Emissions Inventory & Ambient Air Monitoring of Natural Gas Production in the Fayetteville Shale Region

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ABSTRACT

Natural gas production in the Fayetteville Shale region of north central Arkansas has grown rapidly since horizontal drilling and hydraulic fracturing began in 2004. Arkansas Department of Environmental Quality received a grant from U.S. Environmental Protection Agency to develop an emissions inventory for gas production activities in the Fayetteville Shale for the year 2008, coupled with ambient air monitoring around gas sites.

Annual emissions from gas production in the Fayetteville Shale were estimated to be 5,002 tons nitrogen oxides (NO_X), 977 tons volatile organic compounds (VOC), 674 tons particulate matter ≤ 10 µm (PM_{10}), 3,377 tons carbon monoxide (CO), 128 tons sulfur dioxide (SO_2), 112,877 tons methane (CH_4), and 1,225,643 tons carbon dioxide (CO_2). Compressor station engines used for gathering and transporting gas were the largest source of NO_X, VOC, CO, SO_2, and CO_2 emissions. Drilling rigs and hydraulic fracturing pumps used in well drilling and completion were the largest source of PM_{10} emissions. Well flowback venting and fugitive sources were the primary source of CH_4 emissions.

Ambient air monitoring was performed around the perimeter of six drilling sites, three hydraulic fracturing sites, four compressor stations, and one control site. Although most pollutant concentrations were below detection limits, VOC concentrations at drilling sites were often elevated around site perimeters with average daily concentrations reaching 678 parts per billion (ppb). The spatiotemporal distribution of VOC concentrations at drilling sites was significantly affected by wind direction and suggests open tanks of oil-based drilling mud and cuttings were the source of VOC emissions.

INTRODUCTION

The Fayetteville Shale is a gas reservoir located in the Arkoma basin of north central Arkansas. Natural gas production in the Fayetteville Shale region has expanded rapidly since 2004, when productive wells were developed with horizontal drilling and hydraulic fracturing. In 2006, the Arkansas Oil and Gas Commission (AOGC) promulgated Rule B-43 to regulate gas production from 21 counties including the Fayetteville Shale. As of June 30, 2011, 3,488 wells have been completed in the B-43 field with a cumulative gas production of 2,129 billion cubic feet (BCF), primarily within Cleburne, Conway, Faulkner, Van Buren, and White counties. The Fayetteville Shale is estimated to contain approximately 40 trillion cubic feet of natural gas (ALL Consulting 2008), and economic forecasts predict that well drilling will continue for at least a decade (CBER 2009).

Air pollutants may be emitted during several stages of the development of natural gas resources including the drilling, hydraulic fracturing, and completion of wells and the treatment, compression, and transport of produced gas. Emission sources include transportable sources, such as drilling rigs, and stationary sources, such as compressor engines. Air pollutants emitted by the combustion of natural gas and diesel fuel include nitrogen oxides (NO_X), carbon monoxide (CO), particulate matter $\leq$ 10 µm (PM_{10}), sulfur dioxide (SO_2), volatile organic compounds (VOCs), and hazardous air pollutants (HAPs), such as formaldehyde and benzene. Air pollutants including VOCs and HAPs may also be emitted from fugitive emission sources such as leaking valves on gas processing equipment. A recent study of the Barnett Shale reported that VOC and NO_X emissions from gas production exceeded the emissions from all on-road mobile vehicles in the Dallas-Fort Worth metropolitan region (Armendariz 2009). Natural gas production also emits greenhouse gases including carbon dioxide (CO_2) and methane (CH_4), which is the primary component of natural gas. The Barnett Shale study estimated that greenhouse gas emissions from gas development were equivalent to the emissions from two 750 megawatt coal power plants. There are several other studies that have investigated both the total emissions (TCEQ 2011; WRAP 2011) and local air quality impacts (TCEQ 2010; PDEP 2010, 2011a, 2011b) of gas production.

The first stage of gas well development is the drilling process. The surface is prepared by establishing a gravel-covered pad for equipment. A transportable drilling rig, typically powered by a diesel or diesel-electric engine, is erected on the pad. The rig initially drills down vertically to the producing zone, which in the Fayetteville Shale ranges from 50 to 550 feet thick with a depth varying from 1,500 to 6,500 feet below the surface (Arkansas Geological Survey 2011). After reaching the target depth, the rig drills a horizontal lateral section through the producing zone. Several wells may be drilled on a single well pad with laterals extending in different directions to maximize gas production relative to surface disturbance. For the first quarter of 2011, Southwestern Energy reported that the average well required 8.4 days of drilling with an average horizontal lateral length of 4,985 feet (SWN 2011). Drilling normally utilizes oil-based drilling mud to lubricate the drill bit. Drill cuttings, a mixture of used drilling mud and rock fragments from the well, are often temporarily stored in open tanks until being removed off-site for recycling or disposal.

The second stage of gas development is hydraulic fracturing and well completion. After a well is drilled, hydraulic fracturing fluid is pumped at high pressure into the well through perforated casing in the lateral section to fracture the shale. Hydraulic fracturing fluid is a mixture of water, chemicals, and proppant, which is sand or specially engineered particles that hold open fractures in the shale so gas can flow out the well. Hydraulic fracturing is performed by a group of diesel-powered pumps. After the hydraulic fracturing of a well is completed, fracturing fluid is allowed to flow back from the well to the surface for up to several days. During the flowback period, gas may be flared or vented to the atmosphere; however, some companies utilize reduced emissions completions and capture most of the flowback gas. Finally, the well is completed by installing a collection of valves, spools, and fittings, called a Christmas tree because of its appearance, on the wellhead to provide surface pressure control.

Before produced gas can be delivered to consumers, it must be processed to meet gas pipeline specifications and compressed to provide pressure for transport, in what are referred to as midstream operations. Typically, several nearby wells are connected by pipelines to a gathering station that contains processing equipment and compressor engines. Processing equipment may include separators, dehydrators, and amine units, depending on the composition of produced gas. Separators are generally used to remove water and heavier hydrocarbons for storage in produced water and condensate tanks until the fluids are trucked offsite; however, condensate tanks are not used in the Fayetteville Shale because produced gas contains less than 0.05% heavier hydrocarbons. Dehydrators remove additional water by circulating gas through glycol that is thermally regenerated. Amine units scrub acid gases such as hydrogen sulfide (H_2S) and CO_2 from produced gas; however, Fayetteville Shale gas has low sulfur content and therefore amine units are rarely required for H_2S removal. The largest source of emissions from midstream gas operations are compressor engines used to pressurize gas for transport. Compressor engines may use diesel fuel, but normally they are powered by natural gas. Newer compressor engines may include pollution control equipment, such as selective catalytic reduction systems to reduce NO_X emissions.

METHODS

EMISSIONS INVENTORY

Annual emissions of NO_X, VOCs, PM_{10}, CO, SO_2, CO_2, and CH_4 from gas production activities within the Fayetteville Shale region were estimated for the year 2008, which was chosen because it is the most recent year for which the United States Environmental Protection Agency (USEPA) developed a comprehensive National Emissions Inventory (NEI). Emissions were estimated at the county level for compressor stations, well drilling and completions, and fugitive sources. Emissions estimates were submitted to USEPA for inclusion in the 2008 NEI version 2.

To estimate compressor station emissions of NO_X, VOCs, PM_{10}, CO, and SO_2, a list of engines located at compressor stations was compiled from the Arkansas Department of Environmental Quality (ADEQ) Facility and Permit Summary database (PDS). Major source compressor stations reported emissions to the ADEQ as part of the 2008 NEI. Minor source compressor station emissions were conservatively assumed to equal their permitted emission limits adjusted by the number of months each engine was operational in 2008. Emissions of CO_2 and CH_4 from compressor stations were estimated using emission factors from Armendariz (2009). Emissions from individual compressor stations were aggregated to the county level.

Emissions from well drilling and completion including drilling rigs, hydraulic fracturing pumps, and well flowback venting were based on the number of wells completed in 2008 as reported by AOGC. Emissions were estimated at the county level using methods similar to Armendariz (2009) and Bar-Ilan et al. (2008), but with emission equations modified to reflect typical operation procedures in the Fayetteville Shale.

Fugitive emissions from gas production, processing, and transmission were based on 2008 gas production rates reported by AOGC. Emissions were estimated at the county-level using methods similar to Armendariz 2009 with emission factors adjusted to reflect the average composition of gas from Fayetteville Shale wells.

AMBIENT AIR MONITORING

Site Selection

Ambient air quality was monitored around the perimeter of 13 natural gas development sites and one control site in the Fayetteville Shale. This study focused on the core area of gas development in Cleburne, Conway, Faulkner, Van Buren, and White counties. Monitored sites included four compressor stations, six drilling rigs, and three hydraulic fracturing operations. All sites were operated by Southwestern Energy or Chesapeake Energy and their subsidiaries. During the study, BHP Billiton acquired all Chesapeake Energy assets in the Fayetteville Shale. Compressor station monitoring sites were randomly selected from a subset of facilities with active air permits for minor source natural gas compression facilities. To focus on sites with the greatest potential health impact, prospective monitoring sites were narrowed to permitted facilities located within five miles of both a major road and municipality and containing four or more stationary engines and one or more glycol dehydrator units. Compressor station engines operated normally during air monitoring. Drilling rig and hydraulic fracturing sites were selected in consultation with the operators for safety and logistical reasons. Drilling rig and hydraulic fracturing sites were actively undergoing drilling or hydraulic fracturing during air monitoring.

Analytical Methods

AreaRAEs Multi-Gas Monitors made by RAE Systems were used to measure the concentrations of VOCs, nitrogen oxide (NO), and nitrogen dioxide (NO_2). Concentrations of NO and NO_2 were determined with electrochemical sensor modules. VOC concentration was determined by a photoionization detector using a 10.6 electron volt (eV) ultraviolet lamp. RAE Systems Technical Note TN-106 provides a list of 266 organic compounds that have an ionization energy of 10.6 eV or lower and sufficient volatility to allow detection in ambient air. AreaRAEs measure the total concentration of VOCs as a class of compounds and cannot identify or quantify the concentration of individual VOC compounds. AreaRAEs transmit data wirelessly to a laptop computer with a RAE Systems RAELink 2 receiver.

RAE Systems hand-held ppbRAE Plus Monitors were used to measure the concentration of VOCs in ambient air. Similar to the AreaRAE, the ppbRAE uses a photoionization detector with a 10.6 eV ultraviolet lamp to detect approximately 266 organic compounds. The ppbRAE plus has a lower detection limit and 100-fold more sensitive resolution than the AreaRAE and can detect VOCs in the parts per billion (ppb) range. Similar to the AreaRAEs, ppbRAEs measure the total concentration of VOCs as a class of compounds and cannot identify or quantify the concentration of individual VOC compounds. Data are logged by the ppbRAE units and later transferred to a computer.

A Coastal Environmental System Weatherpak was used to measure temperature, relative humidity, wind speed, and wind direction on a continuous basis. The Weatherpak transmits data wirelessly to a laptop computer with a RAE Systems RAELink 2 receiver.

Monitoring Protocol

AreaRAEs were used to measure the concentrations of NO, NO_2, and VOCs in ambient air. Four AreaRAEs were positioned at the mid-point of each perimeter side named for the corresponding cardinal direction. A fifth AreaRAE was collocated with another AreaRAE and functioned as a duplicate for quality control. When conditions permitted, a sixth AreaRAE was located approximately 100 meters upwind of the site to monitor background ambient air quality. All AreaRAEs were mounted on tripods at a height of approximately five feet. AreaRAEs were allowed to monitor on a continuous basis at five second intervals for approximately four to six hours.

ppbRAEs were used to measure low concentrations of VOCs that fall below the detection limit of the AreaRAEs. Monitoring personnel measured VOC concentration around the perimeter of sites by carrying ppbRAEs along perimeter transects approximately every one to two hours. For quality control, each person carried two ppbRAEs during simultaneous perimeter transects starting at opposite sides of the site. ppbRAEs were co-located with AreaRAEs for quality control of VOC measurements when not in use for transects. ppbRAEs were set to monitor continuously at five second intervals for the entire sampling period.

A Coastal Environmental System Weatherpak was deployed at monitoring sites to record measurements of temperature, relative humidity, wind speed, and wind direction on a continuous basis at five second intervals during the entire monitoring period. A Trimble GeoXM handheld GPS unit was used to record the coordinates of stationary monitor locations and site perimeters.

Sampling protocols were occasionally modified due to equipment failure or site-specific safety considerations. ADEQ staff followed safety regulations at all times when on site.

Quality Assurance

AreaRAEs and ppbRAEs were zeroed and calibrated onsite prior to monitoring and challenged with calibration gas after monitoring. Data were flagged from instruments that failed calibration or experienced over 20% drift. Additional quality assurance (QA) came from co-locating instruments; one of the stationary AreaRAEs was co-located with a second AreaRAE throughout the monitoring period. During perimeter transects, two ppbRAEs were used to simultaneously measure VOC. When not in use for transects, ppbRAEs were co-located with stationary AreaRAEs to serve as quality control for VOC measurements.

Data Analysis

Data from AreaRAEs, ppbRAEs, and the Weatherpak were synchronized and averaged at one minute intervals. While all other values used the arithmetic mean as an average, wind direction and wind speed used vector averages. Stationary monitoring data were analyzed by calculating the average, standard deviation, and range of values measured at each location over the monitoring period. Transect data were analyzed by calculating the average, standard deviation, and range of values measured at each perimeter side for both individual transects and all transects made during the day.

Scatterplot matrices of data were created to determine the interaction among variables. After determining that wind direction, but not temperature or relative humidity, was an important variable affecting VOC concentration, a general linear model was performed on data from stationary monitors. The general linear model used the formula: [VOC] = Monitor Location * Wind Direction. Statistics were performed using the program R with the R Commander package (Fox 2010).

GPS data was processed using Trimble GPS Pathfinder Office and displayed using Esri ArcGIS 10. Geospatial data and overlaid on maps of aerial photography from Microsoft Bing Maps using the WGS1984 datum. Wind roses were created using Lakes Environmental WRPlot to calculate the distribution of wind speed and direction during the monitoring period.

RESULTS

EMISSIONS INVENTORY SUMMARY

Natural gas production activities within the Fayetteville Shale during the year 2008 were estimated to emit 5,002 tons NO_X, 977 tons VOC, 674 tons PM_{10}, 3,377 tons CO, 128 tons SO_2, 112,877 tons CH_4, and 1,225,643 tons CO_2 (Table 1). Compressor engines were the largest source of all pollutants except for PM_{10}, which was primarily emitted by drilling rigs, and CH_4, which was primarily emitted by fugitive sources and well flowback venting.

In 2008, the Fayetteville Shale had 1,303 active wells that produced 273 billion cubic feet (BCF) of gas. Of those wells, 704 were new wells that were drilled, hydraulically fractured, and completed in 2008. The highest estimated emissions were from Van Buren, White, and Conway counties, which together produced over 90% of the gas in the Fayetteville Shale in 2008 (Table 2.)

There were 356 compressor engines at 106 permitted minor source compressor stations that were active in 2008. None of the 31 large major source compressor stations were included in the emissions inventory because they are used for compressing gas in interstate gas lines rather than for gas produced in the Fayetteville Shale.

AMBIENT AIR MONITORING SUMMARY

Air monitoring was performed around the perimeter of six drilling sites, three hydraulic fracturing sites, four compressor stations, and one control site (Table 3). At all sites, concentrations of NO and NO_2 rarely exceeded the AreaRAE detection limits (2,000 ppb and 300 ppb, respectively). The few times NO concentration did exceed the detection limit (e.g. Poole-Kirtley and Jacobs 7-23H24), quality assurance measures indicated that the readings were erroneous due to instrument failure. At the hydraulic fracturing sites, compressor stations, and control site, VOC concentration was almost always below or near the AreaRAE and ppbRAE detection limits (100 and 20 ppb, respectively). At drilling sites, VOC concentrations were elevated with the average concentrations ranging from 38 to 427 ppb during perimeter transects and <100 to 678 ppb at stationary monitors. General linear model results indicate that the spatial and temporal distribution of VOC concentrations at most drilling sites was significantly affected by monitor location, wind direction, and the interaction between location and wind direction. Air monitoring equipment performed adequately overall but was not sensitive enough to detect pollutants, especially NO and NO_2, at the low concentrations usually existing at the sites. There were a few minor quality assurance issues that caused the rejection of some data. AreaRAE NO and NO_2 sensors were susceptible to drift that occasionally caused false positive readings of concentrations above the detection limits. Drift appeared to be more pronounced on days with higher temperatures, which sometimes exceeded 100°F. For VOC measurements, there was some discrepancy between the concentrations measured by co-located AreaRAEs and ppbRAEs. In general, ppbRAEs tended to read higher VOC concentrations than AreaRAEs but a strong correlation still existed between the instruments. At the low range of VOC concentration, ppbRAEs are expected to be more accurate than the AreaRAEs, which are designed for measuring high concentrations. There were also some issues with temporary contamination of ppbRAEs. If a ppbRAE was used to monitor air quality in an area with a VOC concentration above 1 ppm and then moved to an area with a low VOC concentration, the ppbRAE would read initially high and steadily decrease, suggesting that it had been temporarily contaminated with VOCs. When possible, this effect would be minimized by waiting for ppbRAE readings to stabilize after moving them from a high to low concentration area.

Table 1. Estimated 2008 emissions by sector of natural gas production activities in the Fayetteville Shale.

	2008 Emissions (tons)						
	NO_X	**VOC**	**PM_{10}**	**CO**	**SO_2**	**CH_4**	**CO_2**
Compressor Engines	3381	787	79	3258	106	13833	1225643
Well Drilling	1336	110	490	98	18	0	51196
Hydraulic Fracturing	285	23	105	21	4	0	10939
Well Venting	0	33	0	0	0	58033	5620
Production Fugitive	0	7	0	0	0	12619	1222
Processing Fugitive	0	4	0	0	0	6309	611
Transmission Fugitive	0	12	0	0	0	22083	2139
Total Emissions	**5002**	**977**	**674**	**3377**	**128**	**112877**	**1297371**

Table 2. Estimated 2008 emissions by county from natural gas production activities in the Fayetteville Shale. Gas production in million cubic feet (MMCF) and the number of active and new wells in each county is also included.

County	**Production**	**Active Wells**	**New Wells**	**Emissions (tons)**						
	MMCF	**#**	**#**	**NO_X**	**VOC**	**PM_{10}**	**CO**	**SO_2**	**CH_4**	**CO_2**
Cleburne	9064	57	38	215	29	35	133	2	4860	36265
Conway	76219	305	142	1038	240	124	674	11	26335	296919
Faulkner	12413	85	32	427	97	32	401	3	5927	129329
Franklin	169	9	0	0	0	0	0	0	25	2
Independence	292	7	7	23	5	6	8	0	640	2378
Jackson	292	3	3	7	1	3	1	0	291	293
Johnson	22	1	0	0	0	0	0	0	3	0
Pope	1823	22	14	107	10	12	52	1	1526	10961
Van Buren	98794	453	271	1973	373	244	1321	16	41789	437426
White	74268	361	197	1211	223	217	786	95	31480	383796
Total	**273355**	**1303**	**704**	**5002**	**977**	**674**	**3377**	**128**	**112877**	**1297371**

Table 3. Data summary by air monitoring site. Average and maximum concentrations of air pollutants measured at 13 natural gas sites and one control site in the Fayetteville Shale region. NO, NO_2, and VOC stationary concentrations are the daily averages and maximum 15 minute rolling averages measured by five AreaRAE monitors at stationary locations along site perimeters. VOC transect concentrations are the daily averaged measured by ppbRAEs during four to ten site perimeter transects and the maximum averages recorded at a single perimeter side during a single transect. Data from instruments that failed quality assurance criteria are indicated with an asterisk (*).

Site Name	Site Type	Monitoring Date	NO (ppb)		NO_2 (ppb)		VOC stationary (ppb)		VOC transect (ppb)	
			Avg.	Max.	Avg.	Max.	Avg.	Max.	Avg.	Max.
Lyle Wilson	Drilling	3/7/2011	<2000		<300		231	2316	180	1134
Wilcox	Drilling	4/13/2011	<2000		<300		678	3914	140	1942
Cockrell	Drilling	4/29/2011	<2000		<300		273	5321	427	2301
Brown	Drilling	5/5/2011	<2000		<300		<100	350	38	194
Boy Scout	Drilling	5/19/2011	<2000		<300		571	4175	408	2247
Poole-Kirtley	Drilling	6/1/2011	2459	4661*	<300	319*	<100	480	159	1534
AGFC	Fracturing	5/26/2011	<2000		<300		<100	324	<20	
Jacobs 7-23H24	Fracturing	6/23/2011	<2000	3833*	<300		<100	379	<20	54
Jacobs 9-23H15	Fracturing	6/28/2011	<2000		<300		<100	837	<20	
Caddis 2	Compressor	11/10/2010	<2000		<300		<100		NA	
Greer Lake 2	Compressor	11/23/2010	<2000		<300		<100		NA	
Greer Lake 3	Compressor	12/1/2010	<2000		<300		<100	158	NA	
Cove Creek 1	Compressor	4/5/2011	<2000		<300		<100		<20	
Woolly Hollow	Control	5/17/2011	<2000		<300		<100	178	NA	

Lyle Wilson drilling site

Results

On March 7, 2011 between 10:45 AM and 3:45 PM, air monitoring was conducted at the Lyle Wilson 7-15 1-9H10 well pad during drilling operations. During the monitoring period, the average temperature was 46°F (7.5°C), and the wind resultant vector was from the southeast. The site is located at 35.25951°N, -92.60703° W in Conway County. The well was operated by Chesapeake Energy during monitoring but has since been sold to BHP Billiton. Drilling was performed by Nomac Rig 53.

At stationary monitor locations, NO and NO_2 did not exceed the detection limits of 2,000 ppb and 300 ppb, respectively. Average VOC concentrations as measured by the AreaRAEs were 1,118 ppb at the south monitor and below the 100 ppb detection limit at all other monitors. Average VOC concentrations as measured by the ppbRAEs were 1,481 ppb at the south monitor, 44 ppb at the background monitor, and below the 20 ppb detection limit at all other monitors. During perimeter transects, the highest average VOC concentration as measured by the ppbRAEs was 38 ppb on the north side, 58 ppb on the east side, 1,134 ppb on the south side, and 40 ppb on the west side. The general linear model of monitor location and wind direction interaction was significant for both sets of stationary monitor measurements. For AreaRAEs, the model had significant effects for location ($p < 2E\text{-}16$; $R^2 = 0.8137$). For ppbRAEs, the model had significant effects for location and location-wind direction interaction ($p < 2E\text{-}16$; $R^2 = 0.2633$).

Discussion

Measured VOC concentration was highest at the south side of the Lyle Wilson well pad during drilling operations. The variation in VOC concentration at the south AreaRAE was closely related to wind direction, with higher VOC concentration occurring when wind was blowing more from the south than east. A possible source of VOC emissions was the open tanks of oil-based drilling mud located immediately south of the rig. The south AreaRAE was positioned on the site perimeter approximately 10 meters southwest of the mud tank. When wind was blowing from the east-southeast, VOC emissions from the mud tanks may have been carried away from the south monitor. When wind was blowing from the south, VOC emissions would have blown against the rig and may have been carried in eddies back to the nearby south AreaRAE.

Wilcox drilling site

Results

On April 13, 2011 between 9:45 AM and 3:45 PM, air monitoring was conducted at the Wilcox 7-15 1-10H well pad during drilling operations. During the monitoring period, the average temperature was 76°F (24.5°C), and the wind resultant vector was from the south. The site is located at 35.260882° N, -92.269304°W in Faulkner County. The well pad was operated by Chesapeake Energy at the time of monitoring but has since been sold to BHP Billiton. Drilling was performed by Nomac Rig 52.

At stationary monitor locations, NO and NO_2 did not exceed the detection limits of 2,000 ppb and 300 ppb, respectively. Average VOC concentrations as measured by the AreaRAEs were 640 ppb at the west monitor and below the 100 ppb detection limit at all other monitors. Average VOC concentrations as measured by the ppbRAEs were 57 ppb at the north monitor, 28 ppb at the south monitor, 1,125 ppb at the west monitor, and below the 20 ppb detection limit at all other monitors. During perimeter transects, the highest average VOC concentrations as measured by the ppbRAEs were 203 ppb on the north side, 34 ppb on the east side, 615 ppb on the south side, and 1,942 ppb on the west side. The general linear model of monitor location and wind direction interaction was significant for both sets of stationary monitor VOC measurements. For AreaRAEs, the model had significant effects for location and location-wind direction interaction ($p < 2E-16$; $R^2 = 0.7493$). For ppbRAEs, the model had significant effects for location only ($p < 2E-16$; $R^2 = 0.3845$).

Discussion

VOC concentration at the Wilcox well pad during drilling operations was highly variable but generally highest at the west stationary monitor and the north, west, and south side transects. The general linear model indicates that wind direction had significant effects on the variability in VOC concentration. A possible source of VOC emissions was the open tank of oil-based drilling mud located on the west side of the drilling site. During the monitoring period, wind direction shifted between south and west winds. When wind was blowing from a southerly direction, the VOC concentration was highest at the west monitor. The relationship between the spatiotemporal variation in VOC concentration and wind direction suggests that elevated VOC concentrations occurred when downwind from the mud tanks.

Cockrell drilling site

Results

On April 29, 2011 between 9:40 AM and 3:00 PM, air monitoring was conducted at the Cockrell 7-23 1-12H well pad during drilling operations. During the monitoring period the average temperature was 76 °F (24.7°C) and the wind resultant vector was from the southwest. The site is located at 35.249596°N, -92.330398°W in Faulkner County. The well was operated by Chesapeake Energy during monitoring but has since been sold to BHP Billiton. Drilling was performed by Nomac Rig 104.

At stationary monitor locations, NO and NO_2 did not exceed the detection limits of 2,000 ppb and 300 ppb, respectively. Average VOC concentrations as measured by the AreaRAEs were 211 ppb at the north monitor, 1,147 ppb at the east monitor, and below the 100 ppb detection limit at all other monitors. Average VOC concentrations as measured by the ppbRAEs were 532 ppb at the north monitor, 2,026 ppb at the east monitor, and below the 20 ppb detection limit at all other monitors. During perimeter transects, the highest average VOC concentrations as measured by the ppbRAEs were 1,054 ppb on the north side, 2,301 ppb on the east side, 1,637 ppb on the south side, and 30 ppb on the west side. The general linear model of monitor location and wind direction interaction was significant for both sets of stationary monitor VOC measurements. For AreaRAEs, the model had significant effects for location and location-wind direction interaction ($p < 2E\text{-}16$; $R^2 = 0.436$). For ppbRAEs, the model had significant effects for location, wind direction, and location-wind direction interaction ($p < 2E\text{-}16$; $R^2 = 0.3602$).

Discussion

The Cockrell drilling site had the highest measured VOC concentrations among all the sites studied. Measured VOC concentration was highest at the east stationary monitor and the north, east, and south side transects. VOC concentration was highly variable and the general linear model indicates that wind direction and monitor location had significant effects on this variability. A possible source of VOC emissions was the open tank of oil-based drilling mud located on the south side of the drilling site. The relationship between the spatiotemporal variation in VOC concentration and wind direction indicates that elevated VOC was measured when monitors were downwind from the mud tank. For example, 175 minutes into the study, the wind decidedly shifted from blowing from the west to blowing more from the south. The monitors at the east and north perimeter sides recorded the highest VOC concentrations when each monitor was downwind from the mud tank.

Brown drilling site

Results

On May 5, 2011 between 10:00 AM and 3:00 PM, air monitoring was conducted at the Brown 09-13 4-31H25 well pad during drilling operations. During the monitoring period the average temperature was 67 °F (19.2°C) and the wind resultant vector was from the south-southwest. The site is located at 35.369294° N, -92.412323° W in Van Buren County. The well is operated by Southwestern Energy and drilling was performed by SEECO Rig 7.

At stationary monitors locations, NO and NO_2 did not exceed the detection limits of 2,000 ppb and 300 ppb, respectively. Average VOC concentrations as measured by the AreaRAEs were 115 ppb at the north monitor and below the 100 ppb detection limit at all other monitors. Average VOC concentrations as measured by the ppbRAEs were 248 ppb at the north monitor, 28 ppb at the east monitor, and below the 20 ppb detection limit at all other monitors. During perimeter transects, the highest average VOC concentrations as measured by the ppbRAEs were 194 ppb on the north side, 178 ppb on the east side, and below the 20 ppb detection limit on the west and south sides. The general linear model of monitor location and wind direction interaction was significant for both sets of stationary monitor VOC measurements. For AreaRAEs, the model had significant effects for location-wind direction interaction ($p < 2E\text{-}16$; $R^2 = 0.3487$). For ppbRAEs, the model had significant effects for location, wind direction, and location-wind direction interaction ($p < 2E\text{-}16$; $R^2 = 0.3694$).

Discussion

Compared to other monitored drilling sites, measured VOC concentrations were lower at the Brown site. The highest VOC concentrations were measured along the north side of the site, which was closest to the open tank of oil-based drilling mud. The north side of the site was also downwind from the mud tank during most of the monitoring period. These findings provide evidence that the mud tank was the likely source of VOC emissions. However, the AreaRAE closest to the mud tank was placed further from the tank compared to other drilling sites due to safety concerns, which may explain why VOC concentrations at Brown were not as high as at the other drilling sites.

Boy Scout drilling site

Results

On May 19, 2011 between 9:25 AM and 2:00 PM, air monitoring was conducted at the Boy Scout 8-14 6-1H35 well pad during drilling operations. During the monitoring period the average temperature was 77°F (24.8°C) and the wind resultant vector was from the south. The site is located in Faulkner County at 35.354404° N, -92.435908°W. The well is operated by Southwestern Energy and drilling was performed by SEECO Rig 7.

At stationary monitor locations, NO and NO_2 did not exceed the detection limits of 2,000 ppb and 300 ppb, respectively). Average VOC concentrations as measured by the AreaRAEs were 1,693 ppb at the west monitor and below the 100 ppb detection limit at all other monitors. Average VOC concentrations as measured by the ppbRAEs were 3,657 ppb at the west monitor and below the 20 ppb detection limit at the other monitors. During perimeter transects, the highest average VOC concentrations as measured by the ppbRAEs were 435 ppb on the north side, 54 ppb on the east side, 73 ppb on the south side, and 2,247 ppb on the west side. The general linear model of monitor location and wind direction interaction was significant for both sets of stationary monitor measurements. For AreaRAEs, the model had significant effects for location and location-wind direction interaction ($p < 2E\text{-}16$; $R^2 = 0.6722$). For ppbRAEs, the model had significant effects for location and location-wind direction interaction ($p < 2E\text{-}16$; $R^2 = 0.7072$).

Discussion

As with other drilling sites, VOC concentrations were elevated, and the open tank of oil-based mud was determined to be a likely source of VOC emissions. The highest maximum and average VOC concentration occurred at the west monitor location, which was closest to the mud tank. Furthermore, VOC concentration at the west monitor location increased as wind shifted from south to southeast and decreased when wind shifted from south to southwest. VOC measurements during perimeter transects also supported the hypothesis that the mud tank was the VOC emissions source, with the highest average concentration at the west side closest to the mud tank and the second highest average concentration at the north side downwind from the mud tank.

Poole-Kirtley drilling site

Results

On June 1, 2011 between 9:30 AM and 1:45 PM, air monitoring was conducted at the Poole-Kirtley well pad during drilling operations. However, between 10:35 and 11:43 AM the laptop receiving AreaRAE and Weatherpak data malfunctioned and therefore only ppbRAE data is available during that 68 minute period. During the monitoring period when Weatherpak data is available, the average temperature was 89°F degrees (31.8°C) and the wind resultant vector was from the south. The site is located at 35.313396° N, -92.576301°W in Conway County. The well is operated by Southwestern Energy and drilling was performed by SEECO Rig 26.

At stationary monitor locations, average NO concentration was measured as 2,417 ppb at the north monitor, 2,119 ppb at the east monitor, 3,544 ppb at the south monitor, 2,601 ppb at the west monitor, and below the 2,000 ppb detection limit at the background monitor. However, the NO data is suspect for a couple reasons. First, NO concentration increased steadily over time in a pattern that suggests sensor drift for all monitors including the background monitor. Second, none of the AreaRAEs met QA criteria for the post-monitoring calibration gas challenge, with a 20 to 60% higher measured value of the 5 ppm NO calibration gas. Average NO_2 concentration did not exceed the detection limits of 300 ppb at all monitors. Average VOC concentrations as measured by the AreaRAEs were 358 ppb at the west monitor and below the 100 ppb detection limit at all other monitors. Average VOC concentration as measured by the ppbRAEs were 274 ppb at the north monitor, 125 ppb at the south monitor, and below the 20 ppb detection limit at all other monitors. During perimeter transects, the highest average VOC concentrations as measured by the ppbRAEs were 1,531 ppb on the north side, below the 20 ppb detection limit on the east side, 212 ppb on the south side, and 1,534 ppb on the west side. The general linear model of monitor location and wind direction interaction was significant for both sets of stationary monitor VOC measurements. For AreaRAEs, the model had significant effects for location ($p < 2E\text{-}16$; $R^2 = 0.7305$). For ppbRAEs, the model had an R^2 of 0.0661 with significant effects for location ($p < 8E\text{-}7$; $R^2 = 0.0661$)

Discussion

Ambient air quality measurements around the Poole-Kirtley well pad during drilling operations detected both VOC and NO above detection limits. However, NO data was likely erroneous due to instrument failure. Similar to other drilling sites, it appears that elevated VOC concentration was due to emissions from the open tank of oil-based drilling mud. Measured VOC concentration was highest on the north side, which was closest to the mud tank. The next highest VOC concentrations were at the west and south sides, which were downwind of the mud tank for part of the day. Wind direction had a strong effect on VOC concentration measured by ppbRAEs at the north monitor, with VOC concentration decreasing as winds shifted from southwest to east. These findings provide evidence that the mud tank was the likely source of VOC emissions.

AGFC hydraulic fracturing site

Results

On May 26, 2011 between 10:10 AM and 3:30 PM, air monitoring was conducted at the AGFC 10-16 1-2H11 well pad during hydraulic fracturing operations. During the monitoring period, the average temperature was 64°F (17.8° C), and the wind resultant vector was from the northwest. The site is located at 35.5449069°N, -92.6540498° W in Van Buren County. The well was operated by Chesapeake Energy during monitoring but has since been sold to BHP Billiton. Hydraulic fracturing was performed by CalFrac Well Services. The site is located in the Arkansas Game and Fish Commission (AGFC) Gulf Mountain Wildlife Management Area and therefore was developed using United States Fish and Wildlife Service best management practices for Fayetteville Shale natural gas activities (USFWS 2007).

At stationary monitor locations, NO and NO_2 did not exceed the detection limits of 2,000 ppb and 300 ppb, respectively. Average VOC concentrations as measured by the AreaRAEs were 211 ppb at the north monitor and below the 100 ppb detection limit at the other monitors, with the exception of the co-located west AreaRAE that failed quality assurance due to instrument malfunction. Average VOC concentration as measured by the ppbRAEs was below the 20 ppb detection limit at all monitors. During perimeter transects, the average VOC concentration as measured by the ppbRAEs was below the 20 ppb detection limit at all perimeter sides. The general linear model of monitor location and wind direction interaction was significant for AreaRAE VOC measurements with significant effects for location ($p < 2E\text{-}16$; $R^2 = 0.9182$).

Discussion

The only pollutant detected above detection limit at the AGFC hydraulic fracturing site was VOC measured by the AreaRAEs, which had maximum 1-minute averages of 400 and 145 ppb at the north and west monitor locations, respectively. However, VOC as measured by ppbRAEs never exceeded 34 ppb during perimeter transects and was below the 20 ppb detection limit when co-located with the AreaRAEs. Although the north and west AreaRAEs passed quality assurance criteria, their data is suspect because ppbRAEs are more accurate than AreaRAEs at the ppb range of VOC concentrations. Most likely, VOC concentrations of below 20 ppb measured by the ppbRAEs more accurately represent air quality at the site.

Jacobs 10-16 7-23H24 hydraulic fracturing site

Results

On June 23, 2011 between 10:15 AM and 3:00 PM, air monitoring was conducted at the Jacobs 10-16 7-23H24 well pad during hydraulic fracturing operations. During the monitoring period, the average temperature was 90°F (32.4°C), and the wind resultant vector was from the west. The site is located at 35.496462° N, -92.664976° W in Van Buren County. The well pad is operated by Southwestern Energy and hydraulic fracturing was performed by Cudd Energy Services.

At stationary monitor locations, average NO concentrations were measured as 2,330 ppb at the west monitor, 2,190 ppb at the south monitor, and below the 2,000 ppb detection limit at all other monitors. However, the NO data from the south and west monitors is suspect for several reasons. First, the measured average NO concentration at the co-located south monitor was 560 ppb, well below the detection limit. Second, the concentration of NO increased steadily over time in a pattern that suggests sensor drift. Finally, the south and west AreaRAEs failed QA criteria during the post-monitoring NO calibration gas challenge, with a respective 80% and 50% increase in measured concentration of the 5 ppm NO standard. NO_2 did not exceed the detection limit of 300 ppb at all monitors. Average VOC concentrations as measured by the AreaRAEs were below the 100 ppb detection limit at all monitors. Average VOC concentrations as measured by the ppbRAEs were below the 20 ppb detection limit at all monitors. During perimeter transects, the average VOC concentrations as measured by the ppbRAEs were below the 20 ppb detection limit on all perimeter sides. The general linear model of monitor location and wind direction interaction was significant for both sets of stationary monitor VOC measurements. For AreaRAEs, the model had significant effects for location and location-wind direction interaction ($p < 2E\text{-}16$; $R^2 = 0.8225$). For ppbRAEs, the model had significant effects for location-wind direction interaction ($p < 2E\text{-}16$; $R^2 = 0.0927$).

Discussion

Ambient air quality measured around the perimeter of the Jacobs site during hydraulic fracturing did not exceed the detection limits for NO_2 or VOC. Two AreaRAE monitors did detect NO concentrations above the 2000 ppb detection limit, but the data is likely erroneous due to instrument failure. The hot weather during monitoring may have contributed to problems with the NO measurements; the temperature reached 96°F, near the 113°F maximum operating temperature for AreaRAE NO sensors (RAE Systems 2008).

Jacobs 10-16 9-23H15 hydraulic fracturing site

Results

On June 28, 2011 between 10:15 AM and 3:00 PM, air monitoring was conducted at the Jacobs 10-16 9-23H15 well pad during hydraulic fracturing operations. During the monitoring period, the average temperature was 75°F (23.8°C), and the wind resultant vector was from the south. The site is located at 35.488552°N, -92.660367° W in Van Buren County. The well pad is operated by Southwestern Energy, and hydraulic fracturing was performed by Cudd Energy Services.

At stationary monitor locations, NO and NO_2 did not exceed the detection limits of 2000 ppb and 300 ppb, respectively. Average VOC concentrations as measured by the AreaRAEs were below the 100 ppb detection limit at all monitors. Average VOC concentrations as measured by the ppbRAEs were below the 20 ppb detection limit at all monitors. During perimeter transects, the average VOC concentrations as measured by the ppbRAEs were below the 20 ppb detection limit at all perimeter sides. The general linear model of monitor location and wind direction interaction was significant for both sets of stationary monitor measurements. For AreaRAEs, the model had significant effects for location and location-wind direction interaction ($p < 2E\text{-}16$; $R^2 = 0.3361$). For ppbRAEs, the model had significant effects for location only ($p < 2E\text{-}16$; $R^2 = 0.4202$).

Discussion

The ambient air quality measured around the Jacobs 10-16 9-23H15 well pad during hydraulic fracturing operations did not exceed the detection limits for NO, NO_2, or VOC at any time during the monitoring period.

Caddis compressor station

Results

On November 10, 2011 between 11:10 AM and 1:00 PM, air monitoring was conducted at the Caddis CPF-2 compressor station during normal operations. During the monitoring period, the average temperature was 73°F (22.8°C), and the wind resultant vector was from the south. The site is located at 35.349136°N, -92.399876°W in Faulkner County. The site is operated by DeSoto Gathering Company, a subsidiary of Southwestern Energy. There are six natural gas powered engines at the site: four 1340 horsepower Caterpillar G3516 engines and two 1775 horsepower Caterpillar G3606 engines. The site also has two dehydrators and two produced water tanks. The facility has an ADEQ minor source air permit under Arkansas Facility Identification Number (AFIN) 23-01027.

At stationary monitor locations, NO and NO_2 did not exceed the detection limits of 2,000 ppb and 300 ppb, respectively. Average VOC concentrations as measured by the AreaRAEs were below the 100 ppb detection limit for all the monitors. Average VOC concentrations were not measured by the ppbRAEs. No perimeter transects were performed. The general linear model of monitor location and wind direction interaction was significant for AreaRAE VOC measurements with significant effects for location and location-wind direction interaction ($p < 2E-16$; $R^2 = 0.5076$).

Discussion

The ambient air quality measured around Caddis CPF-2 did not exceed the detection limits for NO, NO_2, or VOC at any time during the monitoring period.

Greer Lake 2 compressor station

Results

On November 23, 2010 between 9:50 AM and 2:20 PM, air monitoring was conducted at the SW Greer Lake CPF-2 compressor station during normal operations. During the monitoring period, the average temperature was 57°F (14.1°C), and the wind resultant vector was from the northeast. The site is located at 35.476934° N, -92.359871° W in Van Buren County. The site is operated by DeSoto Gathering Company, a subsidiary of Southwestern Energy. There are six natural gas powered engines at the site: four 1,340 horsepower Caterpillar G3516 engines and two 1,775 horsepower Caterpillar G3606 engines. The site also has two dehydrators and two produced water tanks. The facility has an ADEQ minor source air permit under AFIN 71-00353.

At stationary monitors locations, NO and NO_2 did not exceed the detection limits of 2,000 ppb and 300 ppb, respectively. Average VOC concentration as measured by the AreaRAEs was below the 100 ppb detection limit at all the monitors. Average VOC concentration was not measured by ppbRAEs. No perimeter transects were performed. The general linear model of monitor location and wind direction interaction was not significant for the stationary monitor VOC measurements ($p = 0.5826$).

Discussion

The ambient air quality measured around SW Greer Lake CPF-2 did not exceed the detection limits for NO, NO_2, or VOC at any time during the monitoring period.

Greer Lake 3 compressor station

Results

On December 1, 2010 between 9:10 AM and 2:40 PM, air monitoring was conducted at the SW Greer Lake CPF-3 compressor station during normal operations. The Weatherpak meteorological station malfunctioned during the monitoring period and therefore temperature and wind direction were not recorded. The site is located at 35.465649°N, -92.424154° W in Van Buren County. The site is operated by DeSoto Gathering Company, a subsidiary of Southwestern Energy. There are six natural gas powered engines at the site: four 1,340 horsepower Caterpillar G3516 engines and two 1,775 horsepower Caterpillar G3606 engines. The site also has two dehydrators and two produced water tanks. The facility has an ADEQ minor source air permit under AFIN 71-00401.

At stationary monitor locations, NO and NO_2 did not exceed the detection limits of 2,000 ppb and 300 ppb, respectively. Average VOC concentration as measured by the AreaRAEs was below the 100 ppb detection limit at all monitors. Average VOC concentration was not measured by ppbRAEs. Perimeter transects were not performed. No general linear model was performed since no wind direction data was recorded.

Discussion

The ambient air quality measured around SW Greer Lake CPF-3 did not exceed the detection limits for NO, NO_2, or VOC at any time during the monitoring period.

Cove Creek compressor station

Results

On April 5, 2011 between 10:15 AM and 3:20 PM, air monitoring was conducted at the Cove Creek CPF-1 compressor station during normal operations. During the monitoring period, the average temperature was 61°F (16°C), and the wind resultant vector was from the west-southwest. The site is located at 35.349136° N, -92.399876° W in Van Buren County. The site is operated by DeSoto Gathering Company, a subsidiary of Southwestern Energy. There are four 1,340 horsepower natural gas powered Caterpillar G3516 engines at the site. The site also has one dehydrator and two produced water tanks. The facility has an ADEQ minor source air permit under AFIN 23-00866.

At stationary monitor locations, NO and NO_2 did not exceed the detection limits of 2,000 ppb and 300 ppb, respectively. Average VOC concentration as measured by the AreaRAEs was below the 100 ppb detection limit at all monitors. Average VOC concentration as measured by the ppbRAEs was below the 20 ppb detection limit at all monitors. During perimeter transects, the highest average VOC concentration as measured by the ppbRAEs was below the 20 ppb detection limit for all the monitors. The general linear model of monitor location and wind direction interaction was significant for both sets of stationary monitor VOC measurements. For AreaRAEs, the overall model but none of the parameters was significant ($p < 3E\text{-}8$; $R^2 = 0.02509$). For ppbRAEs, the model had significant effects for location, wind direction, and location-wind direction interaction ($p < 2E\text{-}16$; $R^2 = 0.2389$)

Discussion

The ambient air quality measured around Cove Creek CPF-1 did not exceed the detection limits for NO, NO_2, or VOC at any time during the monitoring period.

Woolly Hollow control site

Results

On May 17, 2011 between 9:25 AM and 1:20 PM, air monitoring was conducted at Woolly Hollow State Park. During the monitoring period, the average temperature was 68°F (19.9°C), and the wind resultant vector was from the west. The site is located at 35.288136° N, -92.287145° W in Faulkner County. Woolly Hollow was monitored as a control site; the park is located in an area of extensive gas development but does not have any gas wells on its property. There is only one well located outside the park that is within one mile of the monitoring location.

At stationary monitor locations, NO and NO_2 did not exceed the detection limits of 2,000 ppb and 300 ppb, respectively. Average VOC concentrations as measured by the AreaRAEs were 122 ppb at one of the north monitors, 106 ppb at the other north monitor, and below the 100 ppb detection limit at the west and east monitors. Average VOC concentration as measured by the ppbRAEs was below the 20 ppb detection limit at all the monitors. Perimeter transects were not performed. The general linear model of monitor location and wind direction interaction was significant for both sets of stationary monitor measurements. For AreaRAEs, the model had significant effects for location ($p < 2E-16$; $R^2 = 0.8137$). For ppbRAEs, the model had significant effects for location ($p < 2E-16$; $R^2 = 0.2633$).

Discussion

As our control site, Woolly Hollow State Park was expected to contain no measurable VOCs. Aside from a very low VOC concentration detected by the north side AreaRAE, there was no measurable VOC concentration within the test site. The north side VOC average was slightly above the 100 ppb detection limit and may be due to instrument drift. These results, along with the results from the background monitors at every other site, show that background VOC concentration is typically below or slightly above the instrument detection limits.

CONCLUSIONS

EMISSIONS INVENTORY

Natural gas production activities within the Fayetteville Shale during the year 2008 were estimated to emit 5,002 tons NO_X, 977 tons VOC, 674 tons PM_{10}, 3,377 tons CO, 128 tons SO_2, 112,887 tons CH_4, and 1,297,371 tons CO_2. The total criteria pollutant emissions from Fayetteville Shale gas production is comparable to the emissions of one large stationary source; for example, the average Arkansas paper mill annually emitted approximately 1,390 tons NO_X, 1,430 tons VOC, 440 tons PM_{10}, 2,500 tons CO, and 550 tons SO_2 in 2008 (USEPA 2008). The greenhouse gases emitted annually from Fayetteville Shale gas production are equivalent to the emissions from approximately 650,000 passenger vehicles (USEPA GHG Equivalencies Calculator). The annual emissions from Fayetteville Shale are expected to have increased substantially since 2008 because of the rapid growth in the number of active wells and gas production.

Compressor engines, drilling rigs, and hydraulic fracturing pumps were primarily responsible for emissions of NO_X, CO, PM_{10}, SO_2, and CO_2. Relative to gas production, NO_X emissions in the Fayetteville Shale (18.3 tons NO_X per BCF) were similar to the Barnett Shale (18.6 tons NO_X per BCF). In contrast, VOC emissions relative to gas production were substantially lower in the Fayetteville Shale (3.6 tons VOC per BCF) compared to the Barnett Shale (33.2 tons VOC per BCF). The lower VOC emissions are due to the low VOC content of Fayetteville Shale gas, which has an average VOC content of 0.05% (SWN, personal communication) compared to 8.2% in Barnett Shale gas (Armendariz 2009). Condensate tanks, which were estimated to be a large source of VOC emissions in the Barnett Shale, are not used in the Fayetteville Shale because of the scarcity of condensable hydrocarbons in produced gas. Similarly, fugitive emission sources such as leaking valves that vent gas to the atmosphere will emit relatively low amounts of VOC in the Fayetteville Shale compared to fugitive sources in areas with VOC-rich gas like the Barnett Shale.

The emissions inventory calculates emissions based on several assumptions that increase the uncertainty of these estimates. The accuracy of future emission inventories could be increased by collecting more detailed operations and emissions data, primarily from gas operators. Compressor station emissions were assumed to equal permitted emissions limits; this method overestimates emissions since most engines emit less than permitted. Better emissions data for compressor stations could be obtained by receiving annual emissions inventory reports for minor source compressor stations from gas operators, which currently only report emissions from larger compressor stations with major source permits. Self-reported emission estimates are often based on several assumptions that may decrease their accuracy; however, compressor stations are required to undergo regular emissions testing that can be used to accurately estimate annual emissions.

Emission estimates from well drilling, hydraulic fracturing, and completion are also based on several assumptions about typical operations. Although these assumptions were updated to reflect standard operating procedures in the Fayetteville Shale, emissions estimates could be further improved by calculating emissions from individual drilling rigs and hydraulic fracturing pumps based on their actual annual usage. There are several emission sources, such as drilling mud tanks, which were not included in this emissions inventory. Developing a more detailed and accurate emissions inventory of well drilling and completion may be best performed by the gas operators themselves since the emission estimates require access to large amounts of internal data.

Fugitive emission estimates were calculated using Fayetteville Shale gas composition and the average percent loss of gas production as reported by other studies (Armendariz 2009). These estimates could be improved with more empirical data on gas leakage during well development, gas processing, and transmission from the Fayetteville Shale. Gas operators may be able to more accurately estimate fugitive emissions as part of their programs for reducing product loss.

Additionally, further uncertainty in the emissions inventory comes from the emissions of the numerous mobile sources involved in gas development, namely the trucks that transport equipment, hydraulic fracturing fluid, sand, and fuel to gas sites. These sources were not included in this emissions inventory because they are part of the on-road mobile source category, which is estimated with mobile source emissions models based on vehicular traffic. The accuracy of future mobile source emissions inventory could be improved by assuring that model inputs, such as vehicle miles traveled by vehicle type, account for traffic associated with gas production activities.

AMBIENT AIR MONITORING

With the exception of elevated VOC concentration at drilling sites, the concentrations of NO, NO_2, and VOC measured around the perimeters of compressor stations, drilling, and hydraulic fracturing sites seldom exceeded detection limits. NO and NO_2 rarely exceeded the AreaRAE detection limits (2,000 and 300 ppb, respectively) at all monitored sites. However, AreaRAE multi-gas monitors are designed primarily for the detection of high concentrations of pollutants during emergency response situations rather than low concentrations typically encountered during ambient monitoring. To determine if ambient concentration of NO_2 exceeds the 1-hour National Ambient Air Quality Standard of 100 ppb, future monitoring would need to utilize more sensitive equipment, such as chemiluminescent detectors that can detect NO and NO_2 in the ppb range.

VOC concentration was usually elevated at drilling sites and near or below detection limit at compressor station and hydraulic fracturing sites. At drilling sites, the spatial and temporal distribution of elevated VOC concentration was influenced by wind direction and indicated that the likely source of VOCs was open tanks of oil-based drilling mud. The potential health impacts of VOC depend on the concentration of individual VOC compounds, which were not determined in this study. However, the VOC emissions from drilling mud tanks may have a similar composition to diesel fuel vapor since diesel fuel is a major component of oil-based drilling mud. The American Conference of Governmental Industrial Hygienists (ACGIH) has determined that the safe limit for long-term exposure to diesel fuel vapor is an eight-hour time-weighted average concentration of 100 mg / m^3, which is equivalent 15 ppm (ACGIH 2011). VOC concentrations measured at drilling sites occasionally peaked around 15 ppm but average concentrations were below 1 ppm and therefore unlikely present a health risk if VOC emissions are similar in composition to diesel vapor. To better understand the potential impacts of VOC emissions from gas drilling on public health, future studies should determine the chemical composition of VOC emissions with instruments such as gas chromatograph-mass spectrometers that can identify and quantify individual VOCs, including higher toxicity pollutants such as benzene that may be present at low concentrations.

Future studies addressing the effects of gas development on air quality have much room to expand on the current study. As previously mentioned, air monitoring instruments used in this study were unable to measure low levels or NO_X or identify individual VOC compounds, both of which are important for assessing if air quality is harmful to public health. In addition to NO_X and VOCs, there are several other pollutants that may degrade local air quality around gas sites. Particulate matter may be of special concern because it can be emitted by both combustion sources such as compressor stations and physical sources such as road dust from truck traffic. Future studies may also want to monitor air quality at a larger group of gas sites located throughout the Fayetteville Shale since the current study focused on sites in Conway, Faulkner, and Van Buren counties. Furthermore, better data could be obtained if air quality was monitored at some sites for the entire well development process, including stages such as well flowback venting that were omitted in the current study.

EMISSIONS REDUCTIONS OPPORTUNITIES

There are several opportunities for reducing emissions from natural gas production. Armendariz discusses many of these options in detail in the Barnett Shale study (Armendariz 2009). Compressor engine emissions can be reduced by installing pollution control equipment such as NO_X-reducing non-selective catalytic reduction technology on engines that currently lack such controls. Additionally, compressor engines might be replaced with emissions-free electric motors in areas where electricity in available. Emissions from drilling rigs and hydraulic fracturing pumps can also be reduced by upgrading or replacing old equipment with lower emissions rigs and pumps.

Emissions of VOC can be decreased by reducing the loss of gas during production, particularly from flowback venting and from fugitive emission sources such as leaking valves. Many wells in the Fayetteville Shale are completed using green completion technology that minimizes the amount of time of gas is vented to the atmosphere; VOC emissions may be reduced if all new wells were required to use green completions. Fugitive emissions can be reduced by replacing natural gas-powered pneumatic devices with low-bleed or no-bleed devices that would leak less gas (Armendariz 2009). Additionally, enhancing the detection and repair of leaks at gas sites would decrease VOC emissions with the added benefit of reducing product loss.

Mud tanks were determined to be a likely source of the elevated VOC concentration measured around the perimeter of drilling sites. Unlike other VOC sources that are caused by leaking gas, mud tanks emit VOCs that are derived from the diesel fuel component of oil-based drilling muds. VOCs are primarily emitted when drilling mud and drill cuttings, a mixture of drilling mud and rock fragments from the well, are exposed to open air, which allows hydrocarbons to volatilize (USEPA 1999). At the drilling sites monitored for this study, fresh drilling mud was kept in enclosed tanks but cuttings were temporarily stored in open-top tanks. To recover mud for reuse, cuttings were often mixed with a backhoe and placed through a shale shaker, which uses vibrating screens to separate ground rock from drilling mud. It may be possible to decrease VOC emissions by modifying procedures for on-site storage and treatment of cuttings, such as covering mud tanks when not in use. Although mud tanks are a temporary and probably minor emissions source, their emissions have a strong hydrocarbon odor that may be a nuisance and potential health risk to people living near well sites during the drilling process. Reducing VOC emissions from mud tanks may provide an opportunity to improve the local air quality around active drilling sites.

SUMMARY

Fayetteville Shale gas production was determined to be a large emissions source for several criteria pollutants and greenhouse gases. Annual emissions in 2008 were estimated to be comparable to one large stationary source, and emissions have likely increased substantially with the continuing development of new gas wells. Air quality monitoring near compressor stations, drilling sites, and hydraulic fracturing sites found that NO and NO_2 concentrations were below detection limits at all sites; however, monitoring equipment was not sensitive enough to detect low concentrations of NO_2 that may cause long-term health risks. VOC concentrations were usually below detection limits at compressor stations and hydraulic fracturing sites. At drilling sites, VOC concentrations were often elevated and increased when monitors were downwind of open tanks of oil-based mud and drill cuttings. The health risk from elevated VOC concentration cannot be assessed by this study because monitoring equipment could not identify individual VOC compounds, which vary in toxicity. However, the measured concentrations are unlikely to be a major health risk if VOC emissions are similar in composition to diesel fuel, a major component of drilling mud. Future studies should monitor air quality with instruments that can detect lower concentrations of pollutants and identify individual VOC compounds to determine if the emissions from gas sites are potentially harmful to public health and welfare.

A full copy of the report can be downloaded from:
http://www.adeq.state.ar.us/air/pdfs/fayetteville_shale_air_quality_report.pdf

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