Research Report 240, *Predictive, Source-Oriented Modeling and Measurements to Evaluate Community Exposures to Air Pollutants and Noise from Unconventional Oil and Gas Development,* by L. Hildebrandt Ruiz 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, driven by 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, nor are horizontal drilling or 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 (millions of gallons of water per well) multistage hydraulic fracturing combined with horizontal drilling (thousands of feet in length).

Unconventional oil and natural gas development (UOGD*) has been associated with a wide range of potential exposures to chemical agents (e.g., radioactive material, those found in 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 health effects on communities.

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. Hildebrandt Ruiz was one of three investigators funded under this RFA. Hildebrandt Ruiz and colleagues at The University of Texas at Austin proposed to develop a model to assess exposures to air pollution from UOGD and to inform future health studies. The study included extensive monitoring and modeling of various air pollutants and focused originally on the Eagle Ford Shale in Texas, a large oil and gas production region. The study was later extended to two other UOGD regions, in close collaboration with the other two studies funded under this RFA.

The HEI Energy Research Committee recommended the study for funding because it had several strong features. In particular, the Research Committee was enthusiastic about the proposed model and the detailed monitoring using state-of-the-art instruments. The Committee also thought that Hildebrandt Ruiz had assembled a strong team with demonstrated air quality monitoring and modeling expertise.

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

SCIENTIFIC AND REGULATORY BACKGROUND

UOGD OVERVIEW

UOGD processes occur on and off the well pad and include the following:

Field development: Exploration, pad preparation, vertical and horizontal drilling, and well completion (casing and cementing, perforating, acidizing, hydraulic fracturing, flowback, 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; 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.

Post-production: 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, whereas state authorities play a major role in governing UOGD more generally. UOGD-related rules vary among states, with some defining minimum setback

Dr. Lea Hildebrandt Ruiz's 2-year study, "Predictive, Source-Oriented Modeling and Measurements to Evaluate Community Exposures to Air Pollutants and Noise from Unconventional Oil and Gas Development," began in January 2022. Total expenditures were $3,419,798. The draft Investigators' Report from Hildebrandt Ruiz and colleagues was received for review in January 2025. A revised report was received in June 2025. A second revised report, received in July 2025, was accepted by the HEI Energy Review Committee in August 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.

distances between UOGD sites and specific land uses such as residences and schools to protect local populations.

UOGD PROCESSES

Different UOGD processes release air pollution, noise, and other chemical and nonchemical agents 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 because of 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 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, flow back 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 flow back to the surface. Over time, the composition of the fluids becomes increasingly dominated by natural brines. This fluid is commonly referred to as produced water and must be managed properly along with flowback, drilling muds, and other wastes.

While developing a well or during production, exposures can be associated with vehicle exhaust and emissions from various types of equipment (e.g., compressors and pneumatic devices). Pneumatic controllers are used to operate valves that control liquid level, pressure, and other process variables, whereas pneumatic pumps use gas pressure to drive a fluid by raising or reducing the pressure of the fluid.

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 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 reason and others (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 addresses potential human exposures to a range of chemical and nonchemical agents that can be associated with UOGD (Deziel et al. 2022; HEI Energy Research Committee 2019; HEI Energy Research Committee 2020). Although many of these studies provide valuable information for understanding population exposures, only a small group has been conducted with the direct aim of estimating potential air pollution and noise exposures from 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 affect human health.

STUDY OBJECTIVES

The overarching goal of Hildebrandt Ruiz's study was to develop the TRAcking Community Exposures and Releases (TRACER) model to assess exposures to air pollutants from UOGD and to inform future health studies. The investigators specified the following seven study aims:

1. Conduct field measurements in the Eagle Ford Shale in Texas.
2. Conduct field measurements in the Permian Basin in New Mexico.
3. Estimate emissions from UOGD, including an application of the TRACER model to the Marcellus Shale in the Northeastern United States.
4. Couple the emissions estimates with dispersion models for primary pollutants.
5. Couple the emissions estimates with chemical transport models for secondary pollutants.
6. Assess the performance of various dispersion models.
7. Analyze exposure from UOGD and consider implications for future health studies.

The study team conducted detailed mobile and fixed-site monitoring campaigns over 3 months in the Eagle Ford Shale in 2023 and over 2 weeks in the Permian Basin. They conducted extensive modeling in the Eagle Ford Shale and the Marcellus Shale regions, including the development of improved UOGD emissions estimates, dispersion modeling for primary pollutants, and chemical transport modeling for secondary pollutants.

SUMMARY OF APPROACH AND METHODS

Hildebrandt Ruiz and colleagues used a combination of measurement and modeling approaches at various study sites to assess the quality of the TRACER model, which they advanced and refined from an existing model for methane emissions. The TRACER model combined emissions modeling with dispersion modeling to assess exposure to various air pollutants from UOGD. The capabilities of the preexisting model were expanded from modeling the emission and dispersion of methane from single UOGD well pads to assessing population exposures from multiple well pads. The expanded model included additional sources of emissions, regional-scale modeling, a broad suite of pollutants of concern to human health, including secondary pollutants, and evaluation of the model for the purpose of exposure assessment in future health studies (**Commentary Table 1**).

The original scope of work focused on the Eagle Ford Shale region in Texas. The project was later expanded to also include monitoring in the Permian Basin in New Mexico and modeling in the Marcellus Shale region in Ohio, Pennsylvania, and West Virginia.

AIR POLLUTION AND NOISE MONITORING

Eagle Ford Shale

The investigators conducted detailed outdoor air pollution and noise monitoring in Karnes City, Texas, and neighboring towns located in the center of the Eagle Ford Shale.

Real-time mobile and fixed-site measurements were collected during 8 weeks in the spring and 4 weeks in the fall of 2023. The mobile measurements were conducted using an electric van that drove routes on public roads to characterize the areas close to UOGD flaring locations. The van was equipped with state-of-the-art instrumentation, such as a Vocus 2R proton transfer reaction time-of-flight mass spectrometer. The Vocus provided high-resolution data, including real-time VOCs. A suite of air pollutants was examined, including particulate matter (PM), nitrogen oxides (NO_x), and numerous air toxics (see Commentary Table 1). When plumes (high or peak concentrations) were observed, the investigators parked the van downwind from the emission sources to better characterize the composition of the plumes. Thirty-five active UOGD locations were characterized in the sampling area. The investigators also conducted noise measurements at the same time. Eleven drives were conducted during the spring campaign, and eight drives were conducted during the fall campaign, amounting to about 2,300 km and 5,600 minutes of measurements.

The van was parked at an ambient "background" US Environmental Protection Agency (US EPA) monitoring station run by the Texas Commission on Environmental Quality (TCEQ) in Karnes City to conduct fixed-site measurements for about 3 weeks during the spring campaign. The site is surrounded by UOGD activity. PM_1 (particulate matter with an aerodynamic diameter of less than 1 µm) mass and composition were measured at this fixed site. Moreover, the investigators leveraged hourly measurements of various nonmethane VOCs collected by TCEQ using an automated gas chromatograph. In the Commentary, this fixed site is referred to as the Karnes City monitoring site.

Monitoring data were checked, preprocessed, and calibrated using standardized methods. Measurements from the mobile monitoring campaign were averaged over 10-second intervals, whereas fixed-site measurements were averaged over 1 hour. The investigators produced time-series plots for various pollutants and noise levels and reported averages and distributions. In addition, the investigators identified 17 plumes for more detailed analysis using observations of flares at individual wells. They used these data to estimate the emission ratios of 12 individual VOCs. Emission ratios were calculated per plume as the ΔVOC to ΔCO_2 ratio for each VOC and expressed per ppt/ppm CO_2. The emission data were integrated into the TRACER model, as described below. The Eagle Ford Shale monitoring results are described in Chapter 3 of the report.

Permian Basin

The investigators conducted a similar mobile monitoring campaign in Carlsbad, New Mexico, and neighboring towns located in the Permian Basin, one of the most productive UOGD regions in the United States. Mobile measurements were collected over 2 weeks in spring 2024. In addition, for several nights over 1 week, the van was parked to conduct fixed-site measurements at the Carlsbad KOA campground. A validation study was conducted over 2 days at a fixed site in Loving, New Mexico, to investigate whether different instruments measuring VOCs (benzene and toluene) produced consistent results.

The mobile measurements followed a similar design to the Eagle Ford Shale campaigns and included over 2,900 km of data and 18,700 minutes of measurements. Note that these mobile measurements were averaged over 1-minute intervals (compared with the 10-second intervals described in the other study area). Similar pollutants were measured as those in the Eagle Ford Shale, except that $PM_{2.5}$ and PM_{10} (particulate matter with an aerodynamic diameter of less than 2.5 and 10 µm, respectively) measurements were added. Results were presented as time-series plots for various pollutants and noise and spatial maps to visualize pollutant concentrations across the study region. From the fixed-site data, the investigators generated wind plots to examine whether high concentrations of hydrogen sulfide were associated with specific wind conditions during the night. The Permian Basin monitoring results are described in Chapter 4 of the report.

AIR POLLUTION EMISSION MODELING

The investigators describe the Methane Emission Estimation Tool (MEET) (Allen et al. 2022), which they developed further to create the TRACER model. *MEET* is an open-source

Commentary Table 1. Summary of Data and Approach

UOGD Region	Pollutants	Period	Monitoring or Modeling Approach	Aim	Chapter
Eagle Ford Shale	Methane, ethane, benzene, and many other volatile organic compounds. Carbon dioxide, nitrogen oxides, ozone, hydrogen sulfide, and sulfur dioxide. PM1 mass and composition, black carbon, and noise	March 28 to May 14, 2023, and October 20 to November 15, 2023	Mobile monitoring: on-road and while parked Collocated fixed-site monitoring at one background site from TCEQ	1	3
Permian Basin	Same as above, except addition of $PM_{2.5}$ and PM_{10}, and omission of PM composition	April 29 to May 12, 2024	Mobile monitoring: on-road and while parked Fixed-site monitoring at one site at night	2	4
Marcellus Shale	Four air pollutants: methane, ethane, total volatile organic compounds, and nitrogen oxides	2023	Emissions modeling	3	5
Eagle Ford Shale	Nitrogen oxides and ozone	2019	Chemical transport model, Comprehensive Air Quality Model with Extensions (CAMx)	5	7
Eagle Ford Shale	Ethane	March 5 to May 24, 2023	Air pollution dispersion model (CALPUFF)	4	6
Eagle Ford Shale	Ethane	March 5 to May 24, 2023	Various air pollution dispersion models (CALPUFF, AERMOD, Gaussian model)	6	8
Eagle Ford Shale	Six volatile organic compounds: methane, ethane, propane, n-hexane, benzene, and toluene	March 20 to May 14, 2023	Various exposure assessment approaches with increasing levels of complexity (e.g., CALPUFF and AERMOD)	7	9

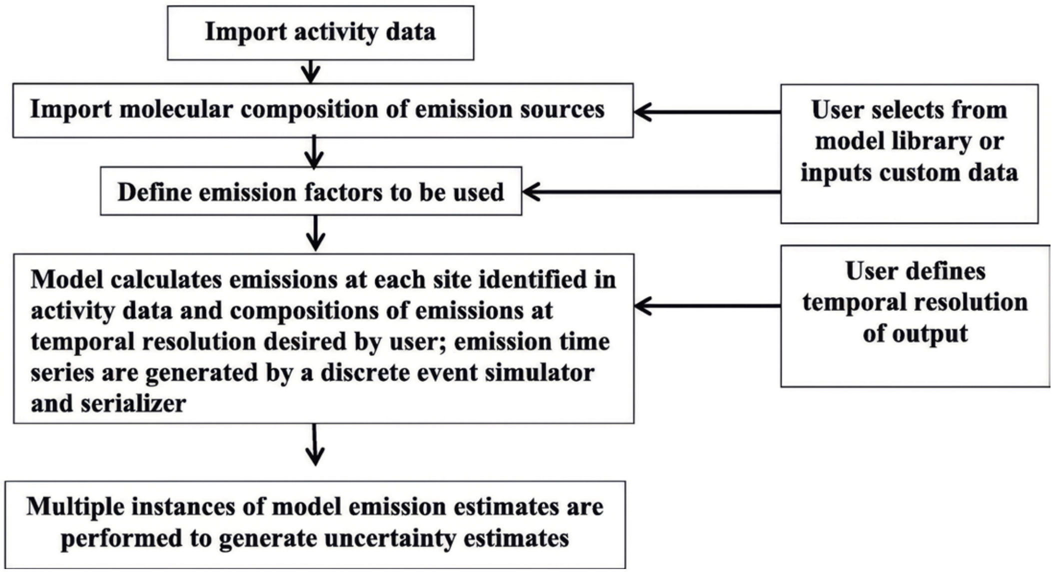
PM = particulate matter with an aerodynamic diameter of less than 1, 2.5, or 10 µm; TCEQ = Texas Commission on Environmental Quality.

modeling tool to help regulators, industry, and the research community more accurately track methane and other emissions in oil and gas production regions. Currently available methods for estimating these emissions, such as the US EPA oil and gas tool (US EPA 2022), provide annual average emission rates and emissions aggregated at the county level, but emissions exhibit variability over much smaller temporal and spatial scales.

MEET estimates emission rates for each UOGD source by multiplying activity data by emission factors, selected from a library of measurements or user-defined data. Activity data describe the number of sources or events within a certain spatial extent or equipment category, and emission factors describe the corresponding emission rates associated with each of these sources or activities. See **Commentary Figure 1** for the basic structure of MEET.

Chapter 5 of the report provides an overview of how the investigators expanded the MEET model to form the TRACER model. The expanded model includes updated emissions from additional UOGD sources from the measurement campaigns, improves the spatial and temporal resolution of UOGD emissions, and broadens to a suite of nonmethane pollutants of concern for human health. Of note is that the investigators improved or expanded emission factors of five UOGD sources: completion flowbacks, pneumatic pumps, pneumatic controllers, liquid unloading, and flares. The TRACER model can create emissions inventories with temporal resolutions ranging from minutes to months, and with spatial resolutions ranging from exact well locations to county-level or even coarser levels.

The investigators provided detailed descriptions of emission estimation methods only for the application to the



Commentary Figure 1. Basic structure of MEET, which was expanded and improved to create the TRACER model. Source: Reproduced from Allen et al. 2022; Creative Commons license *CC BY 4.0*.

Marcellus Shale region because the data required for the modeling — rather than the calculation procedures — vary by location.

Application of the TRACER Model to the Marcellus Shale

The investigators describe an application of the TRACER model to the Marcellus Shale region. The investigators used the TRACER model to estimate emissions for different UOGD sources for four air pollutants (methane, ethane, total VOCs, and NO_x). For this application, they created emissions inventories with hourly resolutions for 2023 with data spatially aggregated using 4 km × 4 km grids. NO_x emissions were estimated for combustion of UOGD sources only (e.g., drilling and hydraulic fracturing, compressors). Emissions from drilling and hydraulic fracturing were allocated only to fractured wells during the 2 weeks preceding production, consistent with the chemical transport modeling described later in this Commentary.

To illustrate key features of the inventories, the investigators reported results for seven grids in five different counties and also provided county-level summaries for two counties. They reported maximum and average hourly emissions rates for all modeled UOGD sources combined and reported separately for each of the grid cells and counties. The emission modeling and the application to the Marcellus Shale region are described in Chapter 5, with further details in the additional materials (Chen et al. 2025).

AIR POLLUTION DISPERSION MODELING IN EAGLE FORD SHALE

Chemical Transport Modeling

The investigators examined the importance of detailed spatial and temporal allocation of NO_x emissions from hydraulic fracturing on predicted ozone formation in the Eagle Ford Shale in 2019 — a region with abundant VOCs. They used this case study to develop parts of the TRACER model.

Base case NO_x emissions were derived from the 2019 emissions inventory developed by TCEQ. The TCEQ emissions inventory provided season-specific NO_x emissions for each of the 27 Eagle Ford Shale counties for 47 UOGD sources. In the case study, these NO_x emissions from oil and gas sources for the Eagle Ford Shale counties were removed from the base case and substituted with spatially and temporally resolved NO_x emissions to create four scenarios. In the first scenario, the county-level NO_x emissions for all UOGD sources were distributed evenly to all active oil and gas wells in the Eagle Ford region (42,038 in total), with assumed continuous emissions throughout the year. In the other three scenarios, NO_x emissions from hydraulic fracturing engines in Karnes County specifically were allocated only to fractured wells, with different durations (2 days, 1 week, or 2 weeks) of emissions for fracturing operations at individual wells. Of 4,185 wells in Karnes County, 436 were fractured in 2019.

The study team used the Comprehensive Air Quality Model with Extensions (CAMx) to simulate ozone impacts from the base case and the four scenarios. CAMx is a chemical transport model with different spatial resolutions depending on the modeling domain (36 and 12 km^2 grids for the contiguous United States and 4 km^2 grids for central and eastern Texas). The modeling period was from June to September 2019, and the temporal resolution of the model was 1 hour.

The investigators calculated the daily maximum of 8-hour average ozone concentrations for all scenarios and maximal and minimum differences across scenarios. The chemical transport modeling results are described in Chapter 7, with further details in the additional materials (Modi et al. 2025).

Air Pollution Dispersion Modeling

The investigators applied the TRACER model to estimate emissions from individual wells and coupled the emissions with an air pollution dispersion model (CALPUFF) to estimate air pollution concentrations at receptor sites in the Eagle Ford Shale. Unlike the chemical transport model described above, the air pollution dispersion model does not account for chemical transformations in the atmosphere.

They used a diagnostic three-dimensional meteorological model (CALMET), with meteorological input data from the Karnes City monitoring site. The investigators note that a variety of compounds could be considered in these analyses, but that they focused on ethane, which, in the Eagle Ford Shale region, is emitted almost entirely by oil and gas operations. The modeling period selected was March 5 to May 24, 2023, to correspond with the Eagle Ford Shale monitoring campaign described earlier in this Commentary.

Emissions were estimated using the TRACER model for individual wells or tank batteries for various UOGD sources. Tank batteries may be located on or off well pads and consist of a group of tanks and other liquid-handling equipment that is connected to receive crude oil and produced water from a well. Emissions were also estimated at the facility level (thus aggregated over multiple wells) using throughput-scaled methane emission factors and facility-specific emission composition estimates derived from earlier studies (e.g., Allen et al. 2013; 2015a; 2015b; Mitchell et al. 2015; Zimmerle et al. 2020).

For the air pollution dispersion modeling, the team selected a domain of approximately 200 km × 200 km centered on the Karnes City monitoring site using data on more than 20,000 oil and gas wells. The domain included three nested regions (inner, intermediate, and outer modeling domain) (**Commentary Figure 2**). Individual wells (3,208 in total) were spatially resolved in a 32 km × 32 km region of the Karnes City monitoring site (inner modeling domain). For computational reasons, wells outside the inner modeling domain were aggregated (up to 4 km × 4 km) into point sources representing multiple wells. The temporal resolution of the model was 1 hour.

They analyzed the contribution of different source distances (5, 10, 20, and 50 km) to the average and peak concentrations predicted when all UOGD sources in the modeling domain were accounted for. The air pollution dispersion modeling results are described in Chapter 6, with further details in the additional materials (Graves et al. 2025).

To assess the performance of CALPUFF and two other air pollution dispersion models (AERMOD and a Gaussian model), the study team compared predicted and observed hourly concentrations of ethane at the Karnes City monitoring site. While all models use the same modeling domain and spatial and temporal resolutions as CALPUFF, they use different meteorological input data and formulations of how the pollutants would disperse in the ambient atmosphere. The investigators assessed model performance using multiple measures, including a "screening" test for regulatory applications, correlations, root-mean square errors, and bias. The screening test is passed when the model's under- or overprediction is less than a factor of 2. The evaluation of the various air pollution dispersion models is described in Chapter 8.

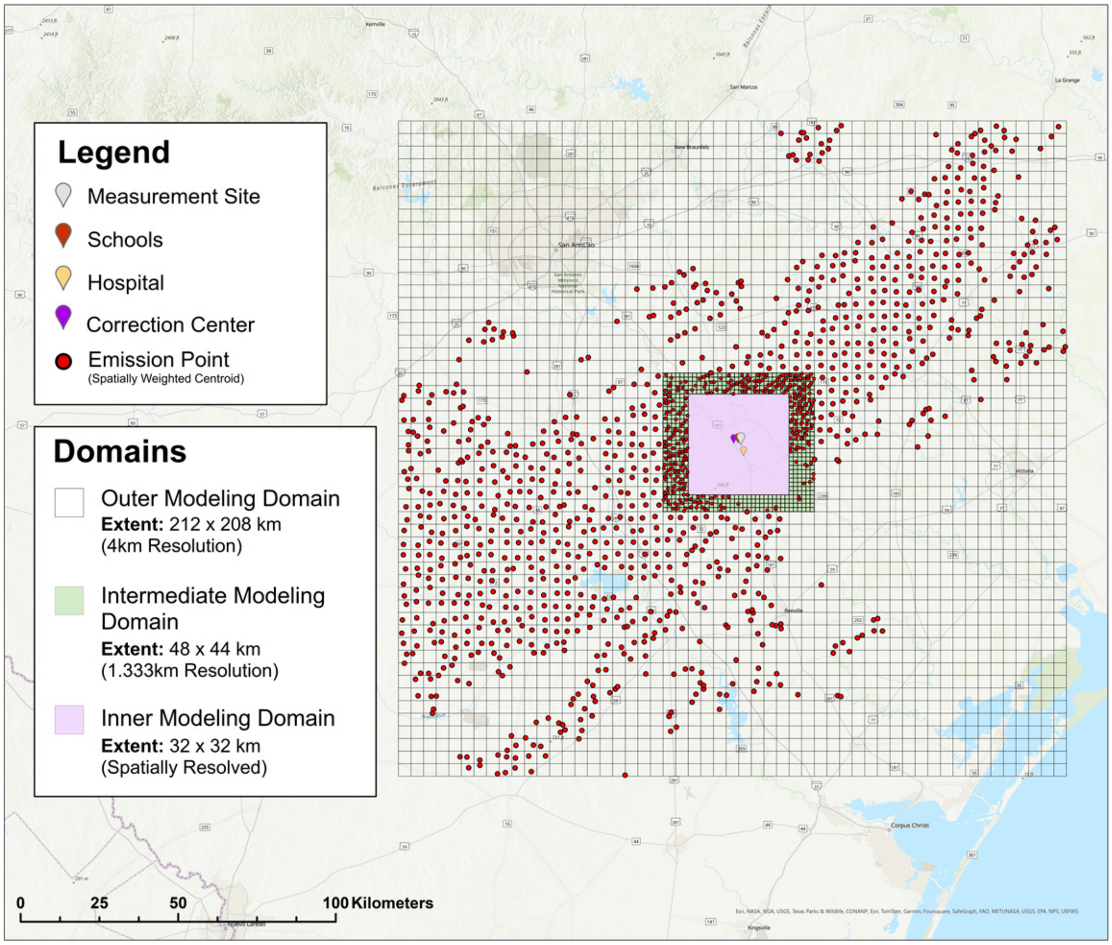
Exposure Modeling

The investigators described various approaches to estimate exposure to six VOCs (methane, ethane, propane, n-hexane, benzene, and toluene) from UOGD in Karnes County with increasing levels of complexity, including various air pollution dispersion models.

The investigators obtained meteorological data and emissions data for subsequent exposure modeling. They obtained meteorological data from the Karnes City monitoring site. The investigators used the TRACER model to estimate emissions for different UOGD sources. They estimated emissions from individual tank batteries, where most emissions occur, rather than from individual wells. Individual tank batteries (402 in total) were spatially resolved in a 15 km × 15 km region of the Karnes City monitoring site (inner modeling domain). For computational reasons, tank battery locations outside the inner modeling domain were aggregated (up to 4 km × 4 km) into point sources representing sometimes multiple locations.

Next, the investigators applied various approaches with increasing levels of complexity to quantify temporal and spatial variability in the exposure of six VOCs. The modeling period selected was March 20 to May 14, 2023, to correspond with the earlier-described Eagle Ford Shale monitoring campaign. The temporal and spatial resolution of the exposure models was 1 hour and 1.3 km × 1.3 km grid cells, respectively.

Multiple methods were used to estimate exposure. First, inverse distance weighting was used, in which the pollutant concentration at a given location is inversely related to the distance from the emission source. The investigators applied this inverse distance weighting approach with and without meteorological data (wind speed and direction). They established a 5 km buffer surrounding each emissions source



Commentary Figure 2. Nested air pollution dispersion modeling domain in the Eagle Ford Shale. Source: Investigators' Report Figure 6-1.

location and calculated the distance between each source and its surrounding grid cells.

Next, a Gaussian plume model was used. This model disperses the pollutants in the shape of a normal (Gaussian) distribution in both horizontal and vertical directions as they move downwind from the source. The Gaussian model does not consider the influence from a source farther than 10 km from the emission point. Lastly, two increasingly complex air pollution dispersion models were applied with a much larger modeling domain, AERMOD and CALPUFF, with different formulations of how the pollutants would disperse in the ambient atmosphere.

The investigators reported emission rates by various UOGD sources for ethane and calculated Pearson correlations between emissions from all sources and the six VOCs. They assessed model performance by comparing model predictions with observations from the Karnes City monitoring site, with a focus on ethane. The investigators conducted additional analyses with AERMOD. For example, AERMOD was used to estimate population-weighted exposure from UOGD across racial and ethnic groups and income levels obtained from census data in Karnes County. The exposure modeling results are described in Chapter 9 of the report.

SUMMARY OF RESULTS

AIR POLLUTION AND NOISE MONITORING

Observations of ambient concentrations of air pollutants in UOGD regions showed strong diurnal variation, with (short-term) peak concentrations occurring during late night and early morning hours. Mean concentrations for various air pollutants and noise from the entire UOGD measurement campaigns in Eagle Ford Shale and Permian Basin were generally relatively low and did not exceed the National Ambient Air Quality Standards concentrations and other health-related guidelines (**Commentary Table 2**). Caution is warranted because the measurements and the short-term health standards and guidelines have different averaging times. Measurements were conducted for a total of 3 months in Eagle Ford Shale in 2023, and for 2 weeks in Permian Basin in 2024.

Commentary Table 2. Mean Concentrations of Various Air Pollutants and Noise from UOGD Measurement Campaigns in Eagle Ford Shale and Permian Basin Regions, together with Short-term Health Standards and Guidelines

	Mean in Eagle Ford Shale	Mean in Permian Basin	
Type of Campaign	**Fixed-Site Monitoring[a]**	**Mobile Monitoring[b]**	**Short-Term Health Standards and Guidelines**
Methane	2.2 ppm	2.2 ppm	
Ethane	35 ppb	NR	–
Benzene	0.1 ppb	0.5 ppb	9 ppb (acute-duration inhalation from ATSDR)
Toluene	0.2 ppb	0.4 ppb	2,000 ppb (acute-duration inhalation from ATSDR)
Formaldehyde	1.0 ppb	1.0 ppb	40 ppb (acute-duration inhalation from ATSDR)
C8 aromatic compounds	0.01 ppb	0.2 ppb	–
Nitrogen oxides	2 ppb	NR	100 ppb (NAAQS for NO_2 – Annual 98th percentile of 1-hour daily maximum concentrations, averaged over 3 years)
Ozone	36 ppb	48 ppb	70 ppb (NAAQS – Annual fourth-highest daily maximum 8-hour concentration, averaged over 3 years)
Hydrogen sulfide	1.7 ppb	2.3 ppb	70 ppb (acute-duration inhalation from ATSDR)
Sulfur dioxide	0.4 ppb	1.0 ppb	75 ppb (NAAQS – Annual 99th percentile of 1-hour daily maximum concentrations, averaged over 3 years)
PM_1	6.7 μg/m^3	5.8 μg/m^3	–
$PM_{2.5}$	NR	8.8 μg/m^3	35 μg/m^3 (NAAQS – 98th percentile of 24-hour concentration, averaged over 3 years)
Black carbon	NR	0.6 μg/m^3	–
Noise (LAeq)	50 dB	NR	70 dB (LAeq US EPA guideline averaged over 24 hours)

NR = not reported; ATSDR = Agency for Toxic Substances and Disease Registry; LAeq = A-weighted, equivalent continuous sound pressure level; NAAQS = National Ambient Air Quality Standards; PM_1 = particulate matter with an aerodynamic diameter of less than 1 μm; US EPA = United States Environmental Protection Agency.

[a] Observations obtained from fixed-site measurement data at the Karnes City monitoring site and averaged over 1-hour intervals from a 3-month sampling campaign in 2023. Data were averaged over the spring and fall campaigns, if available. Note that an automated gas chromatograph operated by TCEQ was used for the various VOCs, if available.

[b] Observations obtained from mobile measurement data and averaged over 1-minute intervals from a 2-week sampling campaign in spring 2024. Note that the Vocus data were for the various VOCs.

Air Pollution Emissions Observations

Hildebrandt Ruiz and colleagues used mobile measurements in the Eagle Ford Shale region to identify 17 plumes and estimate emission ratios derived from observations of flares at individual wells. The largest emission ratios were reported for benzene (average 89 ppt/ppm CO_2), followed by C8 aromatic compounds and acetaldehyde (both 64 ppt/ppm CO_2), and then toluene (44 ppt/ppm CO_2). The emission ratios of all other measured VOCs were small (all <4.8 ppt/ppm CO_2). The investigators found high variability in emission ratios of VOCs across the flaring sites.

AIR POLLUTION EMISSION MODELING IN MARCELLUS SHALE

For methane, ethane, and VOC emissions, maximum hourly emission rates for all UOGD sources were typically several times the mean annual emission rate (**Commentary Table 3**). In contrast, maximum NO_x emissions from UOGD combustion sources varied less than hydrocarbon emissions. The variability in emissions decreased when aggregated at a county-level scale compared with a grid-level scale. Note that the emission rates were averaged over 4 km × 4 km.

AIR POLLUTION DISPERSION MODELING IN EAGLE FORD SHALE

Chemical Transport Modeling

Hydraulic fracturing appeared to be an important contributor of NO_x emissions from UOGD in the Eagle Ford Shale, accounting for approximately 10% of total NO_x emissions from UOGD in 2019.

The study team reported spatial and temporal variability in NO_x emission rates from hydraulic fracturing that ranged over two to three orders of magnitude across the scenarios. This variability occurs because, at a given time, only a small percentage of the total wells have fracturing emissions, which last for 2 days to 2 weeks before production begins.

The improved emissions estimates might have led to increased estimated ozone formation in the Eagle Ford Shale region — a region with abundant biogenic VOCs and a region that is generally upwind of the San Antonio ozone nonattainment region. For several days in August 2019, for example, estimated ozone concentrations were consistently 6 to 10 ppb higher in the areas north of the Eagle Ford Shale (such as San Antonio) for the 2-day to 2-week emission periods compared with the annual county-level distribution.

Air Pollution Dispersion Modeling

The study team reported that mean and peak ethane concentrations at the Karnes City monitoring site are influenced by both near and distant UOGD sources in the Eagle Ford region. Mean concentrations were affected by UOGD emission sources up to 50 km away from the Karnes City monitoring site. In contrast, peak concentrations at night were primarily due to sources within 20 km of the site. On average, sources within 5 km of the Karnes City monitoring site contributed 38% to the mean ethane concentrations predicted when all sources in the 200 km × 200 km domain were accounted for. Sources within 10, 20, and 50 km contributed on average 67%, 88%, and 99%, respectively, to the mean ethane concentrations.

Commentary Table 3. Maximum and Hourly Emission Rates of Methane and Nitrogen Oxides for the Seven Grid Cells (4 km × 4 km) in the Marcellus Shale Region

			Methane (All UOGD Sources)		Nitrogen Oxides (Combustion Sources)	
Grid Cell	County	Marcellus portion	Average (kg/hr)	Factor Difference[a]	Average (kg/hr)	Factor Difference[a]
1	Tyler, WV	Southwest	79.8	3.2	26.2	4.4
2	Greene, PA	Southwest	102.9	2.8	35.3	3.2
3	Lewis, WV	Southwest	80.3	1.3	18.2	1.1
4	Bradford, PA	Northeast	50.8	4.9	11.8	1.0
5	Bradford, PA	Northeast	27.6	15.3	6.1	1.0
6	Bradford, PA	Northeast	74.8	6.8	19.3	4.4
7	Susquehanna, PA	Northeast	42.6	4.6	9.9	1.0

[a] Factor difference between the maximum and hourly emission rate.

There was a high degree of variability in those percentages from hour to hour, depending on whether the nearest UOGD sources were upwind from the site and whether stable atmospheric conditions with low wind speed occurred, which may facilitate peak concentrations.

The air pollution dispersion models (CALPUFF, AERMOD, and the Gaussian model) predicted the timing and ranking of the plumes with reasonable precision, but the actual magnitude of the plumes varied considerably. The best-performing model depends on which performance measure is important and for which application. For example, both CALPUFF and AERMOD passed a "screening test" for regulatory applications, and the Gaussian model did not. AERMOD generally underpredicts across the observed range of ethane concentrations, CALPUFF underpredicts only at low observed concentrations, and the Gaussian model overpredicts at high observed levels. CALPUFF seemed to perform better when looking at correlations with ethane observations compared with the other two models.

Further examination of AERMOD showed that UOGD emissions and meteorology, primarily wind speed and direction, were the most influential factors on modeled ethane concentrations at the Karnes City monitoring site.

Exposure Modeling

Ethane emission rates from three specific UOGD sources were estimated to be the largest in the Eagle Ford Shale: emissions from liquid unloading (1,026 kg/hr), tank flashing (998 kg/hr), and pneumatic controllers (792 kg/hr). Emissions from unloading are typically very short in duration, whereas tank flashing and pneumatic emissions, expressed as hourly averages, are relatively constant. Emission rates were typically highly correlated across pollutants (correlation >0.7).

Similarly high correlations (>0.7) were reported across the different exposure models for ethane and the other VOCs, except for the inverse weighting models without meteorological data. The latter model did not correlate with the other models.

Daily estimates from the exposure models were moderately to highly correlated (0.6–0.8) with ethane observations at the Karnes City monitoring site, except for the inverse weighting model (0.2) (**Commentary Table 4**). A negative bias was reported for all models except CALPUFF, with models underestimating ethane measurements by up to 20 ppb (70%). CALPUFF appeared to be the best-performing model in reducing bias. However, it is also the most computationally intensive model. The next best model in reducing bias was AERMOD, a less computationally demanding model.

Using the AERMOD model, population-weighted exposure estimates of six VOCs across racial and ethnic groups and income levels from UOGD in Karnes County were generally low.

HEI ENERGY REVIEW COMMITTEE 'S EVALUATION

In its independent review of the study, the HEI Energy Review Committee found that the study presented a comprehensive approach to evaluating air pollution from UOGD. The Committee thought the study findings and the TRACER model would be of broad interest and value to a wide audience, such as resource managers, state and federal policymakers, UOGD industry practitioners, research scientists, and local communities.

STRENGTHS OF THE STUDY

The Review Committee noted several strengths of the research. First, the Committee was impressed by the detailed mobile and fixed-site monitoring campaigns and use of state-of-the-art instrumentation that provided high-resolution data. The investigators collected 3 months of data in the Eagle Ford Shale in Texas and used advanced instrumentation, such as mass spectrometry, to measure real-time VOCs. A suite of air pollutants was examined, including PM and its composition, NO_x, and numerous air toxics. The Committee also appreciated the 2-week measurement campaign in the Permian Basin in New Mexico.

Commentary Table 4. Performance Measures of the Different Exposure Models for Daily Mean Ethane Concentrations at the Karnes City Monitoring Site

Exposure Model	Correlation	Root-Mean Square Error (ppb)	Mean Bias (ppb)	Normalized Mean Bias (%)
Inverse distance weighting without meteorology	0.21	34	−16	−61
Inverse distance weighting with meteorology	0.76	33	−19	−71
Gaussian plume model	0.57	33	−17	−63
AERMOD	0.70	23	−9	−33
CALPUFF	0.59	27	2	7.6

Second, the extensive modeling efforts were notable, including the development of improved UOGD emissions estimates, dispersion modeling, and chemical transport modeling. The development of the TRACER model could provide a useful tool for future exposure and health studies of UOGD in the United States. The TRACER model could also be a useful tool to track UOGD exposure over time, given that UOGD industry practices and governance might change.

Third, the Committee appreciated the broad scope of the study with extensive monitoring and modeling across three key UOGD regions: Eagle Ford Shale, Permian Basin, and Marcellus Shale. Such a broad and ambitious scope makes the results relevant and widely applicable across geographical boundaries.

Fourth, the Committee found the many methodological contributions valuable, including a detailed evaluation of various air pollution dispersion models in predicting the structure of plumes from oil and gas facilities, exploration of influencing factors of the models, and a comparison of various exposure approaches with increasing levels of complexity.

Although the Committee broadly agreed with the investigators' conclusions, the report had some weaknesses and limitations that should be considered when interpreting the results.

LIMITATIONS

Need for More Discussion, Integration, and Synthesis

Although the investigators have conducted an impressive amount of work, the report reads as a standalone, sometimes overly technical, project that is not well integrated across the chapters. Moreover, some chapters, such as the introductory chapters, were not well developed. The lack of integration might stem partly from the study's history because the mobile monitoring in the Permian Basin and modeling in the Marcellus Shale began after other aspects of the research had already started. Hence, it is unsurprising that some of the results, such as the monitoring data, are not fully integrated in later chapters.

The Review Committee noted that many important details were lacking regarding the emissions inventory used in the current study. Details lacking include what data sources were used and during which years, what the spatial and temporal resolution was, and, importantly, how the emissions estimates from UOGD were improved. It is unclear whether and how the monitoring data were used in the emissions estimates and subsequent modeling in later chapters.

The Committee noted the lack of discussion in some chapters and a very short overarching synthesis chapter, which limited the discussion of the findings and their implications. Whereas some discussions have been added in response to earlier feedback from the Committee, further exploration of the following topics could increase the utility of the report:

1. A discussion of what would be the best exposure model given the uncertainties in emissions and other sources of uncertainty, how to best evaluate model performance, and the practical feasibility of the models for different applications and user groups.
2. An expanded discussion on the applicability of the TRACER model to other UOGD regions and potential future UOGD practices.
3. Further discussion of the generalizability of the study results to different industry practices within and across basins.
4. Elaboration on the public health implications, particularly because the mean air pollution levels from UOGD were generally low, albeit with short-term peak concentrations, particularly at night.

The Committee thought the lack of thorough discussion, integration, and synthesis across the many parts of the study was a missed opportunity to maximize the study's impact and limited the generalizability of the findings.

RECOMMENDATIONS FOR AREAS OF FUTURE WORK

The Review Committee identified three specific areas of future work that would be valuable and of interest. First, it would be important to apply the TRACER model in the Permian Basin, one of the most productive UOGD regions in the United States. Such an application would demonstrate the usefulness and broad applicability of the model in different types of regions with different industry practices within and across basins. It is encouraging that the study team is planning to complete this work in 2026.

Second, the Committee strongly encourages a more thorough evaluation of the TRACER model with measurements for multiple pollutants and for additional sites. In the current study, the investigators only used measurements obtained at a single site (the Karnes City monitoring site) and mainly for one pollutant (ethane).

Third, the Committee recommends exploration of a range of potential exposures to chemical agents (e.g., radioactive material, those found in wastewater, and volatile compounds) and nonchemical agents (e.g., noise, light, and vibration) that can be associated with UOGD in addition to air pollution (Deziel et al. 2022; HEI Energy Research Committee 2019; HEI Energy Research Committee 2020). The current study addressed air pollution only, and, to a limited extent, noise. Hence, more work is needed to assess the wide range of different types of exposures from UOGD and to inform future health studies.

CONCLUSIONS

The study by Hildebrandt Ruiz and colleagues used a combination of measurement and modeling approaches at various study sites to assess the quality of the TRACER model, which they advanced and refined from an existing model for methane emissions. The TRACER model combined emissions modeling with dispersion modeling to assess exposure to various air pollutants from UOGD. The expanded model included additional sources of emissions, regional-scale modeling, a broad suite of pollutants, and evaluation of the model for the purpose of exposure assessment in future health studies. The original scope of work focused on the Eagle Ford Shale region in Texas. The project was later expanded to also include monitoring in the Permian Basin in New Mexico and modeling in the Marcellus Shale region in Ohio, Pennsylvania, and West Virginia.

The broad scope of the study, detailed monitoring campaigns, and use of state-of-the-art instrumentation that provided high-resolution data were the strengths of the study. Other strengths were the extensive modeling efforts, including the development of improved UOGD emissions estimates, dispersion modeling, and chemical transport modeling.

Among the main findings was that the investigators found that ethane concentrations were affected by UOGD emission sources up to 50 km away. The study reported typically high correlations between ethane and other VOCs from different exposure models and with direct observations. CALPUFF appeared to be the best-performing model in reducing bias for ethane.

While comprehensive, the HEI Energy Review Committee thought the lack of discussion, integration, and synthesis in the report limited the generalizability of the findings. The lack of integration might stem partly from the study's history because mobile monitoring in the Permian Basin and modeling in the Marcellus Shale region began after other aspects of the research had already started. The Committee recommends three areas of future work: application of the TRACER model in the Permian Basin, one of the most productive UOGD regions in the United States; a more thorough evaluation of the TRACER model beyond mainly ethane; and expansion of research efforts to other potential chemical and nonchemical exposures related to UOGD, in addition to air pollution.

Overall, the Committee thought the study findings and the TRACER model would be of broad interest and value to a wide audience, such as resource managers, state and federal policymakers, UOGD industry practitioners, research scientists, and local communities.

ACKNOWLEDGMENTS

The HEI Energy Review Committee thanks the ad hoc reviewers for their help in evaluating the scientific merit of the Investigators' Report. The Committee is also grateful to Donna Vorhees for oversight of the study, to Hanna Boogaard for assistance with review of the Investigators' Report and preparation of its Commentary, to Tara Hamilton for editing the Investigators' Report and its Commentary, and to Kristin Eckles and Hope Green for their roles in preparing this HEI Research Report for publication.

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