COMMENTARY
HEI Energy Review Committee

HEI

Research Report 231, *Assessing Source Contributions to Air Quality and Noise in Unconventional Oil Shale Plays*, M. Franklin et al.

INTRODUCTION

The scale and rate of onshore oil and natural gas development in the United States since the early 2000s differ markedly from earlier periods due to technological changes involving increased use of hydraulic fracturing and horizontal drilling. Although hydraulic fracturing has captured much public attention, the process itself is not new. Neither is horizontal drilling, the extraction of oil and gas from unconventional formations such as tight (i.e., low permeability) sandstone and shale. What is new is the use of high-volume multistage hydraulic fracturing that uses millions of gallons of water per well, combined with horizontal drilling that can extend thousands of m in length.

Unconventional oil and natural gas development (UOGD*), the development and production of oil and natural gas through multistage hydraulic fracturing in horizontal wells, has been associated with a wide range of potential exposures to chemicals (e.g., radioactive material, those found in the wastewater, and odorous compounds) and nonchemical agents (e.g., noise, light, and vibration). The rapid expansion of this development has caused concerns about its potential effects on human health and has created knowledge gaps about exposures that must be addressed to better understand potential impacts on health.

In August 2020, HEI Energy issued Request for Applications *E20-1*, Community Exposures Associated with Unconventional Oil and Natural Gas Development. HEI sought to fund studies that would apply a combination of approaches to quantify the spatial and temporal variability in population exposures to UOGD-generated outdoor air pollutants and noise (see Preface).

Dr. Franklin at the University of Southern California† and colleagues proposed to address critical research needs by improving the spatial and temporal characterization of UOGD-related air pollution, radioactivity, and noise in oil-producing regions via stationary, passive, and satellite monitoring, along with modeling that could be leveraged to ultimately assess human health exposures. The HEI Energy Research Committee recommended the study for funding because it had several strong features. In particular, the blending of a variety of sampling methods using state-of-the-art instruments would result in a robust dataset with information on the variability of ambient chemical concentrations over space and time. Moreover, the data could be used in future health studies. Franklin had assembled a strong team with demonstrated air quality measurement expertise and connections to communities in the study areas.

This Commentary provides the HEI Energy Review Committee's evaluation of the study. It is intended to aid the sponsors of HEI and the public by highlighting the study's strengths and limitations and placing the results presented in the Investigators' Report in a broader scientific and regulatory context.

SCIENTIFIC AND REGULATORY BACKGROUND

UOGD OVERVIEW

UOGD processes occur on and off the well pad and include

- **field development:** exploration, pad preparation, vertical and horizontal drilling, well completion (casing and cementing, perforating, acidizing, hydraulic fracturing, flowback [the fluid mixture of injected water, sand, and chemicals and the natural brines from rock that returns to the surface after a well has been hydraulically fractured], and well testing) in preparation for production and management of wastes
- **production operations:** extraction, gathering, processing, and field compression of gas; extraction and processing of oil and natural gas condensates (byproducts of gas production that include organic compounds that condense from a gas phase into a liquid form); management of wastes and produced water that is naturally present in underground water formations in the soil and brought to the surface during oil and gas extraction; and construction and operation of field production facilities
- **postproduction:** well closure and land reclamation.

Some UOGD operations are regulated at the federal level under the Clean Air Act, the Clean Water Act, and the Safe Drinking Water Act, while state authorities play a major role

Dr. Meredith Franklin's 2-year study, "Assessing Source Contributions to Air Quality and Noise in Unconventional Oil Shale Plays," began in February 2022. Total expenditures were $1,203,523. The draft Investigators' Report from Franklin and colleagues was received for review in February 2025 and accepted by the HEI Energy Review Committee in April 2025.

During the review process, the HEI Energy Review Committee and the investigators had the opportunity to exchange comments and clarify issues in both the Investigators' Report and the Review Committee's Commentary. This Commentary has not been reviewed by public or private party institutions, including those that support HEI Energy, and may not reflect the views of these parties; thus, no endorsements by them should be inferred.

* A list of abbreviations and other terms appears at the end of this report.

† Dr. Franklin is now based at the University of Toronto.

in governing UOGD more generally. UOGD-related rules vary among states, with some defining minimum setback distances between UOGD and specific land uses such as residences and schools to protect local populations.

UOGD PROCESSES

Different UOGD processes release air pollutants, noise, and light into the environment (e.g., outdoor air, soil, surface water, and groundwater) that are complex and highly variable. These releases and resulting human exposures are caused by numerous UOGD process-related factors, including variation in operator practices and regulatory requirements. Releases can also happen due to accidental spills and leaks. The level of UOGD activity can vary widely between and across regions and over time in response to fluctuating market conditions.

The well pad preparation phase involves land clearing and other activities similar to many other types of construction. Various chemicals are used to drill, develop, and complete the well. The completion step often includes the process of hydraulic fracturing. Following hydraulic fracturing, pressure is released and the injected fluids, along with natural brines in the source rock, flowback to the surface during a period referred to as flow or flowback (Guarnone et al. 2012). Once a well is completed, it enters the production phase during which fluids continue to flowback to the surface, with the composition of the fluids increasingly dominated by natural brines over time. This fluid is commonly referred to as produced water and must be managed properly along with flowback, drilling muds, and other wastes.

During the development of a well or production, exposures can be associated with vehicle exhaust and emissions from various types of equipment (e.g., compressors).

UOGD EMISSIONS AND TRANSPORT PATHWAYS

UOGD processes can release methane, volatile organic compounds (VOCs), and other pollutants of concern to human health. UOGD emissions to air can occur on or off well pads and originate from equipment and other points and mobile sources, or releases (e.g., leaks, venting from storage tanks, or volatilization from surface spills). The unloading of liquids can be an important source of emissions; this process involves clearing liquids (i.e., water and liquid hydrocarbons) that have accumulated in mature gas wells and that can slow or even halt gas production. Flaring of natural gas is a major source of emissions in some oil-producing regions where gas is produced along with oil, but insufficient infrastructure is available to transport and sell the gas. For this and other reasons (e.g., safety), natural gas is sometimes burned on-site (i.e., flared).

Chemicals that have been released into the environment then disperse and can react in the atmosphere, leading to widely varying concentrations and potential exposures at local and regional scales (Allen 2014; Bell et al. 2017; Mitchell et al. 2015; Vaughn et al. 2018; Zavala-Araiza et al. 2015). A few studies have used air quality monitoring data or modeling to address regulatory needs, such as assessing setback distances between UOGD and residences (Banan and Gernand 2018; Garcia-Gonzales et al. 2019; Haley et al. 2016; McCawley 2013).

UOGD EXPOSURE

A growing body of scientific literature exists about potential human exposures to a range of chemical and nonchemical agents (e.g., noise, light, and vibration) that can be associated with UOGD (Deziel et al. 2022; HEI Energy Research Committee 2019, 2020). While many of these studies provide valuable information for understanding population exposures, only a small group of studies have been conducted with the direct aim of estimating potential air pollution and noise exposures to UOGD (Allshouse et al. 2019; Maskrey et al. 2016; Paulik et al. 2018; Pennsylvania Department of Environmental Protection 2018). Knowledge gaps remain, however, about how these exposures potentially impact human health.

STUDY OBJECTIVES

The overarching objective of Dr. Franklin's study was to characterize air pollutants, greenhouse gas emissions, airborne radioactivity, and noise associated with UOGD in two shale production basins, the Permian Basin (eastern New Mexico and western Texas) and the Eagle Ford Shale (south-central Texas). These two production basins are among the most active drilling and oil production regions in the United States. Collectively, they have over 180,000 active wells that produce approximately 7 million barrels of oil and over 30 billion cubic feet of gas daily (*US Energy Information Administration*).

The investigators developed the following three aims:

1. Characterize the effect of UOGD activities on ambient air pollution, radioactivity, and noise by collecting high temporal resolution data from a stationary monitoring platform in the Permian Basin
2. Understand the spatial distributions of selected petroleum hydrocarbons in ambient air by leveraging a dense network of passive samplers in the Permian Basin and Eagle Ford Shale
3. Combine satellite observations with surface air pollution data to characterize the location and magnitude of flaring and its impact on air quality and radioactivity in the Permian Basin

To address Aim 1, Franklin and colleagues conducted sampling campaigns at a field laboratory located near an active UOGD well pad in the shale production field and at various locations in populated areas close to UOGD activities. At the field laboratory, they used a combination of continuous fixed-site monitoring instruments to identify UOGD processes that resulted in ambient air pollution, radioactivity, and noise. This laboratory was operational in an area of active UOGD activity in the Permian Basin from May 1, 2023, to May 31, 2024. They measured approximately 30 different components, including 20 VOCs. They also compared their observations with measurements collected at other UOGD sites and in urban areas.

To address Aim 2, the investigators recruited local volunteers to deploy passive samplers for approximately 1 year at 12 locations in populated areas in the Permian Basin and Eagle Ford Shale. They coupled the resulting measurements of 15 hydrocarbons with data on meteorology and well density within about 10 kilometers (km) of the samplers to better understand the factors influencing UOGD-related exposures in the area and to inform future health studies.

Aim 3 of the study focused on flaring. This is a common waste disposal practice associated with oil and gas development, but its effect on air quality is not well characterized. To address this question, the investigators used remote sensing observations of heat sources to identify locations and timing of UOGD-related flaring. They combined these observations with the stationary data of flaring emissions to identify exposures related specifically to flaring.

SUMMARY OF METHODS AND STUDY DESIGN

Aim 1: Stationary Monitoring at a Field Laboratory to Characterize the Effect of UOGD Activities on Ambient Air Pollution, Radioactivity, and Noise

Franklin and colleagues obtained a year's worth of detailed data on meteorology, air pollutant concentrations, noise, and radioactivity at a location directly associated with UOGD activity. An oil and gas operator in Loving, New Mexico, permitted the investigators to install a field laboratory on its property. This stationary field laboratory (i.e., a mobile trailer) was installed in April 2023 and was in continuous operation from May 1, 2023, through May 31, 2024. The laboratory included meteorological sensors for wind conditions, temperature, relative humidity, rainfall, barometric pressure, and solar radiation, and inlets for ambient air that led to instruments inside the trailer. They measured airborne radioactivity as alpha radiation, both in the gas phase and on a filter collecting airborne particles.

Gas analyzer instruments for measuring ozone, methane, carbon dioxide, carbon monoxide, hydrogen sulfide, sulfur dioxide, and nitrogen oxides were located inside the station. They also measured approximately 20 VOCs with a custom-made gas chromatograph. All instruments collected data continuously at 1-minute time resolution or were averaged to 1-minute intervals, except radioactivity and the VOCs, which were measured over a 10-minute interval once every hour. The data were logged automatically to a computer inside the station and were accessible remotely. **Commentary Table 1** provides an overview of all the components and how they were measured.

The investigators compiled descriptive statistics for all components measured at the station and calculated correlations between selected hydrocarbons. They also compared the Permian Basin observations with measurements collected at five sites in the Denver Julesburg Basin — a large oil- and gas-producing basin that extends through Colorado, Wyoming, Nebraska, and Kansas — that were in operation at the same time.

They monitored sound pressure levels using a unidirectional microphone, a preamplifier, and a main processor. This instrument was positioned on a tower above the laboratory at a height of 4 meters (m). The instrument was able to compute A-weighted (i.e., midfrequencies that are audible by humans) and C-weighted noise levels, which reflect overall loudness. C-weighted noises can cause vibrations and travel greater distances than A-weighted noises.

The investigators leveraged these high temporal resolution noise and air quality data to quantify potential sources of noise associated with specific UOGD activities. Flaring is known to produce sporadic, rapid pressure fluctuations, whereas drilling or truck traffic might produce more frequent, continuous noise levels. To analyze this, they followed an approach they had used previously, using extreme gradient boosting (a machine learning algorithm) to identify sources of air pollution associated with specific frequencies of noise (Fallah-Shorshani et al. 2024). The investigators also used non-negative matrix factorization (NMF) to identify and quantify sources of the various emissions. The goal of NMF is to simplify complex data into a smaller set of factors that collectively explain much of the variance in the underlying data. In this case, the factors are intended to represent sources of UOGD emissions. Here, the investigators included 26 components in the input matrix (i.e., all measured VOCs, sulfur dioxide, hydrogen sulfide, carbon monoxide, carbon dioxide, methane, and nitrogen oxides).

Aim 2: Passive Sampling to Describe Patterns of Petroleum Hydrocarbons in Ambient Air in Populated Areas Close to UOGD Activity

Franklin and colleagues observed patterns of petroleum hydrocarbons at a dozen locations near UOGD activities and populated areas. They recruited local volunteers to help deploy a network of seven passive hydrocarbon sampling stations in the Carlsbad–Loving, New Mexico, region and five in the Texas Eagle Ford Shale area. The Permian Basin stations were installed at different times between the spring of 2023 and summer 2024, with some in operation for a full year. Most were located on private property with the owners' permission; one was next to the main field laboratory described earlier. The Eagle Ford stations were installed in summer 2024 and operated for half a year. Four stations were located across the shale area in Karnes County, and another was located in College Station, Texas, which was considered an urban reference station. The Eagle Ford network covered a 10 km × 27 km area, with the College Station sampler located about 240 km away.

Commentary Table 1. Components Measured at a UOGD Field Laboratory, Instruments Used, and Summary Statistics[a]

Measurement	Unit	Instrument	Annual Mean	Standard Deviation	Minimum	Median	Maximum
Carbon Dioxide CO_2	ppm	PICARRO G2301	432.06	8.67	412.78	430.03	554.01
Methane CH_4	ppb	PICARRO G2301	2,667.62	1,305.26	1,918.60	2,283.10	139,140.00
Carbon Monoxide CO	ppb	Thermo Scientific 48C	170.49	99.40	20.00	149.90	10,420.00
Ethane C_2H_6	ppb	Agilent 6890 TD-GC-FID	93.68	133.08	0.78	43.92	2,060.00
Ethene (Ethylene) C_2H_4	ppb	Agilent 6890 TD-GC-FID	0.74	0.85	0.01	0.47	16.97
Propane C_3H_8	ppb	Agilent 6890 TD-GC-FID	58.22	80.75	0.22	27.88	1,211.00
Propene (Propylene) C_3H_6	ppb	Agilent 6890 TD-GC-FID	0.15	0.18	0.01	0.09	5.53
1,3-Butadiene C_4H_6	ppb	Agilent 6890 TD-GC-FID	0.01	0.02	0.01	0.01	1.21
i-Butane (Isobutane) C_4H_{10}	ppb	Agilent 6890 TD-GC-FID	10.15	15.81	0.03	4.58	376.60
n-Butane C_4H_{10}	ppb	Agilent 6890 TD-GC-FID	26.23	39.39	0.06	11.91	536.90
Acetylene C_2H_2	ppb	Agilent 6890 TD-GC-FID	0.56	0.57	0.02	0.37	13.69
Cyclopentane C_5H_{10}	ppb	Agilent 6890 TD-GC-FID	0.53	0.73	0.01	0.25	13.46
i-Pentane (Isopentane) C_5H_{12}	ppb	Agilent 6890 TD-GC-FID	7.91	11.88	0.02	3.50	215.90
n-Pentane C_5H_{12}	ppb	Agilent 6890 TD-GC-FID	8.98	13.58	0.02	3.90	258.80
n-Hexane C_6H_{14}	ppb	Agilent 6890 TD-GC-FID	2.96	4.51	0.02	1.25	93.36
Isoprene C_5H_8	ppb	Agilent 6890 TD-GC-FID	0.01	0.01	0.01	0.01	0.40
n-Heptane C_8H_{18}	ppb	Agilent 6890 TD-GC-FID	1.09	1.63	0.00	0.46	37.25
Benzene C_6H_6	ppb	Agilent 6890 TD-GC-FID	0.67	0.82	0.01	0.35	12.26
n-Octane C_8H_{18}	ppb	Agilent 6890 TD-GC-FID	0.35	0.48	0.00	0.16	8.87
Toluene $C_6H_5CH_3$	ppb	Agilent 6890 TD-GC-FID	0.65	0.81	0.00	0.32	11.07
Ethylbenzene $C_6H_5C_2H_5$	ppb	Agilent 6890 TD-GC-FID	0.06	0.07	0.00	0.03	0.94
m&p-Xylene $C_6H_4(CH_3)_2$	ppb	Agilent 6890 TD-GC-FID	0.22	0.30	0.00	0.10	5.25
o-Xylene $C_6H_4(CH_3)_2$	ppb	Agilent 6890 TD-GC-FID	0.08	0.10	0.00	0.04	1.19
Ozone O_3	ppb	Thermo Scientific 49C	33.25	21.28	0.50	33.15	112.30
Nitrogen Oxide NO	ppb	Teledyne T200UP	5.08	20.04	0.03	0.39	1,204.00
Nitrogen Dioxide NO_2	ppb	Teledyne T200UP	9.64	9.70	0.03	6.32	335.60
Nitrogen Oxides NO_x	ppb	Teledyne T200UP	14.62	25.00	0.03	7.34	1,382.00
Hydrogen Sulfide H_2S	ppb	Teledyne T101	1.02	1.14	0.20	0.73	78.65
Sulfur Dioxide SO_2	ppb	Teledyne T101	0.37	0.45	0.20	0.20	12.61
Gas Radioactivity Rn-222, Rn-220	Bq m^{-3}	AlphaGUARD/Alpha PM	19.77	13.71	1.00	17.07	173.20
Particle Radioactivity	Bq m^{-3}	AlphaGUARD/Alpha PM	9.59	9.45	1.00	7.00	98.51
Temperature	°C	METSENS500 multi-sensor, pyranometer	19.83	7.56	-11.10	20.23	43.09
Wind Speed	m s^{-1}	METSENS500 multi-sensor, pyranometer	3.50	2.29	0.03	3.01	23.60

Bq m^{-3} = Becquerel; FID = flame ionization detector; GC = gas chromatography; ppb = parts per billion; ppm = parts per million; TD = thermal desorption; UOGD = unconventional oil and gas development.

[a] Sampling was conducted over a 12-month period (May 2023 to May 2024) at a field laboratory located in Loving, New Mexico. Source: Investigators' Report Tables 1a and 2.

Each station consisted of a shepherd hook that supported an assembly holding two samplers with diffusion tubes and adsorption cartridges, covered with a shield to protect the samplers from rain and solar radiation. These instruments measured the following 15 hydrocarbons: the alkanes 2-methylpentane, 3-methylpentane, n-hexane, 2,4-dimethylpentane, 2-methylhexane, n-heptane, and n-octane; the naphthenes cyclohexane and methyl-cyclohexane; and the aromatics benzene, toluene, ethylbenzene, m-, o-, and p-xylene. Temperature data were also collected at four of the stations.

The samplers were exchanged weekly by a local volunteer and shipped to a laboratory in College Station, Texas, for analysis. The general approaches that the investigators followed for installing and operating these stations had been used in earlier studies (Schade and Heienickle 2023).

The investigators also compiled information from several state and commercial databases on nearby oil and gas wells, including location, type (i.e., horizontal, vertical, directional, unknown), status (e.g., active, inactive, permanently closed), and monthly oil and gas production rates. They used these data to identify the active wells and to determine the total oil and gas production during the sampling periods within 2-, 5-, and 10-km buffers around each passive sampling station and within 10 km of the larger, stationary station.

Aim 3: Combining Satellite Observations and Surface Air Pollution Data to Characterize Flaring and Its Effect on Air Quality and Radioactivity

The burning of waste gas (i.e., flaring) is a common waste disposal practice in these study areas, but its effect on air quality is not well characterized. Franklin and colleagues analyzed flaring activities in the Permian Basin by combining satellite observations from the Visible Infrared Imaging Radiometer Suite using the Nightfire algorithm (Elvidge et al. 2013) with the field measurements of air pollutants and VOCs described earlier. Specifically, the investigators sought to estimate flaring activity including the volume of flared gas and the contribution of flaring to observed levels of methane, nitrogen oxides, carbon dioxide, radioactivity, and select VOCs.

Visible Infrared Imaging Radiometer Suite is a multispectral instrument that records near-infrared and short-wave infrared (i.e., radiant heat) data in several spectral bands. Data are collected nightly with a 750-m spatial resolution. The observed signals can be attributed readily to the flaring combustion source. The Nightfire algorithm also allows users to relate the observed radiant heat to the volume of combusted gas. The investigators used these data and tools, along with a method they developed previously (Franklin et al. 2019) to estimate the volume of gas combusted per flare. They also calculated the numbers of nighttime flares within 5-, 10-, 20-, 30-, and 50-km buffers around the field laboratory to model the relationships between satellite-observed flares and ground-observed air pollutant concentrations.

SUMMARY OF KEY RESULTS

OBSERVATIONS OF AMBIENT AIR POLLUTION, RADIOACTIVITY, AND NOISE AT THE UOGD FIELD LABORATORY (AIM 1)

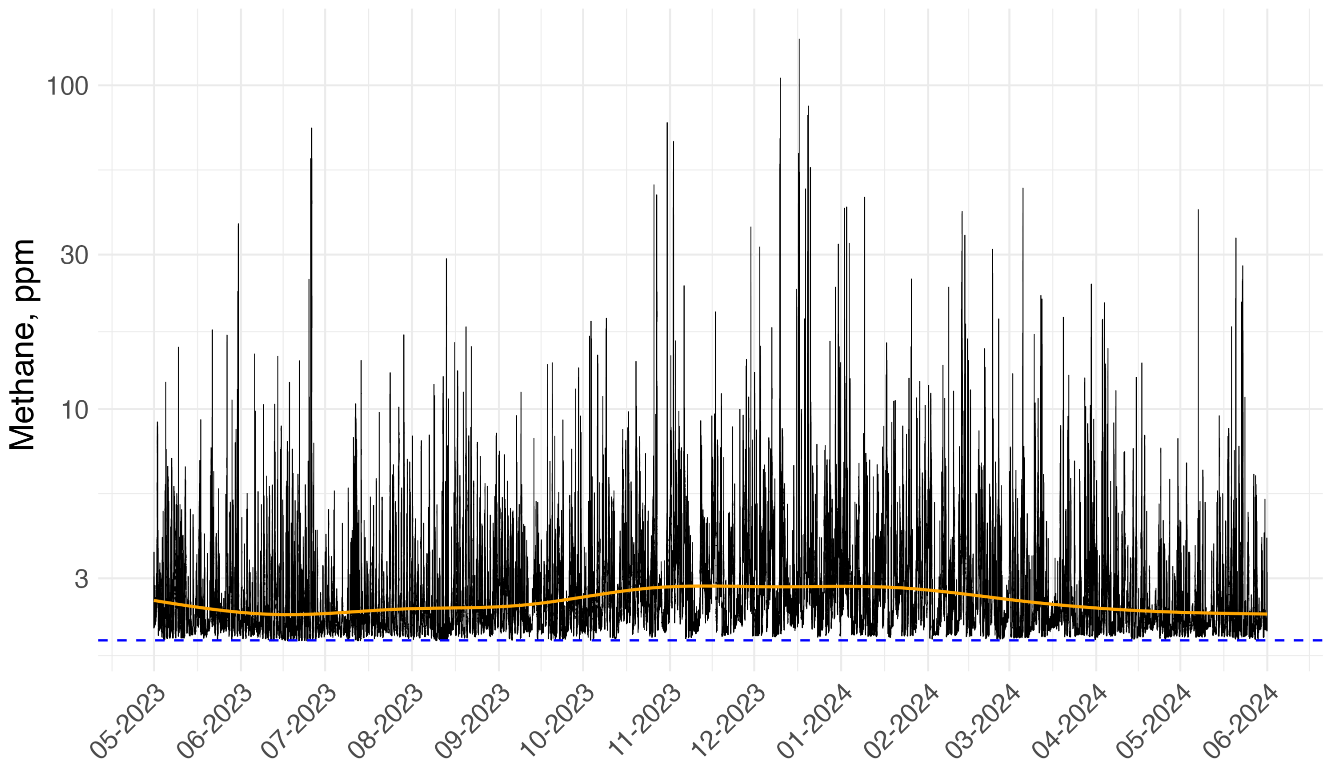
Summary statistics for the components measured at the field laboratory are presented in Commentary Table 1. Franklin and colleagues observed high diurnal and seasonal variability in the observed levels of most components measured during the study period. Many of the observed components experienced frequent occurrences of elevated spikes in concentrations. For example, although the mean concentration of methane over the study period was 2.6 ppm, it exceeded 20 ppm in nearly every month of the study and exceeded 100 ppm on several occasions (**Commentary Figure 1**). Mean concentrations of VOCs with low carbon numbers (e.g., ethane and propane) were the highest, and those with high carbon numbers (e.g., octane and xylenes) were the lowest.

Concentrations of most pollutants measured in this study were higher than those reported at comparison sites in the Denver Julesburg Basin and elsewhere. This was the case for average hourly and annual concentrations, as well as maximum values. For example, the observed annual mean concentrations of benzene (0.67 ppb) were substantially higher than those observed at the Colorado Denver Julesburg Basin sites (all below 0.15 ppb; Investigators' Report Figure 16) and at air quality stations in several large Texas cities that served as reference locations (all below 0.60 ppb; Investigators' Report Figure 40). All carbon monoxide and sulfur dioxide data were below the corresponding short- and long-term NAAQSs for those pollutants.

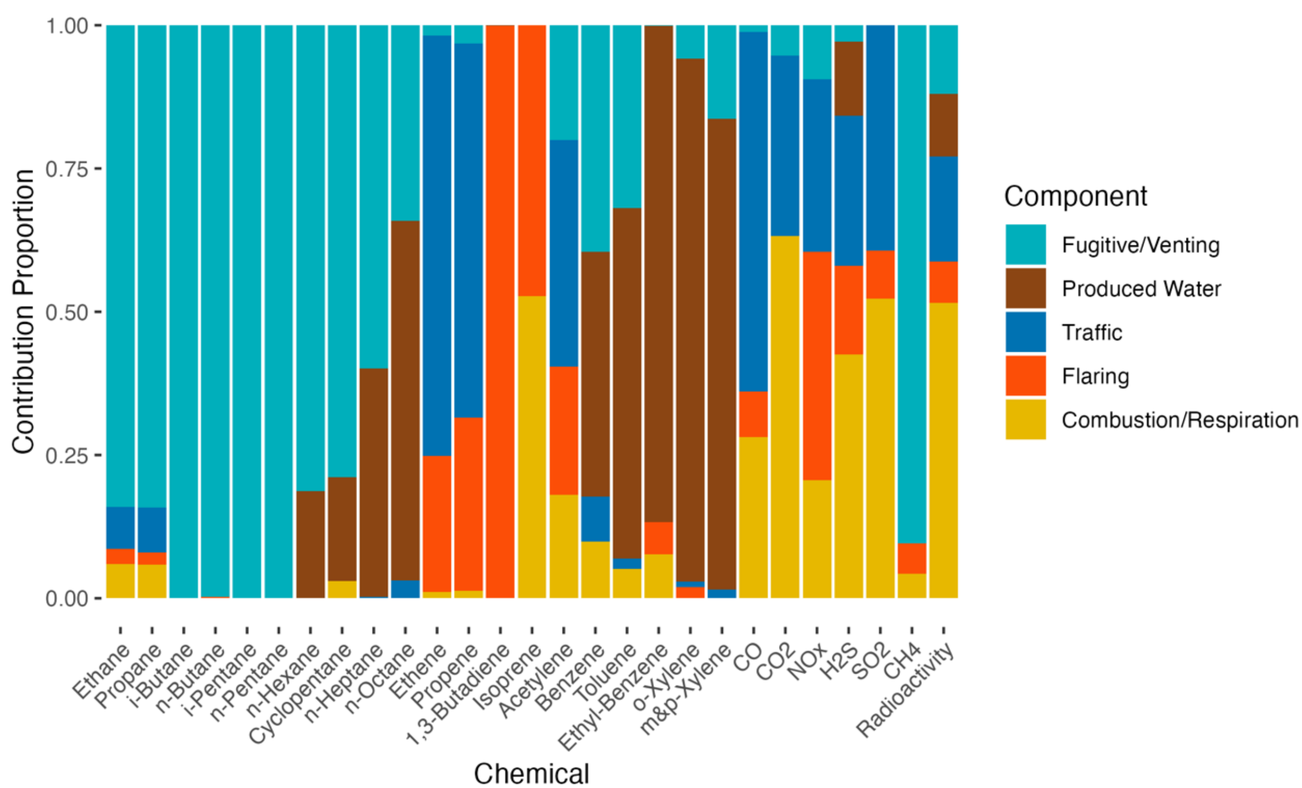
The radioactivity data showed high diurnal and seasonal variability, with values ranging from below the detection limit up to 173 Bq m^3 for gas-phase radioactivity and up to 99 Bq m^3 for particle-associated radioactivity. For reference, the EPA estimates that the average concentration of indoor radon among homes in the United States is about 50 Bq/m^3, and they recommend that action be taken to mitigate concentrations greater than 150 Bq/m^3 in homes.

Overall, many of the components measured at the field laboratory were correlated significantly with each other, which suggests that nearly all the components measured were emitted from similar or co-located sources.

The investigators collected over 300,000 1-minute observations of A- and C-weighted noise levels during the study period. Mean and median values of A-weighted levels (which emphasize midfrequencies) were approximately 60 decibels (dB), and those for C-weighted levels (which include lower sound frequencies) were approximately 70 dB. Noise levels between 60 and 70 dB correspond to what might be experienced as background noise in a typical office setting (i.e., normal level conversation, background music, or the sounds of common office equipment).



Commentary Figure 1. Time series plot showing methane measurements at the field laboratory located in Loving, New Mexico. The orange line represents the monthly running mean, and the blue dashed line represents the global background level of 1.93 ppm. Source: Investigators' Report Figure 10.



Commentary Figure 2. Contribution proportions of each compound to the five factors identified through the source apportionment analysis. Source: Investigators' Report, Figure 32.

The results of the machine learning models indicated that carbon dioxide was the pollutant whose variability was the most correlated with the noise measurements (i.e., had the best model fit according to R^2 and root mean square error; Investigators' Report Table 4). Nitrogen oxides were the only pollutants to have a high-frequency sound signal, differentiating themselves from carbon dioxide, carbon monoxide, and hydrogen sulfide, which had only low-frequency sound signals. The low frequencies associated with carbon dioxide suggested a source related to compressors, which have combustion as well as venting aspects. Methane was also associated with low-frequency sound signals, which, unlike carbon dioxide, were likely from flowback operations, leaks, and fugitive emissions from compressors.

In the source apportionment analysis, the investigators identified five factors representing various sources of UOGD emissions. These factors together explained about 95% of the overall variance in the data: oil and gas fugitive emissions and venting (45%), handling, storage, and evaporation from produced water ponds (39%), traffic emissions (10%), flaring (9%), and widespread combustion and radon emissions (4%) (**Commentary Figure 2**). Note that the sum of factor-specific variance explained values can exceed 100% due to shared explanatory power between factors.

Overall, most of the pollutants measured showed high variability, with frequent occurrences of elevated concentration spikes.

PATTERNS OF PETROLEUM HYDROCARBONS IN AMBIENT AIR BASED ON PASSIVE SAMPLING IN POPULATED AREAS CLOSE TO UOGD ACTIVITY (AIM 2)

Sampling of hydrocarbons in populated areas close to UOGD activity indicated that concentrations of n-hexane and 2-methylpentane were the highest and most variable among the hydrocarbons collected on the samplers, while concentrations of ethylbenzene and the xylenes were the lowest (Investigators' Report Appendix Tables B1 and B2). The observed concentrations of most hydrocarbons were strongly correlated with each other.

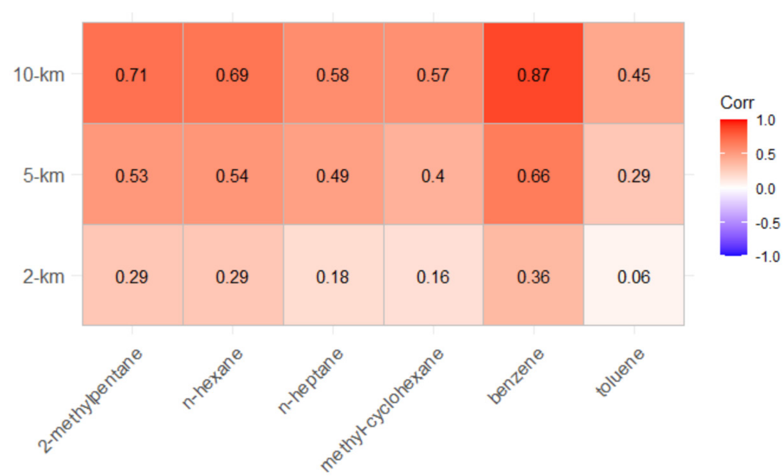
Observed concentrations of benzene were highest during fall and winter and lowest during spring and summer. The investigators attributed these patterns to seasonality in atmospheric dynamics, with deeper, more turbulent atmospheric boundary layers in spring and summer and more shallow boundary layers in fall and winter. Overall median and maximum values for benzene were 0.20 and 0.90 ppb, respectively, at the Eagle Ford Shale sites, as compared with 0.50 and 1.68 ppb at the fixed-site field laboratory.

The investigators found that average hydrocarbon concentrations were correlated positively (and statistically significantly) with the number of wells surrounding each site within several buffer distances examined. For example, concentrations of benzene were correlated ($r = 0.87$ and 0.66) with well counts within 10- and 5-km buffers, respectively (**Commentary Figure 3**). Average hydrocarbon concentrations were not correlated significantly with the production volumes at the surrounding well sites, however, regardless of buffer size.

Overall, the data collected from the passive sampling network suggested northwest to southeast (i.e., from Carlsbad toward Loving) increases in ambient concentrations of the measured hydrocarbons, which corresponded to the known UOGD and traffic activities in the area.

CHARACTERIZING THE LOCATIONS AND MAGNITUDE OF FLARING AND ITS EFFECT ON AIR QUALITY AND RADIOACTIVITY (AIM 3)

Franklin and colleagues detected a total of 71,401 individual nightly gas signals in the Permian Basin study area during the study period (i.e., May 2023 to June 2024). Their analyses produced estimates of individual flare temperature, source area, and radiant heat for each flare. Unfortunately, however, they were able to estimate methane flared gas volume for only 40% of these (mean volume per time = 0.100 m^3/s). Notably, only 36 flares (recorded over 32 nights) were recorded within 5 km of the field laboratory. That is, most flares were located at greater distances (i.e., between 10 and 50 km) from the sampling station. They found that nightly average concentrations of several VOCs (benzene, ethane, and ethene), methane, carbon monoxide, carbon dioxide, nitrogen oxides, and total radioactivity were correlated with the number of flares and with the estimated flared gas volume within 50 km of the field laboratory (Investigators' Report Figure 50). These findings suggested that the flaring contributed to the concentrations of these components.



Commentary Figure 3. Correlation matrix (r values) between the half-annual averages of five hydrocarbons measured at the seven passive sampling stations and the counts of wells in 2-, 5-, and 10-km buffers around them. Source: Investigators' Report Figure 44.

HEI ENERGY REVIEW COMMITTEE'S EVALUATION

STUDY DESIGN, DATASETS, AND ANALYTICAL APPROACHES

This study provided important insights into the contributions of UOGD activities to potential local and regional exposures to noise, airborne radioactivity, and many air pollutants in the Permian Basin and Eagle Ford Shale areas. The results of the study document that UOGD, along with older oil and gas operations, are the dominant source for air pollution in the study area, with emissions arising specifically from production and storage activities, gas flaring, and truck traffic.

In its independent evaluation of the report, the HEI Energy Review Committee identified several strengths of the study design. One strength was the use of multiple measurement methods, such as stationary, passive, and satellite monitoring. Others were the long, continuous sampling period of over 1 year and the use of creative and novel exposure modeling approaches. Committee members were impressed with the large number of components the investigators measured, including several criteria air pollutants and many VOCs, along with detailed measurements of weather and noise, using a wide variety of different instruments.

The investigators compiled detailed information on the locations of and activities at well pads throughout the study areas during the sampling period. The Committee appreciated the comparisons of samples collected at the study sites with those collected at locations in other nearby UOGD regions and with urban background air quality stations. An additional strength of the study was the involvement of volunteers from the local communities to support the collection of the passive sampling data.

The Committee recognized that the development and implementation of the approach that combined remote sensing tools, machine learning, and ground-based observations to characterize counts and locations of flaring events and their contributions to regional concentrations of methane was important work. The Committee members also found that the analyses that linked well pad locations and activity with the various components measured were effective for attributing them directly to the UOGD activities. Moreover, the analyses that linked specific noise levels to the timing of individual emissions source were clever and produced original findings.

A limitation of the study was the investigators' use of a single noise monitoring site. Additionally, the instrument used for measuring noise levels could detect A-level frequencies that were only relatively nearby. The device was better able to detect levels of C-weighted frequencies, which can travel longer distances from their source. Finally, the monitoring methods could not distinguish between UOGD and older oil and gas operations

FINDINGS AND INTERPRETATION

Overall, Franklin and colleagues presented their findings very thoroughly and fairly. They included in the report over 50 figures, including a mix of maps, charts, and photographs, along with several tables, to help readers visualize and understand the results clearly. The Committee agrees with the investigators that UOGD activities appear to be the dominant source of air pollution in the study area.

Many of the findings arising from this study were interesting and useful. For example, the temporal richness of the extensive sampling program allowed the investigators to observe and describe both diurnal (short-term) and seasonal (long-term) patterns for many of the components they measured.

Their ability to interpret the relevance of key findings in ways that were meaningful to potential policymakers and industry alike, and to compare their findings with those from other locations and studies, was an additional strength of the report.

CONCLUSIONS

In summary, this study contributed to our knowledge about potential exposures to a variety of emissions from UOGD activities at local and regional scales. The study showed that UOGD activities are the dominant source of air pollution in the study area. The results indicate that communities living near UOGD activities are potentially exposed to pollutants of health concern. The investigators, however, did not investigate specific health effects related to their findings. Further study is therefore needed to determine local exposures to hazardous air pollutants, such as benzene and ozone. The work presented by Franklin and colleagues is among the most detailed air quality sampling to be conducted in an active oil and gas production region during a peak production period. Whereas many previous studies on air emissions from UOGD activities in the Permian Basin focused exclusively on methane emissions, this study added valuable data on a variety of VOCs and other air pollutants such as nitrogen oxides and ozone. It also added information on less-commonly studied exposures associated with this industry, such as airborne radioactivity and noise emissions.

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