthworks' tank methane emission measurements in both 2018 and 2019 are much lower than the maximum emission rates reported in the literature across all years.

Earthworks methane emission rates measured from unlit flares, pipe fittings, and pneumatic controllers in the SJB are expanded over a wider range of values compared to the reported estimates in the literature (Figure 4-B to Figure 4-D). The mean methane emission rate observed by Earthworks for unlit flares in 2019 in the SJB (50 lbs/hr) exceeds the average methane emission rate for unlit flares in 2015 (32 lbs/hr) in the same basin, but falls within the range of methane emission rates observed in the literature in 2015 (3 - 68 lbs/hr) (Figure 4-B). For pipe fittings and pneumatic controllers, comparable methane emission measurements in the literature were only available in the SJB (Figure 4-C and Figure 4-D, respectively). Earthworks detected higher average methane emission rates from these sources, but with a wider range of values as compared to a study using OGI technology for leakage detection and high flow samplers for quantification of methane leakage (Pacsi et al., 2019).

5.0 Discussion

This report contributes to the current research on methane leakage associated with oil and gas development by comparing equipment-level emission rates in the Denver Julesburg, San Juan and Permian Basins, measured using QOGI technology, with methane emission measurements and estimates published in the peer-reviewed literature and emissions inventories. Additionally, this assessment also evaluates trends of crude oil and natural gas production and basin-level methane emission estimates in the select basins in recent years. The QOGI sampling conducted by Earthworks provides additional methane emission measurements to improve understanding about methane leakage associated with oil and gas development and to help to inform efforts aimed to reduce methane emissions from the oil and gas sector to realize climate and air quality benefits.

The majority of methane emission measurements collected by Earthworks fell within the range of methane emission estimates provided in the literature and emissions inventories for corresponding sources in the select basins. Earthworks' methane emission measurements from tanks were lower than average values reported from tanks in the SJB and in the Permian Basin, but higher than average values reported from tanks in the DJB. Methane emission rates from unlit flares detected by Earthworks also fell within the ranges presented in the literature. Earthworks' average methane emission rates detected from unlit flares were above the average of values available in the literature in both the SJB and Permian Basin. In the SJB, Earthworks' maximum detected emissions from unlit flares exceeded the maximum value reported in the literature for this basin. However, the maximum methane emission rate associated with unlit flares in the Permian Basin was far less (approximately half of) the maximum value reported in the literature and emissions inventories in the Permian Basin, indicating that in certain cases Earthworks' measurements may underestimate methane emission rates from certain sources, such as unlit flares in this particular basin. Earthworks' methane emission rates for pipe fittings and pneumatic controllers in the SJB were expanded over a wider range of values as compared to the reported estimates in the literature, often exceeding the maximum emission rate reported from these sources in the literature.

Studies of combined equipment-level methane emissions associated with oil and natural gas activities in the DJB, SJB, and Permian Basin indicated generally increasing trends over time (Alvarez et al., 2018; U.S. EPA, 2020b). Though sources included in the Earthworks dataset that allowed for comparison (i.e., tanks, unlit flares, pipe fittings, pneumatic controllers) do not represent all potential sources of methane emissions in the basins of interest, the cumulative methane emissions from these equipment sources demonstrate increases between 2012 and 2019 (except from 2017-2018 in DJB and from 2016-2017 in the Permian Basin). While previous studies have observed a positive correlation between oil and natural gas production and methane emissions (Brantley et al., 2014; Lyon, et al., 2016; Omara et al., 2016; Robertson et al., 2017), a causal relationship cannot be directly determined from the high-level analysis in this report. However, assuming a positive and potentially proportional relationship between methane emissions and oil and natural gas production, future projections of production in the SJB, DJB and Permian Basin imply that methane emissions from these basins are anticipated to remain a matter of climate concern. According to the EIA (Annual Energy Outlook 2020, reference case[7]), domestic production of crude oil throughout the U.S. is predicted to increase from 2019 levels by 12.5% in 2022 (mainly from the Permian Basin), continuing at a relatively constant rate until the mid 2030s, followed by a slow decline (AEO2020, 2020). Additionally, oil production is projected to increase in the Rocky Mountains region (which includes the DJB and SJB) until 2050 (AEO2020, 2020). Domestic natural gas production is projected to increase until 2050, due to the growth in natural gas production from shale gas and tight oil plays, primarily including plays in the Permian Basin (AEO2020, 2020).

In the absence of effective regulations and strategies, the continued increase in oil and natural gas production over the next decades in these select basins could result in an increase in methane emissions. Also, such increases in oil and gas production may lead to overuse of equipment and as components become worn-out, may further intensify methane leakage associated with oil and gas infrastructure (Omara et al., 2016). Therefore, there is a continued need for preventive actions to detect and resolve potential methane leakage associated with malfunctioning equipment.

5.1 Limitations

Our assessment faced several limitations associated with the Earthworks' methane emissions dataset, additional data sources in the peer-reviewed literature and government reports and databases, and the process of comparing various methane emission measurements and other data sources related to upstream oil and gas activities and equipment. These limitations are discussed in detail below.

Limited data availability and uncertain representativeness of methane measurements and estimates

As discussed previously in this report, Earthworks' relied on methane as the proxy gas for QOGI measurements collected; however, additional gases may comprise the plumes observed during field sampling. Without specific information on gas composition, as was provided to Pacsi et al. (2019) by industry, methane serves as the most logical proxy gas to evaluate the oil and gas-related sources for which measurements could be collected.

Additionally, while understandable with respect to time, resources, and restrictions on proximity and despite including different site types in field sampling, Earthworks collected few data points (56 in total) for different equipment and component types in the three select

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[7] The AEO2020 Reference case represents EIA's best assessment of U.S. and world energy markets through 2050, assuming that current laws and regulations that affect the energy sector are unchanged throughout the projection period (AEO2020, 2020).

basins, especially in the DJB. The 56 samples collected by Earthworks included 5 samples from pipes, 2 samples from vents, 4 samples from pipe fittings, 18 samples from tanks, 11 samples from pneumatic controllers and 16 samples from unlit flares. In the DJB, only 8 samples were collected (5 samples from pipes, 2 samples from vents, and one sample from tanks). Seven samples (from pipes and vents in the DJB) collected by Earthworks were excluded from our comparative analysis, as these source categories were too broad to compare to methane emission estimates and measurements in the literature and emissions inventories.

Additionally, these samples represent measurements over a very limited time frame (e.g., several runs lasting a few minutes each). While such estimates provide a snapshot of hourly leakage rates from different components, methane emission contributions may vary greatly over time and estimates of longer-term trends (e.g., annual methane emissions) crucially rely on continuous measurements of emissions or at least estimates considering different activity factors for each known source of methane leakage. For example, it is possible that Earthworks filmed intense emission releases (e.g., from unlit flares) that if continuously emitted with the same intensity and left unaddressed would have a large cumulative impact over time; however, it is also possible that such releases were intermittent, or that they ceased or were reduced and then occurred again or increased in intensity at a later point in time.

As described above, Earthworks' QOGI work categorizes a limited number of emissions source types associated with oil and natural gas development and this report considered Earthworks' data for just three oil and gas basins (SJB, DJB and Permian Basin). This restricted our evaluation to a narrow area of research with limited relevant peer-reviewed publications. Overall, the compatibility of the scope of our assessment and geographic areas under study limited the number of relevant studies available that could reliably contextualize Earthworks' methane emission measurements.

Furthermore, Earthworks recorded methane emissions in the select basins in 2018 and 2019 however, data from the literature are primarily based on measurements or reported estimated values to GHGRP for the years before 2018. Therefore, the majority of the data published in the literature to compare with the Earthworks measurements are temporally discordant. It is difficult to know the degree to which this temporal discordance may be relevant while presenting methane emissions estimates; therefore, we chose to show and summarize methane emission estimates by year and compare estimates across years.

The published studies identified for comparison with the Earthworks QOGI measurements had their own limitations in methodology and data quality. Alvarez et al. (2018), GHGRP and Skone et al. (2016) used operators' self-reported data to the U.S. EPA. However, U.S. EPA allows reporting entities to use different methods to calculate GHG emissions from emission sources and adopt different approaches (direct measurements, previous analyses, software programs, and methods published by a consensus-based standards organization) to determine the inputs of these calculation methods. Under GHGRP, operators can use algorithms and software programs to model leakage, and use annual average values for different parameters (e.g., operating conditions, flow rate and production stream composition). These variabilities could result in under- or over-estimation of methane emissions from associated sources.

Pacsi et al. (2019), which included emissions sampling during specific time periods at oil and gas sites using source categories compatible with the Earthworks dataset, was also limited by a small overall sample size (36 measurements for pipe fittings and 9 measurements for pneumatic controllers). Pacsi et al. (2019) collected measurements at only 9 sites in the Permian Basin and 11 sites in SJB, which may not represent the full range of methane leakage in these basins. While Earthworks' employed a quantification method using QOGI technology and did not have gas composition information, Pacsi et al. (2019) relied on high-volume samplers and had access to site-specific gas composition data provided by the participant companies or the average gas composition from other gas production sites in the same basin.

None of the studies included in this report that collected methane measurements provided information about overall site selection and sampling procedures, and therefore, representativeness of selected sites in these basins is another source of uncertainty. Use of simulation methods such as Monte Carlo (Skone et al., 2016) helped produce uncertainty ranges to represent a likely distribution of emissions. However, this simulation method involved assumptions regarding probability distributions of parameters in the natural gas model due to limited data points (including data from bottom up emissions inventory and self-reported GHG emission data, and top-down data collected by NOAA's satellite sensors and the World Bank-led Global Gas Flaring Reduction Partnership) to represent better informed distributions, and these assumptions introduced other uncertainties into final estimates.

Defining and comparing emission source categories

In this report, we extracted methane measurements and estimates from numerous data sources, each of which used different criteria and methods to estimate and categorize their data. It is important to acknowledge the differences in definitions and criteria when analyzing these data to contextualize Earthworks' QOGI data, because these additional data sources ultimately dictate the range of emission estimates for specific equipment or components evaluated in this report. Sources of methane emissions evaluated by Earthworks were not clearly defined. To address this limitation, we merged and matched source categories based on the available information regarding sources of emissions, QOGI records (e.g., field sampling notes and video footage), and available definitions of categories in literature and the Code of Federal Regulations.

Certain categories are not clearly captured in the literature or standardized emissions inventory reporting, particularly regarding gas that is directly vented to the ambient air. Earthworks' source category 'unlit flare' includes uncombusted gas (primarily methane) directly vented to the ambient air from flare stacks. However, the GHGRP combines emissions from combusted flare, unlit flare and vented gas — all of which may emit very different quantities of methane and at varying rates — into a single reporting category. If not captured explicitly in emissions inventories, methane emissions associated with venting — that likely release larger proportions of methane as compared to flaring activities — may be underestimated both in emissions inventories and the peer-reviewed literature, as well as the Earthworks' dataset.

While we were able to discern additional details about field sampling approaches from Earthworks' staff and from viewing recorded QOGI video footage, key challenges during sampling contributed additional uncertainty about methane emissions attributable to a specific equipment or component source to allow for comparison. For example, lack of site access and thus proximity limitations rendered it difficult for Earthworks staff to capture plumes clearly attributable to a particular component or equipment source. Additionally, the QOGI tool is limited in its ability to register large and intense emission plumes. Further consideration of commonly defined methane emission source categories in the literature and emissions inventories prior to and during field sampling can further inform and improve the quality of comparisons in future assessments.

Comparing estimates from top-down and bottom-up methane estimation methodologies

Many studies discussed the underestimation of methane emissions from oil and natural gas sources from evaluation of bottom-up inventories (Hmiel et al., 2020; Marchese et al., 2015; Petron et al., 2012; Petron et al., 2014; Willyard and Schade, 2019). For regulatory purposes and from a climate perspective, it is important to account for all related sources of methane leakage associated with oil and gas activities. However, the U.S. EPA only requires facilities with total annual GHG emissions greater than 25,000 metric tons CO_2-equivalent to report their emissions under GHGRP. This introduces a level of uncertainty regarding the accuracy of emissions estimates reported by U.S. EPA (Barkley et al. 2019). Part of these uncertainties could be attributable to thousands of sources not included in the self-reported GHG emissions under either the matched source categories evaluated in this report or other categories (relevant to basin-level emissions discussion) (Barkley et al., 2019; Brandt et al., 2014; 40 C.F.R. §98, 2010).

Additionally, the U.S. EPA defines a “facility” as including all wells owned or operated by a single company in a specific hydrocarbon producing basin to serve as a practical and cost-effective definition (40 C.F.R. §98, 2010). Therefore, the ranges of values from GHGRP include cumulative values of methane emissions from different sources of any facility with multiple site locations in a basin which were below the threshold in total emissions. As such, the ranges of emissions from GHGRP are not comprehensive due to the probable exclusion of lower and higher levels of emissions from corresponding sources in excluded facilities. However, emissions recorded by Earthworks in any of the select basins do not capture the full range of reported emissions in literature, which is also likely the case for GHGRP reporting, considering EPA’s definition and reporting criteria for a “facility”.

EPA allows for different methods and approaches to calculate GHG emissions from emission sources which could result in under- or over-estimation of methane emissions from associated sources as well, although the literature comparing bottom-up to top-down emission estimations suggests that that bottom-up emissions reporting is likely under-estimated. The systematic underestimation of emissions reported in inventories is also attributable to limited sampling methods and measurements, which fail to capture high emissions in case of malfunctions (Alvarez et al., 2018). Therefore, a proportion of the differences between the emission estimates published in the literature and the *in-situ* measurements collected by Earthworks could be attributable to these variabilities.

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Appendix A - Supplementary Tables

Table A-1. Basin-level rate of methane emissions derived from literature for DJB, SJB and Permian Basin.

Reference	Emission Rate (lbs/hr)	Emission Rate (% of Production)	Year	Emission Source	Methodology / Approach
DENVER-JULESBURG BASIN (DJB)					
Petron et al. (2012)	29,798	4	2008	Venting.	TD[1]/NOAA Boulder Atmospheric Observatory tower/Mobile Lab (Picarro).
	13,364	1.68	2008	Venting from oil and gas exploration, production and processing.	BU[1]/WRAP Phase III inventory.
Petron et al. (2014)	42,549 ± 15,212 [2]	4.1 ± 1.5 [2]	2012	Oil and gas sources.	TD/Aircraft observation.
Peischl et al. (2018)	39,683 ± 17,637 [2]	2.1 ± 0.9 [2]	2015	Oil and natural gas production operations emit natural gas to the atmosphere both as a result of routine operations, such as through venting and the use of pneumatic controls, and unintentionally, via leaks and other fugitive emissions.	TD/NOAA WP-3D (P-3) aircraft/Picarro.
Omara et al. (2018)	81,571 (52,911 - 108,026) [3]	2.8 [4]	2015	Routine operations (e.g., equipment leaks, venting from pneumatic controllers and storage tanks) or were unplanned (e.g., unintended emissions from malfunctioning equipment). Not including methane emissions from completion flowback or liquids unloading, storage or coalbed methane well sites.	BU/TF[1], OTM[1] 33A, MM-Gaussian. BU (predicted): (i) a robust regression model, and (ii) a nonparametric model.

Reference	Emission Rate (lbs/hr)	Emission Rate (% of Production)	Year	Emission Source	Methodology / Approach
SAN JUAN BASIN (SJB)					
Omara et al. (2018)	68,343 (44,092 - 90,389) [3]	4.5 [4]	2015	Routine operations (e.g., equipment leaks, venting from pneumatic controllers and storage tanks) or were unplanned (e.g., unintended emissions from malfunctioning equipment). Not including methane emissions from completion flowback or liquids unloading, storage or coalbed methane well sites.	BU/TF, OTM 33A, MM-Gaussian. BU (predicted): (i) a robust regression model, and (ii) a nonparametric model.
PERMIAN BASIN					
Omara et al. (2018)	242,508 (147,710 - 330,693) [3]	2.5 [4]	2015	Routine operations (e.g., equipment leaks, venting from pneumatic controllers and storage tanks) or were unplanned (e.g., unintended emissions from malfunctioning equipment). Not including methane emissions from completion flowback or liquids unloading, storage or coalbed methane well sites.	BU/TF, OTM 33A, MM-Gaussian. BU (predicted): (i) a robust regression model, and (ii) a nonparametric model.

[1] Abbreviations: TD: top-down; BU: bottom-up; TF: Tracer Flux; OTM: [EPA's] Other Test Method.

[2] Reported values are mean ± uncertainty (defined as the 1-standard deviation confidence interval)

[3] Values are mean (minimum - maximum), respectively.

[4] Reported value pertains to the mean emission rate listed in the second column.

Table A-2. Equipment-level methane emission rates collected by Earthworks or reported in the literature and/or emissions inventories. Emission rates are shown in lbs/hr and organized by basin and by year. Summary statistics presented in this table include zero values reported in the literature and/or emissions inventories.

	EARTHWORKS			LITERATURE / EMISSIONS INVENTORY			
SOURCE CATEGORY (Year)	**ER[1] Mean (Min – Max)**	**ER Median**	**Sample Count**	**ER Mean (Min – Max)[2]**	**ER Median[2]**	**Sample Count**	**Reference(s)**
DENVER-JULESBURG BASIN (DJB)							
Pipe Fitting	-	-	-	-	-	-	-
Pneumatic Controller	-	-	-	-	-	-	-
Tank							
2015	-	-	-	7 (0 – 42)	2	31	GHGRP; Alvarez et al. (2018)
2016	-	-	-	9 (0 – 28)	4	14	GHGRP
2017	-	-	-	13 (0.02 – 68)	6	16	GHGRP
2018	-	-	-	9 (0 – 37)	3	18	GHGRP
2019	21[3]	-	1	-	-	-	-
Unlit Flare							
2015	-	-	-	0 (0 - 0)	0	18	Alvarez et al. (2018)
SAN JUAN BASIN (SJB)							
Pipe Fitting							
2015	-	-	-	0.21 (0.0005 – 2)	0.02	36	Pacsi et al. (2019)[4]
2018	10 (7 – 13)	11	4	-	-	-	-
Pneumatic Controller							
2015	-	-	-	0.24 (0.00025 – 1)	0.02	9	Pacsi et al. (2019)[4]
2019	2 (0.20 – 4)	2	11	-	-	-	-
Tank							
2015	-	-	-	45 (0 – 459)	9	27	GHGRP; Alvarez et al. (2018)
2016	-	-	-	63 (0 – 459)	13	12	GHGRP

	EARTHWORKS			LITERATURE / EMISSIONS INVENTORY			
SOURCE CATEGORY (Year)	**ER[1] Mean (Min – Max)**	**ER Median**	**Sample Count**	**ER Mean (Min – Max)[2]**	**ER Median[2]**	**Sample Count**	**Reference(s)**
2017	-	-	-	81 (0 – 813)	11	12	GHGRP
2018	1 (0.02 – 3)	1	4	152 (0 – 1070)	19	9	GHGRP
2019	26 (1 – 92)	9	5	-	-	-	-
Unlit Flare							
2015	-	-	-	7 (0 – 68)	0	13	Alvarez et al. (2018)
2019	50 (12 – 120)	33	4	-	-	-	-
PERMIAN BASIN							
Pipe Fitting							
2012	-	-	-	0.0007 (0.0005 – 0.0009)	0.0007	2	Skone et al. (2016) [4]
2015	-	-	-	0.05 (0.001 – 1)	0.01	21	Pacsi et al. (2019) [4]
Pneumatic Controller							
2012	-	-	-	0.007 (0.005 – 0.01)	0.007	2	Skone et al. (2016) [4]
2015	-	-	-	0.132 (0.00 – 1)	0.009	25	Pacsi et al. (2019) [4]
Tank							
2015	-	-	-	79 (0 – 2119)	12	103	GHGRP; Alvarez et al. (2018)
2016	-	-	-	128 (0 – 2887)	17	62	GHGRP
2017	-	-	-	96 (0.01 – 1878)	21	62	GHGRP
2018	30 (8 – 52)	30	8	123 (0.01 – 4613)	15	68	GHGRP
Unlit Flare							
2015	-	-	-	16 (0 – 291)	0	53	Alvarez et al. (2018)
2018	82 (39 – 151)	73	12	-	-	-	-

[1] ER: Emissions rate in pounds per hour (lbs/hr).

[2] Numbers smaller than 0.5 were not rounded to the appropriate number of significant digits in order to be distinguished from zero (i.e 0.0). Such numbers included mainly minimum values, but also average and maximum values presented for pipe fittings and pneumatic controllers in the SJB and Permian Basin.

[3] Single value was recorded by Earthworks using QOGI technology.

[4] To standardize this table by unit, emission rates reported in the literature by volumetric flow rate (scf/hr) were converted to mass flow rate (lbs/hr) using pure methane density (0.0418 lb/ft^3) at standard temperature and pressure (60˚F and 14.7 PSI).