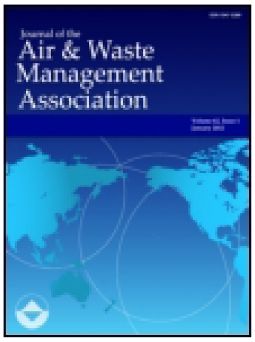

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TECHNICAL PAPER

Air pollutant emissions from the development, production, and processing of Marcellus Shale natural gas

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The Marcellus Shale is one of the largest natural gas reserves in the United States; it has recently been the focus of intense drilling and leasing activity. This paper describes an air emissions inventory for the development, production, and processing of natural gas in the Marcellus Shale region for 2009 and 2020. It includes estimates of the emissions of oxides of nitrogen (NO_x), volatile organic compounds (VOCs), and primary fine particulate matter ($\leq$2.5 μm aerodynamic diameter; $PM_{2.5}$) from major activities such as drilling, hydraulic fracturing, compressor stations, and completion venting. The inventory is constructed using a process-level approach; a Monte Carlo analysis is used to explicitly account for the uncertainty. Emissions were estimated for 2009 and projected to 2020, accounting for the effects of existing and potential additional regulations. In 2020, Marcellus activities are predicted to contribute 6–18% (95% confidence interval) of the NO_x emissions in the Marcellus region, with an average contribution of 12% (129 tons/day). In 2020, the predicted contribution of Marcellus activities to the regional anthropogenic VOC emissions ranged between 7% and 28% (95% confidence interval), with an average contribution of 12% (100 tons/day). These estimates account for the implementation of recently promulgated regulations such as the Tier 4 off-road diesel engine regulation and the U.S. Environmental Protection Agency's (EPA) Oil and Gas Rule. These regulations significantly reduce the Marcellus VOC and NO_x emissions, but there are significant opportunities for further reduction in these emissions using existing technologies.

Implications: The Marcellus Shale is one of the largest natural gas reserves in United States. The development and production of this gas may emit substantial amounts of oxides of nitrogen and volatile organic compounds. These emissions may have special significance because Marcellus development is occurring close to areas that have been designated nonattainment for the ozone standard. Control technologies exist to substantially reduce these impacts. $PM_{2.5}$ emissions are predicted to be negligible in a regional context, but elemental carbon emissions from diesel powered equipment may be important.

Introduction

The Marcellus Shale is a rock formation lying below the states of Pennsylvania, Ohio, West Virginia, New York, and Maryland, spanning a basin area of 95,000 square miles. It is estimated to contain between 1.2 and 4.1 trillion m^3 of technically recoverable natural gas (U.S. Geological Survey [USGS], 2008). It is one of the largest natural gas reserves in the United States and recently has been the focus of intense drilling and leasing activity (Considine et al., 2009, 2010, 2011; Considine, 2010).

Gas development, production, and processing activities can be a significant source of air pollution (Archuleta, 2009; Katzenstein et al., 2003). In a large basin such as the Marcellus formation, these activities involve a large number of relatively small sources that are widely distributed in space. For example, drill rigs and hydraulic fracturing ("fracing") pumps powered by off-road heavy-duty diesel engines emit oxides of nitrogen (NO_x), fine particulate matter ($\leq$2.5 μm aerodynamic diameter; $PM_{2.5}$), and volatile organic compounds (VOCs) (EPA, 2004a; 2013a,b). Diesel-powered trucks used to bring materials to and from the well site emit the same suite of pollutants (EPA, 2005). Completion venting performed to bring a well into production can be a significant source of VOCs (Bar-Ilan et al., 2008; Grant et al., 2009, Armendariz, 2009). Natural-gas-fired compressors used to maintain gas pressure emit NO_x and VOCs (Bar-Ilan et al., 2008; Grant et al., 2009). Speciation profiles such as the U.S. Environmental Protection Agency's (EPA's) SPECIATE database (EPA, 2006) and natural gas source speciation profiles (e.g., Hendler et al., 2009) indicate that VOCs emitted from these sources include alkanes (diesel engines, venting and fugitives), alkenes (diesel engines), aromatics (diesel engines), and aldehydes (diesel- and natural-gas-fired engines). NO_x and VOCs react in the presence of sunlight to produce ozone, which causes health problems such as asthma and decreased lung function (Bernard et al., 2001; Levy et al., 2001; Godish et al., 2004). The health effects of $PM_{2.5}$ are well documented and include premature mortality (Dockery and Pope, 1994; Kaiser, 2005). A major component of $PM_{2.5}$ emitted by diesel-powered engines is

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elemental carbon (EC), which may be an important driver for climate change (e.g., Bond et al., 2004).

Previous studies indicate that the aggregate emissions from shale gas activities can be significant. For example, Armendariz (2009) estimated that the combined NO_x and VOC emissions from natural gas sources exceeded on-road mobile sources in the Barnett Shale region. Furthermore, field and modeling studies have also shown that these emissions can have important impacts on local and regional air quality. Schnell et al. (2009) reported peak 1-hr ozone levels as high as 100 ppb in the Jonah Pinedale region in Wyoming, which is a hotspot for gas development and production. Elevated VOC levels were also found in large regions of Colorado, Texas, Oklahoma, and Kansas, where there is significant gas production (Katzenstein et al., 2003; Zielinska et al., 2011; Archuleta, 2008). Cook et al. (2010) used a chemical transport model to predict that gas development in the Haynesville Shale could increase the maximum daily 8-hr average ozone levels by as much as 17 ppb over parts of Louisiana and Texas. In order to protect public health and welfare, the EPA has promulgated National Ambient Air Quality Standards (NAAQS) for ozone and $PM_{2.5}$ (EPA, 2012a). Many counties in the Marcellus region currently violate these standards (EPA, 2012c), and Marcellus development may complicate these existing problems.

The goal of this work is to develop an air emission inventory for gas development, production, and processing activities in the Marcellus Shale region. Emissions were estimated for a base year (2009) and then projected out to 2020 using well drilling and production projections from the literature. For 2020, three possible control scenarios were considered: pre-2009 controls, baseline, and tight controls. The inventory estimates NO_x, $PM_{2.5}$, and VOC emissions for major sources, including drilling, hydraulic fracturing, completion venting, compressors, and truck traffic. A Monte Carlo approach was used to derive distributions of estimates to account for the uncertainty in emissions. The inventory is designed for use in a chemical transport model to simulate the effects of gas development and production on regional air quality. Natural gas development can have other environmental impacts as well. These include groundwater contamination by fracing fluid and potential displacement of coal use by natural gas, a cleaner burning fuel. These issues are outside the scope of this study. Impacts of emissions on regional air quality will be considered in a future paper.

Methodology

The emission inventory was constructed using a bottom-up, process-level approach that combines activity and emission factor data for major source categories. A flowchart of the overall approach is shown in Figure 1. The inventory was constructed in a three-step process. First, emissions were estimated for each source or process associated with the development, production, or processing of Marcellus gas (e.g., emissions associated with drilling one well). Second, the process-level emission estimates were combined to estimate the emissions for three broad types of activities: well development, gas production, and midstream processing. Well development includes the emissions from all of the processes associated with setting up one well and bringing it into production, including drilling the well, fracturing the shale rock to release the gas, and completion venting. Production emissions are associated with one producing well; they include wellhead compressors and fugitive emissions from valves, pneumatic devices, and other sources. Midstream emissions are associated with processing one unit of gas downstream of the wellhead and include gas processing plants and compressor stations. Third, the activity-level emission estimates were combined with basin-level activity data (e.g., number of wells drilled, cumulative number of wells active, or volume of gas produced) to estimate the overall, Marcellus-wide emissions for each pollutant. The input data for basin-level activity data are shown in Table 1. This analysis was performed separately for NO_x, $PM_{2.5}$, and VOCs. Table 2 lists sources considered in this study, their activity category, the pollutants they emit, and basin-level scaling parameter.

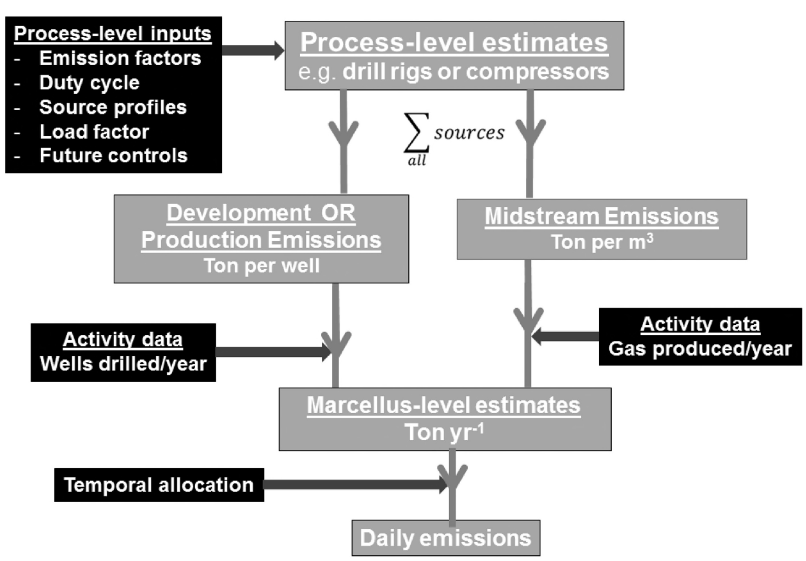

Figure 1. Flowchart showing inventory development.

Table 1. Activity data for the Marcellus region

Activity	State	2009	2020		
		Actual Data	Low	High	Reference
Number of new Marcellus wells drilled (per year)	Pennsylvania	710 (PADEP, 2011)	1500	3600	Considine (2010), Considine et al. (2011), The Nature Conservancy (2010)
	West Virginia	411 (WVGES, 2011)	273	883	Considine (2010), NETL (2010)
	New York	n/a	0	500	Considine (2010), Weinstein and Clower (2009), Lillpopp and Lindell (2011)
Cumulative number of Marcellus wells	Overall	2050 (PADEP, 2011; WVGES, 2011)	29000	49000	Considine (2010), NETL (2010), The Nature Conservancy (2011)
Marcellus gas production, billion cubic feet per day	Pennsylvania	8.6 (PADEP, 2011)	93.5	382	Considine (2010), Considine et al. (2009, 2010, 2011)
	West Virginia	5.2	17.3	382	Considine (2010), NETL (2010)
	New York	0	0	51	Considine et al. (2010)
	Overall	13.8	101	815	

Table 2. List of sources and their corresponding scaling activity parameters

Category	Source	Pollutant			Activity Scaling Parameter
		NO_x	$PM_{2.5}$	VOCs	
Well development	Drill rigs	Y	Y	Y	Number of wells
	Frac pumps	Y	Y	Y	Number of wells
	Truck Traffic	Y	Y	Y	Number of wells
	Well completion	N	N	Y	Number of Wells
Gas production	Production fugitives	N	N	Y	Cumulative number of wells
	Pneumatics	N	N	Y	Cumulative number of wells
	Wellhead compressors	Y	Y	Y	Cumulative number of wells
	Blowdown venting	N	N	Y	Cumulative number of wells
	Heaters	Y	Y	Y	Cumulative number of wells
	Condensate tanks	N	N	Y	Condensate production
Midstream	Dehydrators	Y	Y	Y	Volume of gas production
	Compressor stations	Y	Y	Y	Volume of gas production
	Fugitives:				
	Transmission	N	N	Y	Volume of gas production
	Processing	N	N	Y	Volume of gas production

Given the uncertainty in the activity and emission data, a Monte Carlo approach was used to develop distributions of emission estimates. Probability distributions were defined for each input parameter (e.g., activity and emission factors) based on a review of the literature and/or interviews with experts. To derive a single emission estimate, values for each parameter were chosen at random from each input distribution using the method of Ross (2006). The process was repeated 20,000 times to calculate a distribution of emission estimates for a given source or activity. Estimated emissions are reported as a mean value bounded by a 95% confidence interval. The basic approach is described by Cullen and Frey (1999); it has been used to develop inventories for different types of sources (Zhao and Frey 2004; Frey and Zhao 2004; Frey and Rhodes 1998; French et al., 2004; Van der Werf et al., 2010) but not for oil and gas development.

The Monte Carlo approach provides an estimate of the uncertainty in the emissions. This requires that each input parameter be represented by a distribution of population mean (or basin-wide) values. Unfortunately, relatively few measurements have been made in the Marcellus formation. Therefore, these distributions are uncertain, so data from other basins, published emission factors for comparably sized engines, and similar data sources must be used. This complicates making formal uncertainty estimates using Monte Carlo analysis.

For this work, published emission factors were often used as input distributions. These distributions represent the unit-to-unit variability in emissions, not the uncertainty in the mean (basin-wide) values. In principle, it would be preferred to sample from the distribution of the sample means during Monte Carlo analysis rather than unit-to-unit variability. However, given the thousands of units in the Marcellus region, the sample means are quite narrow and using them was judged to lead to unrealistically narrow uncertainty bounds on overall emissions. Sampling from the unit-to-unit variability is a conservative approach that results in wide uncertainty bounds in emission estimates. This approach has been previously used to construct Monte Carlo–based estimates of emission inventories with multiple sources, each having its own set of inputs, with the uncertainty being described by the 95% confidence interval of the resulting emission distributions (e.g., North American Research Strategy for Tropospheric Ozone [NARSTO], 2011; Bond et al., 2004; Frey and Zheng, 2002; Intergovernmental Panel on Climate Change [IPCC], 2000). This is the approach adopted here.

An alternative approach is to use a bootstrap or some other technique to construct distributions of means for each parameter, which would then be sampled using the Monte Carlo approach (e.g., Frey and Zhao 2004). For example, for equipment such as drill rigs that have multiple engines, a sample size equal to the number of engines on a rig (e.g., seven) was drawn every time to calculate a mean emission factor for the entire rig. This results in much narrower distributions of emission factors and other input data. For example, drill rig NO_x emission factors vary by a factor of 4, which reduces to a factor of 1.4 in the 95% confidence interval in the distribution of means.

The emission factors for major sources (which make up more than 10% of the total Marcellus emissions for a given criteria pollutant) are described in Table 3; other input data are listed in Table 4. The type of distribution assumed for each input parameter is listed in Table S10 in Supplemental Materials. For inputs with rich data sets (e.g., emission factors), the Monte Carlo analysis was performed using the distributions of actual data. For inputs with more limited data, triangular or uniform distributions were used to represent the available information. Triangular distributions were used if the available data indicated that there was a best estimate (e.g., drill rig horsepower); a uniform distribution assumes that each value was equally probable (e.g., projected future Marcellus development).

Spatial coverage of inventory

A map of the entire Marcellus formation is shown in Figure 2a. The inventory was constructed for the subset of this region shown in Figure 2b, specifically the Marcellus fairway in Pennsylvania, and portions of West Virginia and New York. The specific counties included in the inventory are listed in Table S1 in Supplemental Materials. Although there is currently a drilling moratorium in New York, it is an area where future development may occur and therefore is included in the analysis. The inventory does not include Maryland and Ohio. To date, there has been little Marcellus development in these states and projections of future development were deemed too uncertain.

Basin-level activity data

Emissions depend on the magnitude of the Marcellus well development and gas production and processing. Emissions associated with well development (e.g., drill rigs) depend on the number of wells drilled. Emissions associated with gas production depend on the cumulative number of producing wells. Midstream emissions depend on the total volume of gas produced. Data and future projections for these activity parameters are listed in Table 1. The values for 2020 reflect the wide range of projections

Table 3. Emission factors for key sources (similar data for minor sources is in Table S10 in Supplementary Materials)

Source	Pollutant	Mean	Range (Min–Max)	Comments
Drill rigs (g bhp^{-1} hr^{-1})	NO_x	5.8	2.5–10	Heavy-duty diesel engines of similar rating (500–1500 hp) (locomotives and generators)[a]
	$PM_{2.5}$	0.35	0.07–1	
	VOCs	0.6	0.25–1.6	
Frac pumps (g bhp^{-1} hr^{-1})	NO_x	5.7	2.5–10	Heavy-duty diesel engines of similar rating (1000–1500 hp) (locomotives and generators)[b]
	$PM_{2.5}$	0.4	0.09–0.9	
	VOCs	0.67	0.3–1.6	
Trucks (g $mile^{-1)}$	NO_x	50	9–90	Heavy-duty truck emission factors from literature[c]
	$PM_{2.5}$	0.32	7×10^{-4} to 1.3	
	VOCs	1.7	0.2–10	
Compressor stations (g bhp^{-1} hr^{-1})	NO_x	1.5	0.5–2.0	Data from PADEP[d]
	$PM_{2.5}$	0.014	2.5×10^{-4} to 4×10^{-2}	
	VOCs	0.46	0.1–1.8	
Condensate tanks (lb $bbl^{-1)}$	NO_x	n/a	n/a	Data from Barnett Shale and CENRAP basins used as surrogate (Armendariz, 2009; Bar-Ilan et al., 2008; Hendler et al., 2009)
	$PM_{2.5}$	n/a	n/a	
	VOCs	29	0.7–215	

Notes: [a]EPA's AP-42, Shah et al. (2006), Chen et al. (2003). [b]Shah et al, (2006), Chen et al. (2003), Sawant et al. (2007), Comer et al. (2010). [c]FHWA (2011), Ban-Weiss et al. (2008), Prucz et al. (2001), Zhu et al. (2011), Shah et al. (2006), Johnson et al. (2009), Mazzoleni et al. (2007), Clagget and Houk (2008), Choi and Frey (2010). [d]Personal communication with Naishadh Bhatt, nabhatt@pa.gov.

Table 4. Values for input parameters for major sources

Source	Parameter	Range (Min–Max)	Mean	Comments
Drill rig	Horsepower (hp)	2000–7000	4260	Personal communication with PADEP (Chris Tersine, NYDEC (Leon Sedefian), and EQT Corporation (Andrew Place)[a]
	Load factor	0.25–0.9	0.57	Texas drill rigs used as surrogate (Baker and Pring, 2009)
	Engine on-time	0.2–1	0.5	CENRAP values as surrogate (Bar-Ilan et al., 2008)
	Drilling time (days)	14–35	26	PADEP (Chris Tersine), NYDEC (Leon Sedefian), and WVGES (Megan Murphy)[b]
	Control factors			Ignition timing retard and selective catalytic reduction for NO_x, diesel particulate filters for PM, diesel oxidation catalysts for VOCs (USEPA Tier 4 standards, 2004)
	NO_x	0.1–0.96	0.44	
	$PM_{2.5}$	0.6–0.97	0.81	
	VOCs	0.6–0.97	0.81	
	Cumulative % fleet turnover	50–100	76	USEPA Tier 4 (2004), Chesapeake Energy Corporation[c]
Fracing	Number of stages			Chesapeake Energy Corporation,[d] EQT Corporation (Andrew Place)
	2009	4–35	19	
	2020	10–35	25	
	Horsepower/stage	35000–45000	40000	Chesapeake Energy Corporation
	Emission control factors			Same controls as drill rigs
	NO_x	0.1–0.96	0.44	
	$PM_{2.5}$	0.6–0.97	0.81	
	VOCs	0.6–0.97	0.81	
	Cumulative % fleet turnover	50–100	76	NONROAD scrappage curve
Trucks	Truck trips/well			Jiang et al. (2011).
	Development	295–1215	661	
	Wastewater	200–1125	460	
	Distance per trip (miles)			Jiang et al. (2011), US National Park Service (2009)
	Distribution center to well (development)	0–20	9.9	
	Well to wastewater disposal facility	3–280	119	
	Emission control factors			NO_x adsorber and SCRs for NO_x, DPF for PM, and DOC for VOCs (EPA Clean Diesel Rule)
	NO_x	0.7–0.95	0.85	
	$PM_{2.5}$	0.6–0.99	0.8	
	VOCs	0.3–0.99	0.8	
Completion	Emission factors (MCF/well)	$(18–24) \times 10^3$	3700	Bar-Ilan et al. (2008), Armendariz (2009); CENRAP and Barnett Shale data as surrogate
	Mole Fraction of VOCs in gas			Chesapeake Energy Corporation
	Dry gas	5.9×10^{-3} to	0.034	
	Wet gas	0.064	0.25	
		0.17–0.33		
	Control factors (VOCs)	0.7–0.95	0.84	Green completion (Bar-Ilan et al., 2007)
Compressor stations	hp/BCF/day	125–145	135	PADEP, Considine (2010)
	Load factor	0.4–0.8	0.6	Data from DNREC (Robert Clausen), Burklin and Heaney (2005)
	Emission control factors			Selective and nonselective catalytic reduction
	NO_x	0.15–0.95	0.5	
	VOCs	0.3–0.95	0.6	
Condensate	Control factors (VOCs)	0.6–0.97	0.73	Flaring, vapor recovery units (Bar-Ilan et al., 2007)

Notes: [a,b]ctersine@state.pa.us; lxsedefi@gw.dec.state.ny.us; aplace@eqt.com. [c]http://www.chk.com/Affiliates/Chesapeake-Oilfield-Services/Documents/COO_Annual_Report.pdf. [d]E-mail from Grover R. Campbell, Manager Regulatory Affairs, Air Regulations, Chesapeake Energy Corporation, to Michael E. Hopkins, Assistant Chief, Permitting Ohio EPA (May 16, 2011, 11:31 a.m. EST).

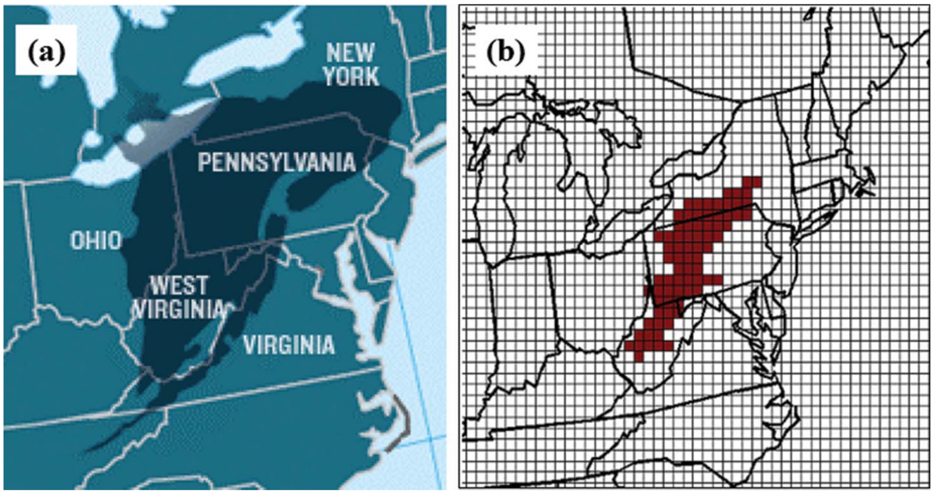

Figure 2. (a) Map of the Marcellus region (USGS, 2009) and (b) subregion covered by the new inventory.

that have been published for future gas production (Considine, 2010; Considine et al., 2011), which depend most critically on the price of gas. In order to account for this uncertainty, a uniform distribution was defined using upper- and lower-bound estimates from a large number of literature values. This assumes that all of the published estimates are equally probable. The moratorium on Marcellus development still exists in New York, but this analysis assumes that this ban will be lifted.

Emission controls

Emission estimates for the year 2020 must account for the effects of controls and fleet replacement with more modern technology. This was done by scaling the base (2009) emission factors using the methodology described in the EPA's National Mobile Inventory Model (NMIM) (EPA, 2009).

$$EF_i(2020) = EF_i(2009)[f_{\text{replaced}}(1 - f_{\text{control}}) + 1 - f_{\text{replaced}}] \quad (1)$$

where $EF_i(2020)$ is the projected distribution of emission factors for 2020, $EF_i(2009)$ is the distribution of emission factors for the base year of 2009, f_{replaced} represents the cumulative fraction of the fleet that has been replaced with newer, lower emitting sources between 2009 and 2020, and f_{control} represents the fractional reduction of emissions brought about by this fleet replacement. The base 2020 analysis assumes full implementation of the EPA's recently revised Oil and Gas Rule (EPA, 2012b) and the Tier 4 (EPA, 2004a) standard for off-road diesel engines. A list of the control technologies for the baseline case for key sources is given in Table 4. The ranges reflect variability across different control technologies.

Results and Discussion

Process-level emission estimates

Table 2 lists the sources or processes associated with the development, production, and processing of shale gas. This section describes the emissions from the major sources. Minor sources (wellhead fugitives, heaters, blowdown venting, and dehydrators) are discussed in Supplemental Materials. Some known sources are not included in the inventory. Due to lack of reliable emission factors, VOC emissions from frac ponds were not considered in this analysis. Road building was also not included.

In subsequent sections, these estimates are combined into activity-level and ultimately Marcellus-wide emissions. A set of process-level estimates along with the corresponding uncertainty associated with each source is presented in Table 5. There is a significant decrease in the emissions from each source between 2009 and 2020 (other than fracing) due to imposition of the controls listed in Table 4.

Drilling. A drill rig has 5–7 independent diesel-powered compression ignition engines, each rated between 500 and 1500 brake horsepower (bhp). These engines are major sources of NO_x and $PM_{2.5}$. Drill rigs are configured in either a direct drive or a diesel electric configuration (Bar-Ilan et al., 2008). These engines power the draw works, mud pump, and electricity generators. Emissions (tons/well) for drilling a single well are given as (Bar-Ilan et al., 2008a, Grant et al., 2009)

$$E_{\text{drilling}} = EF_i \times HP \times LF_{\text{average}} \times t_{\text{drilling}} \times \%\ \text{on-time} \quad (2)$$

where EF_i is the emission factor from a drill rig engine for pollutant i, HP is the combined horsepower of all the engines on the rig, LF_{average} represents the load factor or fraction of the total horsepower that is actually used, t_{drilling} is the time to drill one well, and % on-time is the fraction of t_{drilling} that the drilling equipment actually operates (Bar-Ilan et al., 2008).

The authors are not aware of any Marcellus-specific drill rig engine emission factors. Therefore, emission factors for the 2009 inventory were taken from the EPA's AP-42 (EPA, 2011a) and literature data for similarly sized engines used in diesel-electric locomotives and diesel generators (e.g., Shah et al., 2006; Sawant et al., 2007; Chen et al., 2003). The NONROAD model (EPA, 2008) was not used to estimate emission factors because it estimates point values and not distributions. These distributions

Table 5. Process-level emission estimates, means (95% confidence intervals), for major sources

Source	Pollutant: NO_x 2009	NO_x 2020	$PM_{2.5}$ 2009	$PM_{2.5}$ 2020	VOCs 2009	VOCs 2020
Drill rigs (tons/well drilled)	4.4 (0.8–11.5)	2.9 (0.5–8.1)	0.3 (0.03–1)	0.1 (0.01–0.4)	0.5 (0.1–1.8)	0.1 (0.02–0.5)
Frac pumps (tons/well drilled)	2.2 (0.7–4.3)	1.8 (0.6–3.4)	0.16 (0.03–0.4)	0.1 (0.01–0.3)	0.25 (0.07–0.7)	0.14 (0.03–0.5)
Trucks (tons/well drilled)	6.9 (1.4–20)	1.5 (0.2–4.5)	0.07 (4×10^{-4} to 0.3)	0.02 (2×10^{-4} to 0.09)	0.4 (0.02–2.2)	0.2 (0.01–1.2)
Completion (tons/well drilled)						
Dry well	n/a	n/a	n/a	n/a	3.8 (2×10^{-3} to 29)	1.01 (5×10^{-4} to 8.3)
Wet well	n/a	n/a	n/a	n/a	21 (0.09–145)	5.5 (0.02–37.5)
Pneumatics (tons/producing well)						
Dry gas	n/a	n/a	n/a	n/a	0.5 (0.08–0.8)	0.1 (0.02–0.2)
Wet gas	n/a	n/a	n/a	n/a	3.3 (2.4–4.4)	0.8 (0.5–1)
Compressor stations (tons/BCF)	3.3 (1.0–5.2)	1.5 (0.3–3.0)	0.3 (4×10^{-4} to 0.1)	0.3 (4×10^{-4} to 0.1)	1.0 (0.3–3.0)	0.4 (0.06–1.0)

Note: Numbers presented for 2020 are for the baseline controls scenario.

of emission factors are summarized in Table 3 and plotted in Figure S1 (Supplemental Materials). The mean emission factors for NO_x, VOC, and $PM_{2.5}$, are 5.8, 0.63, and 0.35 g hp^{-1} hr^{-1}, respectively. These values are compared with the values for drill rigs used by other authors in Table S7 in Supplemental Materials. The average drill rig NO_x emission factor was 5.7 g hp^{-1} hr^{-1} (4.7–6.7), which is ~30% lower than to the value of 8 g bhp^{-1} hr^{-1} used by Grant et al. (2009) and Bar-Ilan et al. (2008). It is roughly comparable (10% lower than) to the value of 6.4 g hp^{-1} hr^{-1} used by New York Department of Environmental Conservation (NYDEC) to construct their Marcellus inventory. The Bar-Ilan emission factor corresponds to the 95th percentile of the distribution presented here. One of the reasons the values in this study are lower than those used by Grant et al. (2009) and Bar-Ilan et al. (2008) is that they assumed emission factors of an uncontrolled Tier 0 engine, with no accounting for fleet replacement with sources that meet more stringent standards (Tier 1 or higher). The majority of the diesel engine emission data used for the 2009 inventory met the Tier 1 standard. The emission factors in this study are based on standardized test cycles. For example, the generator engines in Shah et al. (2006) were tested on a 5-mode test cycle for nonroad compression ignition engines (Code of Federal Regulations 2004, Title 40, Part 89). One concern is that nonroad diesel vehicles are often operated under transient loads, which can significantly increase emissions (Clark et al., 2010; Lewis et al., 2011; Frey and Kim, 2006; Frey et al., 2010). However, the NONROAD model does not recommend any adjustment for transient loading in oil and natural gas equipment.

To estimate emissions for the 2020 inventory, the control factors listed in Table 4 were applied to the 2009 emission factors in Table 3. For example, for NO_x, a triangular distribution of control factors was used with a mode at 30% (the most probable value for the reduction in 2020 relative to 2009), which is somewhat smaller than the control factor (40%) assumed for the Haynesville Shale region (Grant et al., 2009). The maximum and minimum values of each distribution are based on implementation of specific technologies. For NO_x, the minimum control factor of 10% corresponds to ignition timing retard (ITR) and a maximum of 95% that corresponds to selective catalytic reduction (Bar-Ilan et al., 2007; EPA, 2004). A similar analysis was performed for $PM_{2.5}$ and VOCs (see Supplemental Materials for details). After applying the control factors, Figure S1a indicates that more than 85% of projected drill rig emission factors used for the 2020 baseline analysis meet the EPA nonroad diesel Tier 2 standards for similarly sized engines. Additionally, more than 70% of the projected emission factors for $PM_{2.5}$ and VOCs fall below the Tier 2 standards.

The cumulative percentage of the drill rig fleet estimated to be outfitted with new control technology in 2020 is summarized in Table 4. The lower end (50% cumulative fleet turnover by 2020) is from the Regulatory Impact Analysis for the Tier 4 Standards (EPA, 2004), and the upper end (100% fleet turnover by 2020) is from data reported by Chesapeake Energy (2011). Activity parameters (drilling time, engine horsepower) were obtained from interviews with personnel at state agencies (Pennsylvania Department of Environmental Protection [PADEP], New York Department of Environmental Conservation [NYDEC], West Virginia Geological and Economic Survey [WVGES]). They are summarized in Table 4. Drilling times in the Marcellus range from 10 to 35 days. The average time is 30 days, which is about half that in the Haynesville Shale because the Marcellus Shale is shallower (~6000 ft) than the Haynesville formation (~12000 ft) (Grant et al., 2009).

Drill rig engines often do not operate at full load or 100% of the time when they are on site (Grant et al., 2009; Bar-Ilan et al., 2008; Armendariz, 2009). In the absence of Marcellus-specific data for these parameters, data from Texas for load factor (Baker and Pring, 2009) and from the Central Regional Air Partnership (CENRAP) region for % on-time (Grant et al., 2009; Bar-Ilan et al., 2008) were used. Grant et al. (2009) and Bar-Ilan et al. (2008) used a point value of 67% for load factor, but the load factor on drill rig engines is highly variable and ranges from 10% to 90% (e.g., Baker and Pring, 2009). The assumption is that these activity parameters are not basin specific.

Figure 3 shows distributions of estimated NO_x, $PM_{2.5}$, and VOCs emissions to drill one well in the Marcellus formation in 2009 and 2020. The 2009 mean NO_x emissions is 4.4 (0.8–11.5; range denotes 95% confidence interval) tons/well, which is comparable to the NYDEC estimate of 3.8 tons/well (NYDEC, 2011). The 95% confidence interval here is the range of the emission distributions, resulting from inter-unit variability in the input parameters. The mean NO_x emissions to drill a single well is estimated to fall by ~35% from 2009 to 2020, from 4.4 to 2.9 (0.5–8.1) tons/well. The mean $PM_{2.5}$ emissions for drilling one well in 2009 is estimated to be 0.3 (0.03–1) tons/well and to fall by 60% to 0.11 (0.01–0.4) tons/well in 2020. The mean VOC emissions to drill a well are 0.5 (0.06–1.8) tons/well in 2009 and are estimated to fall to 0.1 (0.02–0.5) tons/well in 2020.

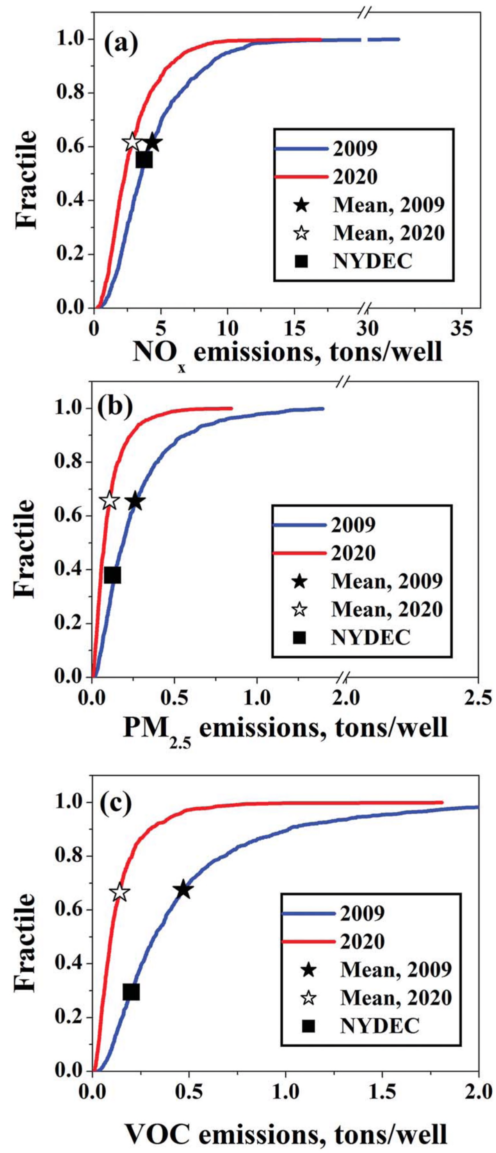

Figure 3. Estimated cumulative distributions of emissions for drilling one well: (a) NO_x, (b) $PM_{2.5}$, and (c) VOCs. The 2020 distributions correspond to the base scenario. The estimates made by (NYDEC, 2011) are shown for reference.

Hydraulic fracturing. Hydaulic fracturing (fracing) is performed to stimulate natural gas production after a well bore has been drilled. Pumps powered by 1000–1500 hp diesel engines pump large quantities of fluid and sand into the well bore to fracture the formation. Typically, there are 8–10 frac pumps per well. For each well, horizontal drilling of "laterals" is performed to access the gas. Perforations known as stages are made in the lateral lines at approximately every 100 m through which fracing fluid is pumped. Typically, there are 5–35 stages per well (Table 4). Emissions (tons/well) for fracturing a single well are estimated according to the number of stages per well:

$$E_{\text{fracing}} = EF_i \times HP \times LF_{\text{average}} \times N_{\text{stages}} \quad (3)$$

where EF_i is the emission factor from one pump engine for pollutant i (g bhp^{-1} hr^{-1}), HP_{total} is the combined horsepower-hour required for one fracturing stage, LF_{average} is the average load factor of the pump engine, and N_{stages} is the total number of stages needed to fracture one well. Distributions of these input parameters are plotted in Figure S2 in Supplemental Materials and summarized in Table 4.

The authors are not aware of frac-pump-specific emission factor data and therefore compiled emission factors for similarly sized heavy-duty diesel engines that are used in other applications, such as locomotives and generators, from the EPA's AP-42 and other literature (see Supplemental Materials). The locomotives considered were diesel electric switching locomotives rated between 1000 and 2000 hp, which use similar engines as those used for fracing oil shale wells (e.g., Sawant et al., 2007). The average NO_x, $PM_{2.5}$, and VOC emission factors for frac pumps are 5.4, 0.4, and 0.67 g hp^{-1} hr^{-1}, respectively, which are 30–50% lower than the data used by Grant et al. (2009) to construct the Haynesville Shale inventory.

The control factors for the 2020 baseline analysis are summarized in Table 4 and plotted in Figures S2f–h in Supplemental Materials. These distributions are the same as those for drill rigs. A distribution for the turnover of frac pumps was calculated by using a scrappage curve from the EPA's NONROAD model (EPA, 2008), assuming median lives of 5 and 10 yr, respectively.

Activity data for fracing include horsepower-hour required per stage and number of stages required to fracture one well. It was assumed that the length of the lateral will increase with time in order to provide more accessibility to the gas; therefore, the mode of the number of stages is assumed to increase to 33 in 2020 (Andrew Place, EQT Corporation, personal communication). Frac pumps usually operate at 50% of the load (Armendariz, 2009; Grant et al., 2009).

The NO_x, $PM_{2.5}$, and VOC emissions associated with fracturing one well are given in Table 5, and their distributions are plotted in Figures S3a–c in Supplemental Materials. The reductions in NO_x, $PM_{2.5}$, and VOCs for fracing in 2020 relative to 2009 are somewhat smaller than those used for drilling because of the assumed increase in the number of stages per well over time.

Trucks. Trucks are used to transport drilling and fracturing equipment, water, chemicals, waste water, and other material to and from a well site. These trucks are typically tractor trailers (U.S. Department of Energy [USDOE], 2009; Chris Tersine at PADEP). Other oil and gas inventories (Grant et al., 2009; Bar-Ilan et al., 2008) have not included truck traffic as a source. Emissions from trucks were estimated as (Jiang et al., 2011)

$$E_{\text{traffic}} = EF_i \times L_{\text{trip}} \times N_{\text{trip}} \qquad (4)$$

where EF_i is the truck emission factor for a given pollutant i (g mile^{-1}), L_{trip} is the distance per trip, and N_{trip} is the number of trips associated with bringing a single well into production, which is multiplied by 2 to reflect the return trip. Distributions of these input parameters are plotted in Figure S4 (Supplemental Materials) and summarized in Tables 3 and 4.

Emission factors for trucks were taken from the large literature for diesel trucks. The average NO_x, $PM_{2.5}$, and VOC emission factors for trucks are 38, 0.33, and 1.71 g mile^{-1}, respectively. The literature documents tests performed on these engines under a wide range of conditions, which include varying load, cold start, hot soak, etc. (e.g., Fujita et al., 2007). The EPA's MOVES model (EPA, 2013c) was not used to estimate emissions, because, like NONROAD, it calculates point values and not distributions. Activity data for truck traffic are summarized in Table 4. The effect of truck load on emissions is not taken into account because there is no definitive conclusion about the behavior of emissions under load. For example, a report by the American Transportation Research Institute (ATRI, 2009) indicated that NO_x, VOC, and $PM_{2.5}$ emissions could decrease by 3–8% under increased loading. However, the work of Gajendran et al. (2003) indicated that NO_x emissions linearly increased with truck loading, whereas $PM_{2.5}$ and VOC emissions were unaffected. The number of truck trips per well ranged from 300 to 1300 based on data from the National Park Service (USGS, 2008). Different trip lengths were assumed for wastewater hauling and all other activities. The reported distances from a well site to a wastewater facility ranges between 3 and 280 miles (Jiang et al., 2011); a median of 80 miles was assumed. Vehicle miles traveled for well setup (from the trucking center to the well site) were assumed to range from 0 to 20 miles with a mode of 10 miles based on data from NYDEC (2011) and Jiang et al. (2011). Truck traffic for both well setup and wastewater disposal could be significantly reduced by the use of pipelines; this scenario is not considered in this analysis.

The trucking emissions per well and their associated uncertainty are presented in Table 5, whereas distributions of the truck emissions per well are presented in Figure S5 in Supplemental Materials. The 2020 baseline values are roughly a factor of 2–4 lower than their 2009 counterparts due to the implementation of controls.

Completion venting. After a well has been drilled and fractured, the well is vented to remove debris, liquids, and inert gases used to stimulate gas production. This procedure is called completion venting (also called flowback); it can be an important source of VOCs, especially for wet-gas wells (gas with significant amounts of higher-molecular-weight hydrocarbons). Emissions for completion venting are estimated as

$$E_{\text{completion}} = \rho_{\text{gas}} \times V \times f_i \qquad (5)$$

where $E_{\text{completion}}$ is the emissions from a single completion event (tons/well), ρ_{gas} is the mass density of the gas, V is the volume of gas vented per completion, and f_i is the mass fraction of VOCs (nonmethane organic compounds) in the vented gas.

In the absence of Marcellus-specific data on the volume of gas vented per completion, data collected in other basins (Armendariz, 2009; Bar-Ilan et al., 2008), reported by the EPA's Natural Gas Star Program (EPA, 2004b), The Williams Companies (2007), and ENVIRON International Corporation (2006) were used as surrogates. The values span several orders of magnitude, ranging from 18 to 24,000 million cubic feet (MCF; 0.5–650 m^3), with a mean value of 3715 MCF (100 m^3) per well completion. The EPA's Oil and Gas Rule (EPA, 2012b) requires reducing these emissions by 90–95% using green completions.

VOC emissions from completion venting depend on whether the well is a dry- or wet-gas well. Dry gas is typically encountered in most of the Marcellus Fairway, but some wet gas is found in West Virginia and some parts of southwestern Pennsylvania (PADEP, 2010; WVGES, 2011; Brown, 2005). The reported VOC fractions, f, vary between 17% and 33% for wet gas and between 0.5% and 6% for dry gas (Chesapeake Energy Corporation, 2011). For 2009, the fraction of wet gas produced is taken from state reports (PADEP, 2010; WVGES, 2011). In 2020, it is assumed that 20–50% (uniform distribution) of gas produced comes from wet-gas-producing regions (Considine, 2010) and that 20–50% of the gas produced in these regions is actually wet (Andrew Place, EQT Corporation, personal communication).

A list of the dry- and wet-gas counties in each state is given in Table S1 in Supplemental Materials. Wet gas is typically encountered in the Washington and Butler counties in southwestern Pennsylvania and also in the counties of northern West Virginia. The rest of the Marcellus region is reported to be dry gas (Brown et al., 2005).

The mean emissions for both dry- and wet-gas wells are summarized in Table 5, and the distributions are plotted in Figure S7 in Supplemental Materials. The emissions per wet well for both years is around a factor of 5 higher than the dry wells because of higher VOC content. The average unit well estimates for both categories go down by roughly a factor of 4 in 2020 due to stricter controls due to the EPA's Oil and Gas Rule (EPA, 2012b).

Wellhead compressors. Wellhead compressors are relatively small (50–250 hp), natural-gas-fired spark-ignited reciprocating internal combustion engines located at the wellhead to raise the pressure of the produced gas to that required in the gathering line. Wellhead compressors emit NO_x, $PM_{2.5}$, and VOCs. Emissions from a single compressor are estimated as

$$E_{\text{Engine}} = EF_i \times HP \times LF_{\text{average}} \times t_{\text{annual}} \quad (6)$$

where EF_i is the emission factor of pollutant *i* in g bhp^{-1} hr^{-1}, *HP* is the horsepower rating of the engine, LF_{average} is the average load factor, and t_{annual} is the number of hours per year the engine operates.

Wellhead compressors are currently not common in the Marcellus formation, but shale gas wells typically have a steep decline curve. Therefore, wellhead compressors are often required as a field ages. For 2020, it was assumed that wellhead compressors are more common, with a mode at 7% and a range from 0% to 45%, which is based on CENRAP data (Bar-Ilan et al., 2008).

Emission factors for wellhead compressors were obtained from permits filed with PADEP (Naishadh Bhatt, PADEP, personal communication). The distributions of wellhead compressor horsepower ratings were taken from CENRAP data (Bar-Ilan et al., 2008) and distributions of load factor data from Texas (Pollution Solutions, 2008). These engines are assumed to operate 24 hours a day, 365 days of the year, with negligible downtime (Energy Information Administation [EIA], 2007; Grant et al., 2009; Bar-Ilan et al., 2008).

The control factor distributions for compressors used to develop the baseline 2020 case are listed in Table 4 and plotted in Figure S8 in Supplemental Materials. These are based on specific technologies (e.g., selective catalytic reduction [SCR]) and recent New Source Performance Standards (NSPS) promulgated by the EPA.

The emission distributions for wellhead compressors are shown in Figure S9 in Supplemental Materials. The NO_x and VOC emissions are reduced in 2020 by a factor of 2 and 4, respectively, due to controls, whereas $PM_{2.5}$ remains unchanged.

Condensate tanks. Condensate tanks store higher-molecular-weight hydrocarbons (carbon number >5) that are separated on site from the produced gases. Emissions from condensate tanks include working, breathing, and flashing (Bar-Ilan, 2008; Hendler et al., 2009). Emissions from condensate volatilization are estimated using the approach of Armendariz (2009) and Bar-Ilan et al. (2008):

$$E_{\text{Condensate,Tanks}} = EF_{\text{Condensate,Tanks}} \times P_{\text{Condensate,Tanks}} \quad (7)$$

where $EF_{\text{Condensate,Tanks}}$ is the VOC emission factor (lb bbl^{-1}) and $P_{\text{Condensate,Tanks}}$ is the region-wide condensate production rate (bbl yr^{-1}). Therefore, key inputs are the condensate production rate (bbl yr^{-1}) and an aggregate VOC emission factor. Condensate is typically produced in wet-gas regions.

In the absence of Marcellus-specific emission factors for condensate tanks, the data from the CENRAP region (Bar-Ilan et al., 2008) and the Barnett Shale (Armendariz, 2009) were used as a surrogate. The data span several orders of magnitude, ranging from 0.7 to 215 lb bbl^{-1} (2.6–850 kg m^{-3} of condensate liquid produced), with an average value of 29 lb bbl^{-1} (123 kg m^{-3}).

For the 2020 inventory, it was assumed that condensate tank emissions are significantly reduced by based on the implementation of the EPA's Oil and Gas Rule (EPA, 2012b). The control technologies include flaring and the use of vapor recovery units (VRUs).

Pneumatic devices. Pneumatic devices are used for a variety of wellhead processes that are powered mechanically by high-pressure natural gas as the working fluid; hence, they are pneumatically powered devices. They are required in remote well sites where electric power is not available (Grant et al., 2009). Because they operate on compressed gas, they can be a source of VOCs. The emissions typically depend on the type and number of devices (e.g., pneumatic-level controllers, valves, etc.), the bleed rate of gas from these devices, and the VOC content of the gas (wet or dry) (Bar-Ilan et al., 2008; Grant et al., 2009). The number and type of devices from the CENRAP region (Bar-Ilan et al., 2008) were used here. The EPA's Oil and Gas Rule (EPA, 2012) states that operators will be required to reduce emissions from pneumatic devices to 6 standard cubic feet (scf) hr^{-1} by 2020. The current and projected bleed rates are given in Table S3.The emissions for a single well are estimated as

$$E_{\text{pneumatics}} = f \times \left(\sum_i V_i \times N_i \times t_{\text{annual}} \right) \times \frac{P}{\frac{RT}{MW_{\text{gas}}}} \quad (8)$$

where V_i is the volumetric bleed rate from device i (scf hr^{-1} device^{-1}), N_i is the total number of device *i* present per well, t_{annual} is the total number of active hours (8760 per year), *P* is the pressure (1 atm), *R* the universal gas constant, MW_{gas} is the molecular weight of the produced gas, *T* is the atmospheric temperature (298 K), and *f* is the mass fraction of VOC in the vented gas. Because the VOC contents of dry and wet gas are significantly different, emissions for these two kinds of wells were estimated separately, using the same VOC content for dry and wet gas as for completion venting. Unit well emissions are listed in Table 5 and plotted in Figure S12 (Supplemental Materials).

Compressor stations. Compressor stations maintain the gas pressure in gas transmission lines. They typically contain multiple (3–15) large (1000–2000-hp) natural-gas-fired compressors, and therefore emit NO_x, VOCs, and $PM_{2.5}$. The emissions from compressor stations are calculated based on installed horsepower:

$$E_{\text{station}} = EF_i \times H \times t \times LF_{\text{average}} \quad (9)$$

where EF_i is the emission factor in g hp^{-1} hr^{-1}, *H* is the horsepower required to pump a billion cubic feet of gas per day (BCFD), *t* is the number of hours a day the compressor is in operation (typically 24 hr), and LF_{average} is the fraction of horsepower that is actually utilized by the compressor engine.

Emission factors for compressor stations are not documented in the literature, but comparison of NO_x emission factors of similarly sized engines (e.g., Bar-Ilan et al., 2008; Pring et al., 2010) indicates that the average NO_x emission factor of 1.5 g bhp^{-1} hr^{-1}, is significantly smaller than those in Texas, 3–12 g bhp^{-1} hr^{-1}. The total number of compressor stations is projected using online gas production data from the PADEP website (PADEP, 2011), and records of installed compressor capacity (Naishadh Bhatt, PADEP, personal communication). Quarterly installed horsepower data from December 2008 to December 2010 are plotted against gas production in Figure S15d (Supplementary Materials). There is a strong linear correlation between total gas produced and net installed compressor station horsepower. A linear regression yields a slope of 0.14 hp/BCFD ($R^2 = 0.95$), the uncertainty ranging from 0.125 to 0.15 hp/BCFD. This range was represented by a uniformly distributed random variable in the Monte Carlo analysis. Compressor engines operate at an average load factor of between 40% and 80% (Robert Clausen, Delaware Department of Natural Resources and Environmental Conservation, personal communication; Burklin and Heaney, 2005).

The control factors for NO_x and VOCs emissions from compressor stations are summarized in Table 4. The data are from Bar-Ilan et al. (2007) and from a draft technical report on oil and gas sector NO_x emissions prepared by the Ozone Transport Committee (Robert Clausen, Delaware Department of Natural Resources and Environmental Conservation, personal communication).

The distributions of compressor stations emissions are summarized in Table 5 and plotted in Figure S16 (Supplemental Materials). NO_x and VOC emissions are reduced by a factor of 2 and 3, respectively, from 2009 to 2020, whereas $PM_{2.5}$ emissions remain unchanged.

Gas processing and transmission fugitives. Processing and transmission fugitive emission factors are from the American Petroleum Institute (API, 2009), Armendariz (2009), and the Canadian Association of Petroleum Producers (CAPP, 2007). Given the limited data, these EFs were assumed to have a triangular distribution. These emission factor distributions ranged between the lower and higher values of 0.35 and 7 tons/BCF and have a mode at the average value of 3.5 tons/BCF. This distribution is then scaled by the gas production data in Table 1. Given the lack of fugitive-specific emission control factors, the same control factors were used as for completion venting.

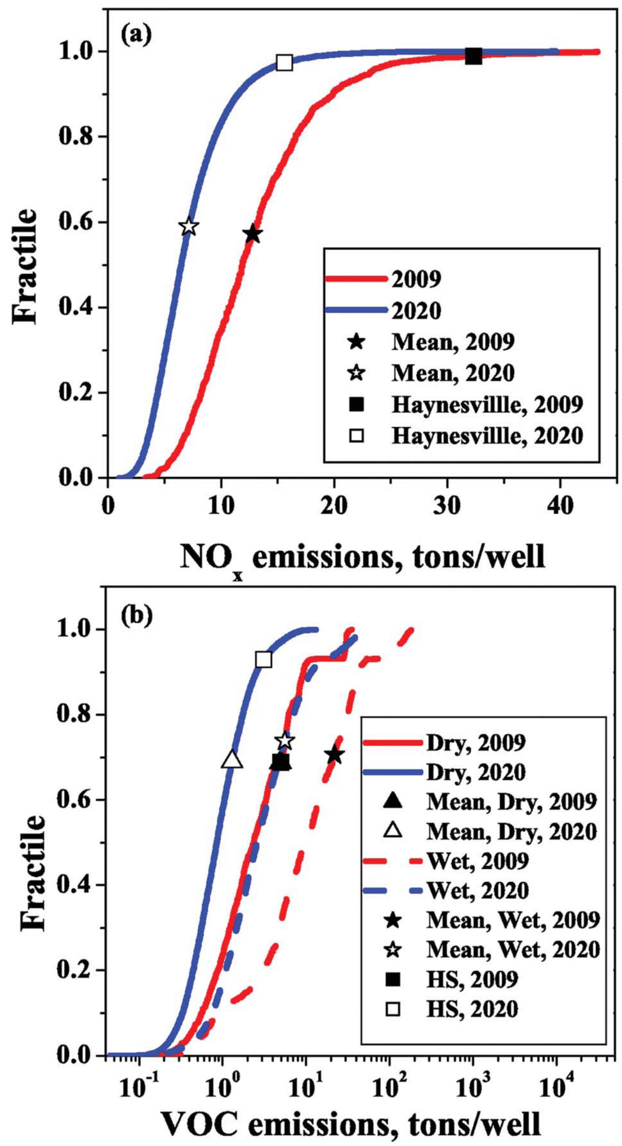

Figure 4. Cumulative distribution functions for well development emissions of (a) NO_x and (b) VOCs. The vertical lines labeled "HS" refers to the Haynesville Shale inventory developed by Grant et al. (2009).

Activity-level emissions

In this section, the different process-level estimates are combined into a unit activity basis for well development, gas production, and gas processing. Parentheses used henceforth denote a 95% confidence interval. Figure 4 plots distributions of NO_x and VOC emissions to develop a single well. Similar plots for gas production and midstream processing are shown in Figure S17 (Supplemental Materials). The mean and 95% CI associated with each of these unit activity estimates is summarized in Table 6. A significant decrease in these unit activity estimates is seen in 2020 as compared with 2009 due to the use of emission control technologies. The source-resolved emissions for each of these activities are plotted in Figure S18 (Supplemental Materials). The average NO_x emissions to bring a single well online in 2009 is 12.8 (5.1–28.3) tons/well, which is reduced by around 40% in 2020, to 7.2 (2.6–16) tons/well. The 2009 NO_x emissions are about 2 times lower than those reported by Grant et al. (2009) for the Haynesville Shale. Grant et al. (2009) used a higher drill rig NO_x emission factor (8 g bhp^{-1} hr^{-1} versus the average here of 5.6 g bhp^{-1} hr^{-1}), and the drilling time in the Haynesville Shale is much longer (63 versus 30 days).

Figure 4b plots distributions of VOCs to develop a single well; the mean VOC emission to set up a dry well in 2009 is 5.0 (0.3–30) tons/well, which is reduced to 1.3 (0.2–5.4) tons/well in 2020 due to the implementation of controls associated with the EPA's Oil and Gas Rule (EPA, 2012b). The 2009 VOC emissions are quite similar to the Haynesville estimate of 4.6 tons/well, which also is for a dry-gas well. The mean VOC emissions for a wet-gas well are much higher than a dry-gas

Table 6. Unit activity emissions: means (95% CIs)

Activity	Pollutant					
	NO_x		$PM_{2.5}$		VOCs	
	2009	2020	2009	2020	2009	2020
Development (tons/well drilled)						
Dry well	12.8 (5.1–28.3)	7.2 (2.6–16)	0.5 (0.1–1.5)	0.2 (0.06–0.5)	5.0 (0.3–30)	1.3 (0.2–5.4)
Wet well	12.8 (5.1–28.3)	7.2 (2.6–16)	0.5 (0.1–1.5)	0.2 (0.06–0.5)	22 (0.4–145)	5.6 (10^{-3} to 36)
Production (tons/producing well)						
Dry wel	1.2 (0.2–2.5)	0.6 (0.1–1.0)	0.01 (6×10^{-5} to 5×10^{-2})	0.01 (6×10^{-5} to 5×10^{-2})	0.9 (0.3–1.9)	0.2 (0.04–0.6)
Wet well	1.2 (0.2–2.5)	0.6 (0.1–1.0)	0.01 (6×10^{-5} to 5×10^{-2})	0.01 (6×10^{-5} to 5×10^{-2})	4.0 (2.6–6)	1.0 (0.6–1.5)
Midstream (tons/BCF)	3.3 (1.0–5.2)	1.5 (0.3–3)	0.3 (4×10^{-4} to 0.1)	0.3 (4×10^{-4} to 0.1)	8.1 (2.6–14)	2.2 (0.7–4.5)

well, 22 (0.5–149) tons in 2009, which reduces to 5.6 (0.4–36.4) tons in 2020. Although unit well development VOC emissions for dry gas in 2009, as plotted in Figure S18 in Supplemental Materials, are similar to that for the Haynesville Shale (Grant et al., 2009), the source distributions are different. For dry-gas wells, completion venting is predicted to dominate the VOC emissions in the Marcellus formation versus drilling in Haynesville. Drilling is dominant in the Haynesville inventory due to larger emission factors and longer drilling time compared with the Marcellus. Additionally, the average unit dry-gas well estimates in 2020 presented here are roughly a factor of 2 lower than the Hayesville estimates of Grant et al. (2009). They did not take into account new controls required by the EPA's recent Oil and Gas Rule (EPA, 2012b) for completion venting, which will significantly reduce VOC emissions. As shown in Figure S17 in Supplemental Materials, the mean NO_x emissions from one producing well are 1.2 (0.2–2.5) tons/well, which falls to 0.53 (0.1–1.0) tons/well in 2020 due to usage of controls. NO_x emissions from a producing well are dominated by wellhead compressors (>99%) with negligible contribution from heaters. The PM emissions remain unchanged because PM controls are unlikely to be implemented on natural-gas-fired engines.

VOC emissions from a single producing well follow the same trend as completion venting emissions, and the emissions from a wet well differ significantly from a dry one. As seen in Figure S18 (Supplemental Materials), these emissions are dominated by pneumatics in both categories (dry and wet). Average midstream NO_x emissions of 1.5 (0.3–3.0) tons/BCF are a factor of 10 lower than the Haynesville estimates of 15 tons/BCF, because the effect of future controls for compressor stations.

Source-resolved Marcellus-wide emissions

Figure 5a–c show the source-resolved Marcellus-wide emissions of total NO_x, $PM_{2.5}$, and VOC emissions for 2009 and the 2020 base case, which assumes that the equipment fleet will have a distribution of control factors in 2020. These values are derived by combining the distributions shown in Figure 4 with the activity data in Table 1. Although emissions decrease from 2009 to 2020 on a per-unit-activity basis, the Marcellus-wide emissions increase substantially in 2020 due to increased activity (Table 1). For example, the Marcellus-wide NO_x emissions increase from 58 (23–123) tons/day in 2009 to 129 (56–211) tons/day in 2020.

Figure 5a indicates that the dominant sources of NO_x include well development activities, including drilling, fracing, and truck traffic from wastewater disposal. In 2020, compressor stations are also predicted to be a major source of NO_x because of increased gas production. Figure 5b indicates that drilling and fracing are the major sources of $PM_{2.5}$ in both 2009 and 2020. Figure 5c indicates that completion venting is the major source of VOC emissions in 2009, but in 2020 VOC emissions are dominated by sources associated with gas production, including condensate tanks, compressor stations, gas plants, and transmission fugitives. The cumulative distributions of the NO_x, $PM_{2.5}$,

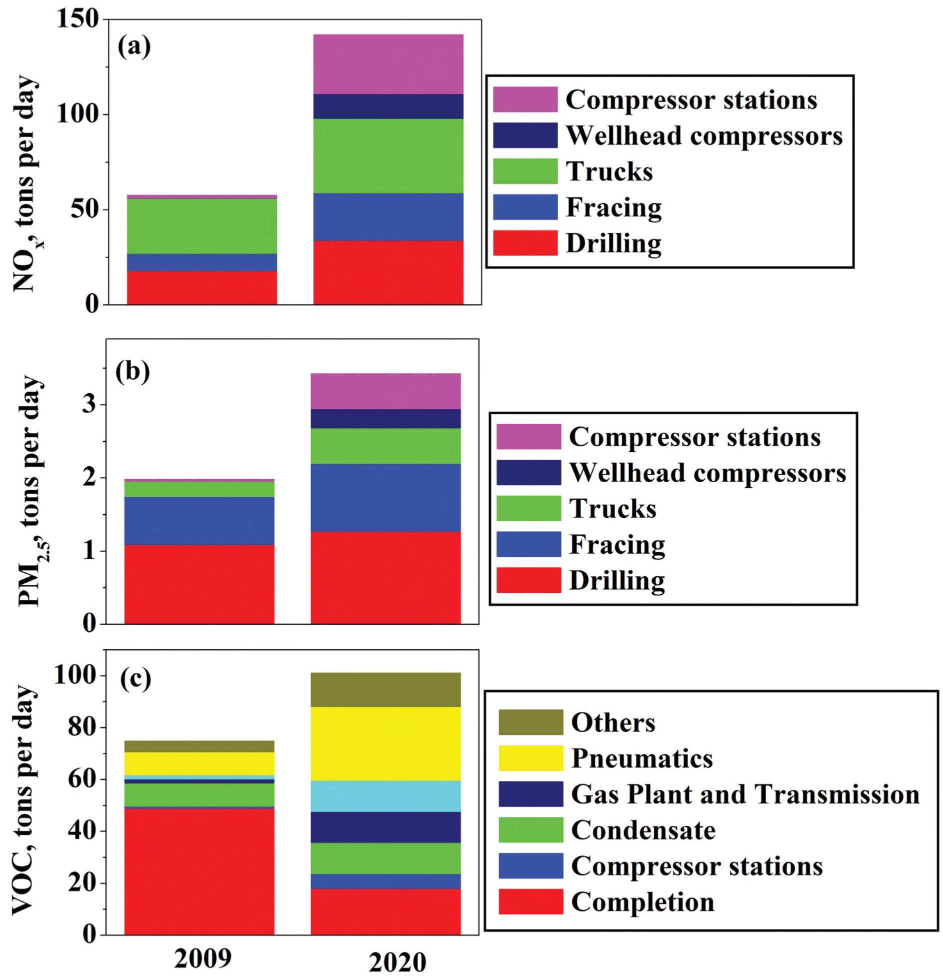

Figure 5. Source-resolved Marcellus emissions for (a) NO_x, (b) $PM_{2.5}$, and (c) VOCs in 2009 and 2020 (base scenario). The results are mean estimates. Other sources of VOCs include drilling, fracing truck traffic, and blowdown venting.

and VOC emissions are given in Figure S19 of Supplemental Materials.

Marcellus versus other sources. Figures 6a–c compare the predicted contribution from Marcellus activities with all the other sources in the Marcellus region, denoted by red grid cells in Figure 2b. These values are the averages from the distributions of emissions shown in Figure S19 (Supplemental Materials). The emissions for non-Marcellus sources are from the National Emissions Inventory 2008 (EPA, 2011b). In order to project these emissions to 2020, source-specific scaling factors were used, outlined in Table S7 in Supplemental Materials. For example, diesel NO_x emissions in 2020 are assumed to be 30% lower than in 2009 based on the projections of the Federal Highway Administration, the EPA's Clean Diesel Rule, and the various tier standards.

Figure 6a indicates that Marcellus development is predicted to contribute 12% (6–18%) of the regional NO_x emissions in 2020. In 2020, the Marcellus NO_x emissions will be roughly equal to those from gasoline vehicles and roughly half those from diesel vehicles.

Figure 6b indicates that Marcellus development will contribute negligibly to regional $PM_{2.5}$ emissions. However, it may be an important source for certain $PM_{2.5}$ components. For example, the contribution of Marcellus to elemental carbon was estimated using a distribution of diesel source profiles from the EPA's SPECIATE database (EPA, 2006). Marcellus development could contribute 14% (2–36%) of the regional elemental carbon emissions.

The contribution of Marcellus activity to regional anthropogenic VOC emissions is plotted in Figure 6c. Although Marcellus development is not as large a source as solvent usage and mobile sources, the increase in VOC emissions due to Marcellus development could significantly offset the reductions in emissions due to controls in other sectors.

Table S9 (Supplemental Materials) shows the predicted contributions to Marcellus NO_x and VOCs in 2020 for different states. It is predicted that Pennsylvania will contribute around 65% to Marcellus NO_x emissions, with West Virginia contributing 21% and New York contributing 14%, which follows the expected level of development in Table 1. Additionally, Pennsylvania is predicted to contribute 60% to Marcellus VOC

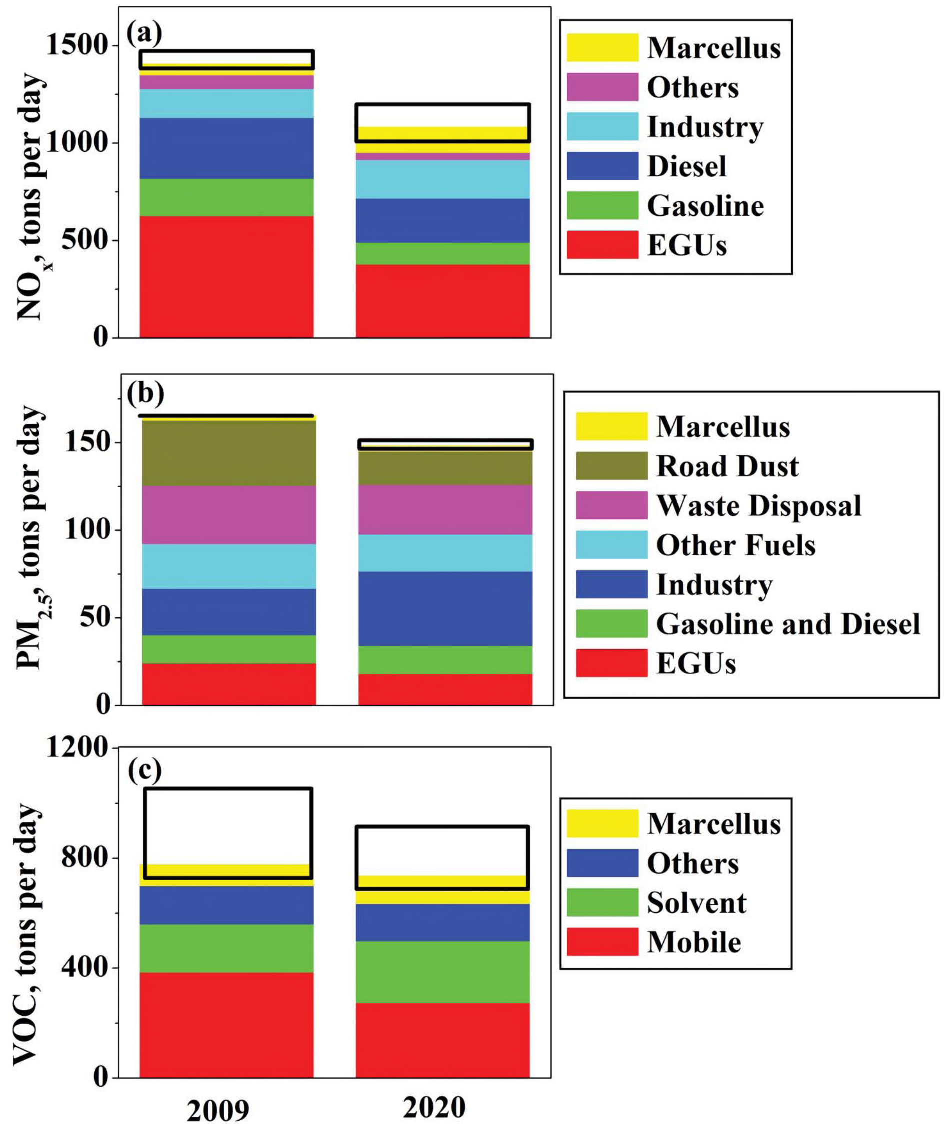

Figure 6. Source-resolved emissions of (a) NO_x, (b) $PM_{2.5}$, and (c) VOCs for the Marcellus region (Figure 1b). The 2020 emissions correspond to the average of the baseline controls scenario. The open black squares denote the 95% confidence intervals on the estimated Marcellus emissions. The cumulative distributions of emissions are plotted in Figure S19. VOCs correspond to anthropogenic VOC emissions.

emissions, with 30% from West Virginia and 10% from New York. West Virginia accounts for a larger share of Marcellus VOCs due to the wet gas and associated condensate in that part of the formation.

Effects of control technology on emissions

The 2020 base case accounts for the ongoing implementation of existing regulations. To investigate the benefits of these and potential future regulations, Figure 7 plots NO_x and VOC emissions for different control scenarios. Results are presented for three cases: base case described previously; "pre-2009" assumes that the equipment in 2020 have the same emission factors as in 2009; and "tight controls," which assumes that all the fleet equipment will be outfitted with the state-of-the-art control technology resulting in highest reduction in emissions, such as selective catalytic reduction (SCR) for NO_x emissions from internal combustion engines (e.g., drill rigs, frac pumps, well-head compressors, and compressor stations) and diesel particulate filter (DPF) for $PM_{2.5}$. Comparing the "pre-2009 controls" and "base" scenarios illustrates the benefits of existing regulations. Comparing the "base" and "tight control" scenarios indicates the potential additional emission reductions that are possible with existing technologies.

Figure 7a plots the cumulative distribution of NO_x emissions for these three scenarios. If the source-level emissions were the same in 2020 as in 2009, Marcellus activity could increase NO_x emissions by 251 (123–507) tons/day or 22% (11–35%) of regional NO_x emissions (Figure 7b). Here, percentage contribution is defined as the ratio of Marcellus emissions to the sum of Marcellus and regional emissions. This is much higher than the base case, which demonstrates the substantial benefit of existing

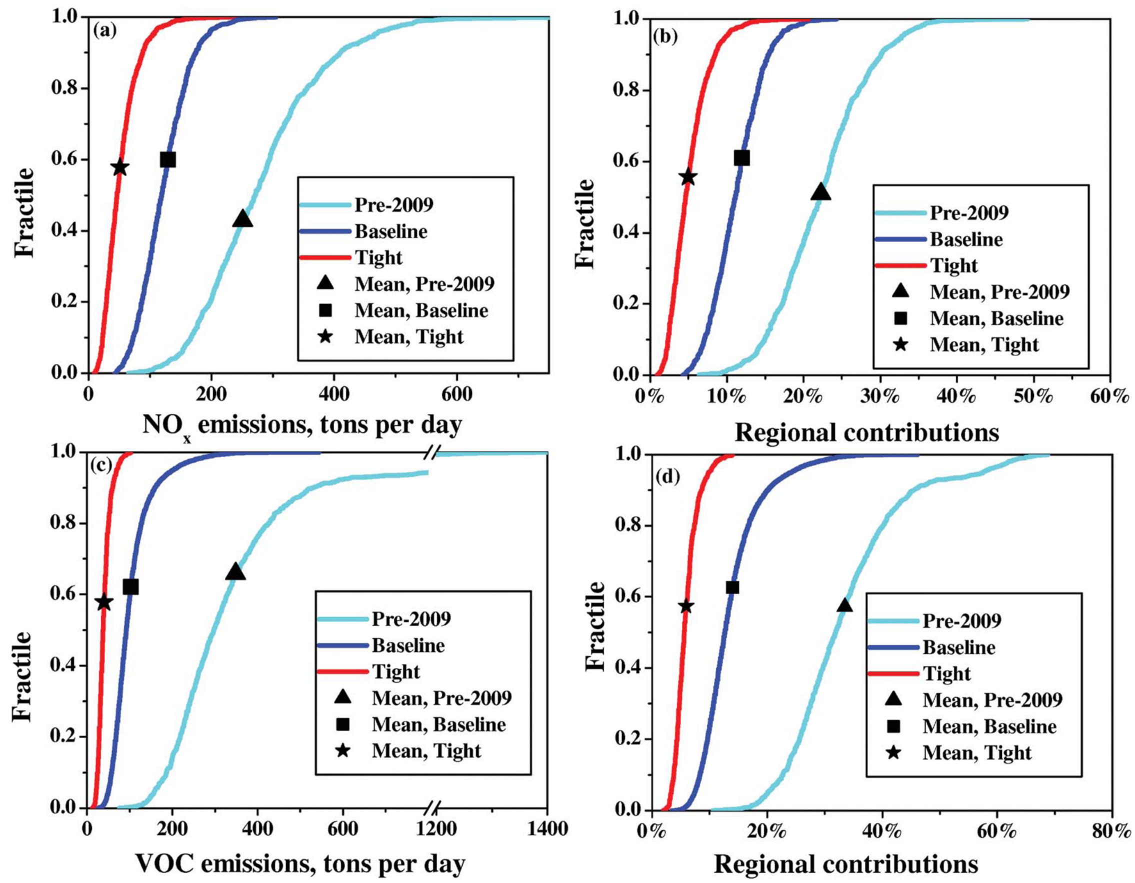

Figure 7. Comparison of different control scenarios for 2020 Marcellus emissions: (a) total NO_x emissions, (b) contribution of Marcellus to regional NO_x emissions, (c) total VOC emissions, and (d) contribution of Marcellus to regional VOC emissions.

regulations for reducing emissions from nonroad diesel engines and compressor stations. The "tight control" scenario reduces the 2020 NO_x emissions to 51 (16–121) tons/day, which is roughly 85% of the 2009 NO_x emissions, despite large increases in activity. Therefore, adoption of additional state-of-the-art controls could reduce Marcellus NO_x emissions to just 5% (1.6–11%) of regional NO_x emissions.

Figures 7c and d show the effects of different control scenarios on VOC emissions. If the source-level emissions were the same in 2020 as in 2009, Marcellus VOC emissions would be 345 (146–1020) tons/day or 34% (19–62%) of the regional anthropogenic VOC emissions in 2020. However, the implementation of tight controls indicates that Marcellus development would emit on average 41 (20–78) tons/day of VOCs into the region, contributing only 6% (3–11%) of the anthropogenic VOC emissions in 2020. A summary of the emissions and regional contributions from each control scenario is in Table 7.

Table 7. Estimates of 2020 Marcellus emissions for three control scenarios

	Pollutant	
Control Scenario	NO_x	VOCs
Pre-2009	251 (122–504)	345 (146–999)
	21% (11–35%)	34% (19–62%)
Baseline	129 (56–210)	100 (45–243)
	12% (6–18%)	14% (7–28%)
Tight	51 (16–120)	41 (20–80)
	5% (1.6–11%)	6% (3–11%)

Notes: The first line of data denotes absolute Marcellus-related emissions in tons per day: mean (95% CI). The second line denotes contributions to percent contribution to regional anthropogenic emissions: mean (95% CI).

Table 8. Correlation coefficients (R^2) between total emissions, key sources, and input parameters for 2020 baseline case

Pollutant	Source	Correlation of Source Contribution with Total Emissions	Key Uncertain Parameter	Correlation of Parameter with Source Emissions
NO_x	Drill rigs	0.61	Engine on-time	0.5
	Trucks	0.75	Trip VMT	0.5
VOC	Completion	0.73	Emission factor (volume vented/event)	0.9

Uncertainty and data limitations

As indicated by the distributions plotted in Figure 6 and in Figure S19 (Supplemental Materials), there is substantial uncertainty in the total emission estimates. For example, the projected 2020 NO_x emissions vary by almost a factor of 4 (56–211 tons/day) for the base case. In order to identify the major uncertainty drivers, sensitivity analysis was carried out on each input parameter listed in Tables 3 and 4 using correlation analysis (Saltelli et al., 2002; Jaffe and Ferrara, 1984). Briefly, the correlation coefficients between total emissions and emissions from a specific source category are computed. Next, correlation coefficients between the emissions from a specific source category and each input parameter are computed. Source categories and input parameters with the highest correlation coefficients are identified as the major sources of uncertainty.

Table 8 shows key findings from the sensitivity analysis. Drilling and truck traffic account for most of the uncertainty in NO_x emissions. Completion venting is the dominant uncertainty in VOC emissions associated with well development. Key uncertainties associated with NO_x emissions are engine on-time for drill rigs and distance driven by trucks; for VOCs, it is volume vented during completion venting. Large inter-unit variability amongst these parameters is the cause of uncertainty for their respective source estimates. Better data for these parameters will help improve emission estimates.

Conclusion

An emission inventory was developed for the Marcellus Shale to estimate emissions of NO_x, VOCs, and $PM_{2.5}$ in Pennsylvania, New York, and West Virginia. Emissions were estimated for 2009 and projected into 2020 using emission factor and activity data from a variety of sources.

The inventory predicts that Marcellus development will likely be an important source of regional NO_x and VOC emissions. In 2020, Marcellus development may contribute 12% (6–18%) of NO_x and VOC emissions in the Marcellus region. The new Marcellus emissions may offset projected emissions reductions in other sectors (mobile and electrical generating units). Given the potential magnitude of NO_x emissions in rural (NO_x-limited) areas, Marcellus development could complicate ozone management in this region. Marcellus development is not predicted to contribute significantly to regional $PM_{2.5}$ emissions. However, elemental carbon could be more of a concern, with Marcellus development predicted to contribute 14% (2–36%) of the regional elemental carbon emissions.

To investigate benefits of existing and potential future controls, the 2020 analysis considered three future control levels: current, baseline, and tight controls. VOC emissions from the base and tight control scenarios were similar (about a factor of 2), indicating a high level of control by existing regulations. However, more stringent controls could significantly reduce the contribution of Marcellus to regional NO_x emissions. For example, widespread implementation of SCR technology could reduce NO_x emissions to less than 3.5% (1.6–11.4%) of regional emissions versus 22% (11–35%) for the pre-2009 scenario.

An analysis was carried out to identify the major sources of uncertainty. Truck traffic (distance traveled) and drilling (engine on-time) were the key contributors to uncertainty in NO_x emission estimates. VOC emissions uncertainty was driven by volume of gas vented during completion. Because the major uncertainties in the inventory stem from activity data as well as emission factor measurements, these results suggest that improved data collection efforts could substantially constrain emission estimates from natural gas development.

The analysis does not consider the potential air quality benefits of increased end use of natural gas. For example, switching electricity generating from coal to natural gas could offset much of the increase in regional NO_x emissions associated with gas development and production. The impacts of the emissions from Marcellus development on regional air quality will be presented in a forthcoming paper.

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Supplemental Material

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References

Abu-Allaban, M., J.A. Gillies, and A.W. Gertler. 2003. Application of a multi-lag regression approach to determine on-road PM_{10} and $PM_{2.5}$ emission rates. *Atmos. Environ.* 37: 5157–5164. doi:10.1016/j.atmosenv.2003.02.002

American Petroleum Institute. 2009. Compendium of greenhouse gas emissions methodologies for the oil and natural gas industry. http://www.api.org/ehs/climate/new/upload/2009_ghg_compendium.pdf (accessed January 20, 2011).

American Transportation Research Institute. 2009. Estimating truck-related fuel consumption and emissions in maine: A comparative analysis for a 6-axle, 100,000 pound vehicle configuration. http://www.maine.gov/mdot/ofbs/documents/pdf/atrimainereport.pdf (accessed May 20, 2013).

Archuleta, C. 2009. Air quality management in Garfield County: 2008 and 2009 air quality monitoring data; prepared for Garfield County Health Department. http://www.garfield-county.com/air-quality/documents/ARS-RGI-Task3.pdf (accessed May 20, 2013).

Armendariz, A. 2009. Emissions from natural gas production in the Barnett Shale area and opportunities for cost-effective improvements. http://www.edf.org/documents/9235_Barnett_Shale_Report.pdf (accessed January 20, 2011).

Baker, R., and M. Pring. 2009. Drilling rig inventory for the state of Texas. http://www.tceq.state.tx.us/assets/public/implementation/air/am/contracts/reports/ei/5820783985FY0901-20090715-ergi-Drilling_Rig_EI.pdf (accessed June 16, 2011).

Ban-Weiss, G.A., J.P. McLaughlin, R.A. Harley, M.M. Lunden, T.W. Kirchstetter, A.J. Kean, A.W. Strawa, E.D. Stevenson, and G.A. Kendall. 2008. Long term changes in emissions of nitrogen oxide and particulate matter from on-road gasoline and diesel vehicles. *Atmos. Environ.* 42: 220–232. doi:10.1016/j.atmosenv.2007.09.049

Bar-Ilan, A., R. Friesen, A. Pollack, and A. Hoats. 2007. WRAP area source emissions inventory projections and control strategy evaluation phase II. http://www.wrapair.org/forums/ogwg/documents/2007-10_Phase_II_O&G_Final)Report(v10-07%20rev.s.pdf (accessed November 9, 2011).

Bar-Ilan, A., R. Parikh, J. Grant, T. Shah, A.K. Pollack. 2008. Final report: Recommendations for improvements to the CENRAP states' oil and gas emissions inventories. http://www.wrapair.org/forums/ogwg/documents/2008-11_CENRAP_O&G_Report_11-13.pdf (accessed January 27, 2011).

Bernard, S.M., J.M. Samet, A. Grambsch, K.L. Ebi, and I. Romieu. 2001. The potential impact of climate variability and change on air pollution-related health effects in the United States. *Environ. Health Perspect.* 109: 199–209. doi:10.2307/3435010

Biswas, S., V. Verma, J.J. Schauer, and C. Sioutas. 2009. Chemical speciation of PM emissions from heavy duty diesel vehicles equipped with diesel particulate filter (DPF) and selective catalytic reduction (SCR) retrofits. *Atmos. Environ.* 43: 1917–1925. doi:10.1016/j.atmosenv.2008.12.040

Bond, T.C., D.G. Streets, K.F. Yarber, S.M. Nelson, J.-H. Woo, and Z. Klimont. 2004. A technology based global inventory of black and organic emissions from combustion. *J. Geophys. Res.* 109(14). doi:10.1029/2003JD003697

Brown, 2005. Appalachain Shale Gas Study: Detailed gas analysis, GIS database and regional interpretation. http://www.geomarkresearch.com/res/Regional%20Studies%20Proosals/North%20America/Appalachian%20Basin%20Shale%20Gas%20Study.pdf (accessed January 27, 2011).

Burklin, C.E., and M. Heaney. 2005. Natural gas compressor engine survey and engine NO_x emissions at gas production facilities: Final report. http://www.utexas.edu/research/ceer/GHG/files/ConfCallSupp/H40T121FinalReport.pdf.

Canadian Association of Petroleum Producers. 2007. A recommended approach to completing the National Pollutant Release Inventory (NPRI) for the upstream oil and gas industry. http://www.capp.ca/getdoc.aspx?DocId=119572&DT=PDF (accessed November 7, 2011).

Chen, G., P.L. Flynn, S.M. Gallagher, and E.R. Dillier. 2003. Development of the low emission GE-7FDL high power medium speed locomotive diesel engine. *J. Eng. Gas Turbines Power* 125: 505–512. doi:10.1115/1.1563241

Chesapeake Energy. 2011. Annual report for the year 2011. http://www.chk.com/Affiliates/Chesapeake-Oilfield-Services/Documents/COO_Annual_Report.pdf (accessed May 14, 2012).

Choi, H.-W., and H.C. Frey. 2010. Estimating diesel vehicle emission factors at constant and high speeds for short road segments. *Transport. Res. Rec.* 2158: 19–27. doi:10.3141/2158-03

Clark, N., K.A. Vora, L. Wang, M. Gautam, W.S. Wayne, and G.J. Thompson. 2010. Expressing cycles and their emissions on the basis of properties and results from other cycles. *Environ. Sci. Technol.* 44(15): 5986–5992. doi:10.1021/es100308q

Cocker, D.R., III, S.S. Shah, K. Johnson, J.W. Miller, and J.M. Norbeck. 2004. Development and application of a mobile laboratory for measuring emissions from diesel engines. 2. Sampling for toxics and particulate matter. *Environ. Sci. Technol.* 38: 6809–6816. doi:10.1021/es049784x

Considine, T., R. Watson, R. Entler, and J. Sparks. 2009. An emerging giant: Prospects and economic impacts of developing the Marcellus Shale natural gas play. http://marcelluscoalition.org/wp-content/uploads/2010/05/PA-Marcellus-Updated-Economic-Impacts-5.24.10.3.pdf (accessed February 4, 2011).

Considine. 2010. The economic impacts of the Marcellus Shale: Implications for New York, Pennsylvania, and West Virginia; a report to the American Petroleum Institute. http://www.api.org~/media/Files/Policy/Exploration/API-Economic-Impacts Marcellus-Shale.pdf (accessed February 4, 2011).

Considine, T.J., R. Watson, and S. Blumsack. May 24, 2010. The economic aspects of the Pennsylvania Marcellus natural gas play: An update. http://marcelluscoalition.org/wp-content/uploads/2010/05/PA-Marcellus-Updated-Economic-Impacts-5.24.10.3.pdf (accessed February 4, 2011).

Considine, T.J., R.W. Watson, and S. Blumsack. 2011. The Pennsylvania Marcellus natural gas industry: Status, economic impacts and future potential. http://marcelluscoalition.org/wp-conent/uploads/2011/07/Final-2011-PA-Marcellus-Economic-Impacts.pdf (accessed February 4, 2011).

Cullen, A.C., and H.C. Frey. 1999. *Probabilistic techniques in exposure assessment: A handbook for dealing with variability and uncertainty in models and inputs.* New York: Plenum Press.

Dockery, D.W., and C.A. Pope III. 1994. Acute respiratory effects of particulate air pollution. *Annu. Rev. Public Health* 15: 107–132. doi:10.1146/annurev.publhealth.15.1.107

Energy Information Administation. 2007. Natural gas compressor stations on the interstate pipeline network: Developments since 1996. http://www.eia.gov/pub/oil_gas/natural_gas/analysis_publications/ngcompressor/ngcompressor.pdf (accessed August 29, 2011).

ENVIRON International Corporation. 2006. An emission inventory of nonpoint oil and gas emissions sources in the western region. Presented at 15th Annual Emissions Inventory Conference, New Orleans, LA, May 15–18, 2006. http://www.epa.gov/ttn/chief/conference/ei15/session12/russell.pdf (accessed January 29, 2011).

Federal Highway Administration. 2011. Assessing the effects of freight movement on air quality at the national and regional level, Appendix B: Estimation of future truck emissions. http://www.fhwa.dot.gov/environment/air_quality/publications/effects_of_freight_movement/chapter07.cfm (accessed November 9, 2011).

French, N.H.F., P. Goovaerts, and E.S. Kasischke. 2004. Uncertainty in estimating carbon emissions from boreal forest fires. *J. Geophys. Res.* 109: D14S08. doi:10.1029/2003JD003635

Frey, H.C., and K. Kim. 2006. Comparison of real-world fuel use and emissions for dump trucks fueled with B20 biodiesel versus petroleum diesel. *Transp. Res. Rec.* 1987: 110–117.

Frey, H.C., W. Rasdorf, and P. Lewis. 2010. Comprehensive field study of fuel use and emissions of nonroad diesel construction equipment. *Transport. Res. Rec.* 2158: 69–76. doi:10.3141/2158-09

Frey, H.C., and D.S. Rhodes. 1998. Characterization and simulation of uncertain frequency distributions: Effects of distribution choice, variability, uncertainty and parameter dependence. *Hum. Ecol. Risk Assess.* 4: 423–468. doi:10.1080/10807039891284406

Frey, H.C., and Y. Zhao. 2004. Quantification of variability and uncertainty for air toxic emission inventories with censored emission factor data. *Environ. Sci. Technol.* 38: 6094–6100. doi:10.1021/es035096m

Fujita, E.M., B. Zielinska, D.E. Campbell, W.P. Arnott, J.C. Sagabiel, L. Mazzoleni, J.C. Chow, P.A. Gabele, W. Crews, R. Snow, N.C. Clark, W.S. Wayne, D.R. Lawson. 2007. Variations in speciated emissions from sparkignition and compression ignition motor vehicles in California's South Coast air basin. *J. Air Waste Manage. Assoc.* 57(6): 705–720. doi:10.3155/1047-3289.57.6.705

Gajendran, P., and N.N. Clark. 2003. Effect of truck operating weight on heavy-duty diesel emissions. *Environ. Sci. Technol.* 37: 4309–4317. doi:10.1021/es026299y

Geller, M.D., S.B. Sardar, H. Phuleria, P.M. Fine, and C. Sioutas. 2005. Measurements of particle number and mass concentrations and size distributions in a tunnel environment. *Environ. Sci. Technol.* 39: 8653–8663. doi:10.1021/es050360s

Godish, T. 2004. *Air Quality.* Boca Raton: Lewis Publishers.

Gillies, J.A., A.W. Gertler, J.C. Sagabiel, and W.A. Dippel. 2001. On road particulate matter ($PM_{2.5}$ and PM_{10}) emissions in the Sepulvida Tunnel, Los Angeles, California. *Environ. Sci. Technol.* 35: 1054–1063. doi:10.1021/es991320p

Grant, J., L. Parker, A. Bar-Ilan, S. Kemball-Cook, and G. Yarwood. 2009. Draft report: Development of emissions inventories for natural gas exploration and production activity in the Haynesville Shale. Environ International Corporation, CA. http://www.netac.org/UserFiles/File/NETAC/9_29_09/Enclosure_2b.pdf (accessed January 27, 2011).

Grieshop, A.P., E.M. Lipsky, N.J. Pekney, S. Takahama, and A.L. Robinson. 2006. Fine particle emission factors from vehicles in a highway tunnel: Effects of fleet composition and season. *Atmos. Environ.* 40: S287–S298. doi: doi:10.1016/j.atmosenv.2006.03.064

Helton, J.C., and F.J. Davis. 2002. Illustration of sampling based methods for uncertainty and sensitivity analysis. *Risk Anal.* 22: 591–622. doi: doi:10.1111/0272-4332.00041

Hendler, A., J. Nunn, J. Lundeen, and R. McKaskle. 2009. VOC emissions from oil and condensate storage tanks. Prepared for the Texas Environmental Consortium. http://files.harc.edu/Projects/AirQuality/Projects/H051C/H051CFinalReport.pdf (accessed June 9, 2011).

Hu, S., J.D. Herner, M. Shafer, W. Robertson, J.J. Schauer, H. Dwyer, J. Collins, T. Huai, and A. Ayala. 2009. Metals emitted from heavy-duty diesel vehicles equipped with advanced PM and NO_x controls. *Atmos. Environ.* 43: 2950–2959. doi: doi:10.1016/j.atmosenv.2009.02.052

Intergovernmental Panel on Climate Change. 2000. Good practice guidance and uncertainty management in national greenhouse gas inventories. Technical Support Unit, National Greenhouse Gas Inventory Programme, Hayama, Japan. http://www.ipcc-nggip.iges.or.jp/public/gp/english/6_Uncertainty.pdf (accessed February 28, 2013).

Jaffe, P.R., and R.A. Ferrara. 1984. Modeling sediment and water column interactions for hydrophobic pollutants: Parameter discrimination and model response to unit uncertainty. *Water Res.* 18: 1169–1174. doi: doi:10.1016/0043-1354(84)90234-3

Jiang, M., W.M. Griffin, C.T. Hendrickson, P. Jamarillo, J. VanBriesen, and A. Venkatesh 2011. Life Cycle greenhouse gas emissions of Marcellus Shale gas. *Environ. Res. Lett.* doi:10.1088/1748-9326/6/3/034014

Johnson, J.P., D.B. Kittelson, and W.F. Watts. 2009. The effect of federal fuel sulfur regulations on in-use fleets: On-road heavy duty source apportionment. *Environ. Sci. Technol.* 43: 5358–5364. doi:10.1021/es8037164

Kaiser, J. 2005. Mounting evidence indicts fine particle pollution. *Science* 307: 1858–1861. doi:10.1126/science.307.5717.1858a

Katzenstein, A., L. Doezema, I.J. Simpson, D.R. Blake, and F.S. Rowland, 2003. Extensive regional atmospheric hydrocarbon pollution in the southwestern United States. *Proc. Natl. Acad. Sci.* 100: 11975–11979. doi:10.1073/pnas.1635258100

Kemball-Cook, S., A. Bar-Ilan, J. Grant, L. Parker, J. Jung, W. Santamaria, J. Mathews, and G. Yarwood. 2010. Ozone impacts of natural gas development in the Haynesville Shale. *Environ. Sci. Technol.* 44: 9357–9363. doi:10.1021/es1021137

Levy, J.I., T.J. Carrothers, J.T. Tuomisto, J.K. Hammitt, and J.S. Evans. 2001. Assessing the public health benefits of reduced ozone concentrations. *Environ. Health Perspect.* 109: 1215–1226. doi:10.1289/ehp.011091215

Lewis, P., M. Leming, H.C. Frey, and W. Rasdorf. 2011. Assessing effects of operational efficiency on pollutant emissions of nonroad diesel construction equipment. *Transport. Res. Rec.* 2233: 11–18. doi:10.3141/2233-02

Lillpopp, R.M., and S.A. Lindell. 2011. Drilling for jobs: What the Marcellus Shale could mean for New York. http://www.ppinys.org/reports/2011/Drilling-for-jobs-what-marcellus-shale-could-mean-for-NY.pdf (accessed January 24, 2012).

Mazzoleni, C., H.D. Kuhns, H. Moosmuller, J. Witt, N.N. Nussbaum, M.-C.O. Chang, G. Parthasarathy, S.K.K. Nathagoundenpalayam, G. Nikolich, and J. G. Watson. 2007. A case study of real world tailpipe emissions for school buses using a 20% biodiesel blend. *Sci. Total Environ.* 385: 146–159. doi:10.1016/j.scitotenv.2007.06.018

Miller, T.L, J.S. Fu, B. Hromis, J.M. Storey, and J.E. Parks. 2011. Diesel truck idling emissions: Measurements at $PM_{2.5}$ hotspot. *Transport. Res. Rec.* 2011: 49–56.

Mokhtari, A., and H.C. Frey. 2005. Sensitivity analysis of a two-dimensional probabilistic risk assessment model using analysis of variance. *Risk Anal.* 25 (6): 1511–1529. doi:10.1111/j.1539-6924.2005.00679.x

NARSTO (North American Research Strategy for Tropospheric Ozone). 2011. http://www.narsto.org/sites/narsto.org/files/EIAssessChpt8.pdf (accessed February 1, 2013).

New York Department of Environmental Conservation. 2011. Revised draft SGEIS on the oil, gas and solution mining regulatory program. http://www.dec.ny.gov/energy/75370.html (accessed March 18, 2011).

National Energy Technology Laboratory, Pittsburgh. 2010. Projecting the economic impact of Marcellus Shale gas development in West Virginia: A preliminary analysis using publicly available data. NETL-402033110. http://www.netl.doe.gov/energy-analyses/pubs/WVMarcellusEconomics3.pdf (accessed February 4, 2011).

Pennsylvania Department of Environmental Protection. 2011. Marcellus Shale. http://www.portal.state.pa.us/portal/server.pt/community/marcellus_shale/20296 (accessed January 31, 2011).

Pollution Solutions. 2008. http://etcog.sitestreet.com/UserFiles/File/NETAC/0607_closeout/Technical%20Deliverables/Task_4.2.pdf (accessed June 9, 2011).

Pring, M., D. Hudson, J. Renzaglia, B. Smith, and S. Treimel 2010. Characterization of oil and gas production equipment and develop a methodology to estimate statewide emissions: Final report, prepared for Martha Maldonado, Texas Commission on Environmental Quality. .tceq.texas.gov/assets/public/implementation/air/am/contracts/reports/ei/5820784003FY1026-20101124-ergi-oilGasEmissionsInventory.pdf (accessed July 7, 2011).

Prucz, J.C., N.N. Clark, M. Gautam, and D.W. Lyons. 2001. Exhaust emissions from engines of the Detroit diesel corporation in transit buses: A decade of trends. *Environm. Sci. Technol.* 35: 1755–1764. doi:10.1021/es001416f

Ramaswami, A., J.B. Milford, and M.J. Small 2005. *Integrated environmental modeling: Pollutant transport, fate and risk in the environment.* New York: John Wiley and Sons.

Ross, S. 2006. *Simulation*, 4th ed. Boston, MA: Elsevier.

Saltelli, A. 2002. Sensitivity analysis for importance assessment. *Risk Anal.* 22: 579–590. doi:10.1111/0272-4332.00040

Sawant, A.A., A. Nigam, J.W. Miller, K.C. Johnson, and D.R. Cocker. 2007. Regulated and non-regulated emissions from in-use diesel-electric switching locomotives. *Environ. Sci. Technol.* 41: 6074–6083. doi:10.1021/es061672d

Schnell, R.C., S.J. ltmans, R.R. Neely, M.S. Endres, J.V. Molenar, and A.B. White. 2009. Rapid photochemical production of ozone at high concentrations in a rural site during winter. *Nat. Geosci.* 2:120–122. doi:10.1038/NGEO415

Shah, S.D., D.R. Cocker, K.C. Johnson, J.M. Lee, B.L. Soriano, and J.W. Miller. 2006. Emissions of regulated pollutants from in-use diesel back-up generators. *Atmos. Environ.* 40: 4199–4209. doi:10.1016/j.atmosenv.2005.12.063

Strawa, A.W., T.W. Kirchstetter, A.G. Hallar, G.A. Ban-Weiss, J.P. McLaughlin, R.A. Harley, and M.M. Lunden. 2010. Optical and physical properties of primary on-road vehicle particle emissions and their implications for climate change. *J. Aerosol Sci.* 41: 36–50. doi:10.1016/j.jaerosci.2009.08.010

The Nature Conservancy, Pennsylvania. 2010. Pennsylvania energy impacts assessment, Report 1: Marcellus Shale natural gas and wind. http://www.nature.org/media/pa/tnc_energy_analysis.pdf (accessed July 7, 2011).

The Williams Companies. 2007. Reducing methane emissions during completion operations. Williams Production RMT–Piceance Basin Operations. Presented at 2007 Natural Gas Star–Production Technology Transfer Workshop, Glenwood Spring, Colorado, September 11, 2007.
U.S. Environmental Protection Agency. 2004a. Nonroad engines, equipment and vehicls. http://www.epa.gov/otaq/documents/nonroad-diesel/420f04032.pdf (accessed June 10, 2012).
U.S. Environmental Protection Agency. 2004b. Natural gas STAR Program. http://www.epa.gov/gasstar/ (accessed May 25, 2013).
U.S. Environmental Protection Agency. 2005. National Clean Diesel Program. http://epa.gov/cleandiesel/documents/420r06009.pdf (accessed September 22, 2013).
U.S. Environmental Protection Agency. 2006. SPECIATE 4.0: Speciation database development documentation: Final report. http://www.epa.gov/ttnchie1/software/speciate/
U.S. Environmental Protection Agency. 2007. Natural gas STAR Program. http://www.epa.gov/gasstar/documents/workshops/glenwood-2007/04_recs.pdf (accessed November 24, 2011).
U.S. Environmental Protection Agency. 2008a. NONROAD model (nonroad engines, equipment, and vehicles). http://www.epa.gov/otaq/nonrdmdl.htm (accessed June 10, 2012).
U.S. Environmental Protection Agency. 2008b. 2005 National emissions inventory data & documentation. http://www.epa.gov/ttnchie1/net/2005inventory.html (accessed October 13, 2011).
U.S. Environmental Protection Agency. 2009. National mobile inventory model (NMIH). http://www.epa.gov/oms/nmim.htm (accessed June 10, 2012).
U.S. Environmental Protection Agency. 2010. http://www.epa.gov/cleandiesel/documents/420b10033.pdf (accessed June 10, 2012).
U.S. Environmental Protection Agency. 2011. Emissions factors & AP-42: Compilation of air pollutant emission factors. http://www.epa.gov/ttnchie1/ap42/ (accessed October 20, 2011).
U.S. Environmental Protection Agency. 2011b. 2008 National emissions inventory data. http://www.epa.gov/ttnchie1/net/2008inventory.html (accessed November 24, 2011).
U.S. Environmental Protection Agency. 2012a. National embient air quality standards (NAAQS). http://www.epa.gov/air/criteria.html (accessed May 24, 2013).
U.S. Environmental Protection Agency. 2012b. Oil and natural gas air pollution standards. http://www.epa.gov/airquality/oilandgas/actions.html (accessed June 10, 2012).
U.S. Environmental Protection Agency. 2012c. http://www.epa.gov/cleandiesel/basicinfo.htm (accessed May 24, 2013).
U.S. Environmental Protection Agency. 2012d. The Green Book nonattainment areas for Criteria Pollutants. http://www.epa.gov/oaqps001/greenbk/ (accessed May 24, 2013).
U.S. Environmental Protection Agency. 2013a. Nonroad engines, equipment and vehicles: locomotives. http://www.epa.gov/otaq/locomotives.htm (accessed May 24, 2013).
U.S. Environmental Protection Agency. 2013b. Nonroad engines, equipment and vehicles: nonroad diesel engines. http://www.epa.gov/otaq/nonroad-diesel.htm (accessed May 24, 2013).
U.S. Environmental Protection Agency. 2013c. Modeling and inventeries: MOVES (Motor Vehicle Emission Simulator). http://www.epa.gov/otaq/models/moves/index.htm (accessed May 24, 2013).
U.S. Geological Survey. 2009. Potential Development of the Natural Gas Resources in the Marcellus Shale New York, Pennsylvania, West Virginia, and Ohio. http://www.nps.gov/frhi/parkmgmt/upload/GRD-M-Shale_12-11-2008_high_res.pdf (accessed November 24, 2011).
Van der werf, G.R., J.T. Randerson, L. Giglio, G.J. Collatz, M. Mu, P.S. Kasibhatla, D.C. Morton, R.S. DeFries, Y. Jin, and T.T. Leeuwen. 2010. Global fire emissions and the contribution of deforestation, savanna, forest, agricultural and peat fires. *Atmos. Chem. Phys.* 10: 11707–11735. doi:10.5194/acp-10-11707-2010
West Virginia Geological and Economic Survey. 2011. http://www.wvgs.wvnet.edu/www/datastat/devshales.htm (accessed February 7, 2011).
Weinstein, B.L., and T.L. Clower. 2009. Potential economic and fiscal impacts from natural gas production in Broome, New York. http://www.gobroomecounty.com/files/countyexec/Marcellus-Broome%20County-Preliminary%20Report%20for%20distribution%207-27-09.pdf (accessed February 10, 2012).
Zhang, K.M., A.S. Wexler, D.A. Niemeier, Y.F. Zhu, W.C. Hinds, and C. Sioutas. 2005. Evolution of particle number distributions near roadways. Part III: Traffic analysis and on-road size resolved particulate emission factors. *Atmos. Environ.* 39: 4155–4166. doi:10.1016/j.atmosenv.2005.04.003
Zhao, Y., and H.C. Frey. 2004. Development of probabilistic emission inventories of air toxics for Jacksonville, Florida. *J. Air Waste Manage. Assoc.* 54: 1405–1421. doi:10.1080/10473289.2004.10471002
Zhu, D., N.N. Nussbaum, H.D. Kuhns, M.-C.O. Chang, D. Sodeman, H. Moosmuller, and J.D. Watson. 2011. Real world PM, NO_x, CO, and ultrafine particle emission factors for military non-road heavy duty diesel vehicles. *Atmos. Environ.* 45: 2603–2609. doi:10.1016/j.atmosenv.2011.02.032
Zielinska, B., E. Fujita, and D. Campbell. 2010. Monitoring of emissions from Barnett Shale natural gas production facilities for population exposure assessment. https://sph.uth.edu/mleland/attachments/Barnett%20Shale%20Study%20Final%20Report.pdf.

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