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Short Communication

The impacts of fracking on the environment: A total environmental study paradigm

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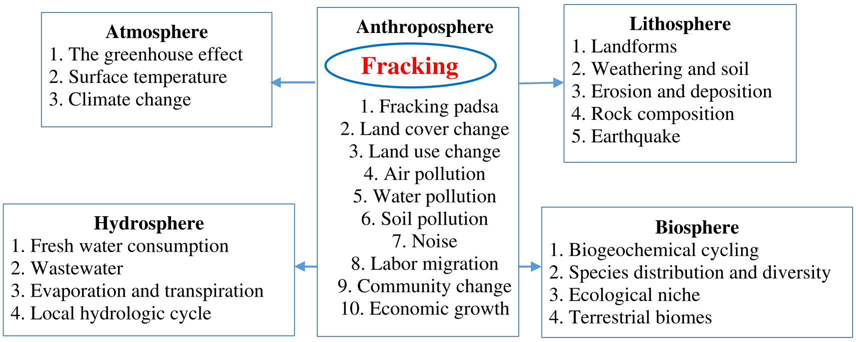
HIGHLIGHTS

- The environmental impacts of fracking are much broader and deeper than current studies observe.
- 26 areas in anthroposphere, atmosphere, biosphere, hydrosphere, and lithosphere are identified.
- Multidisciplinary theory and cutting-edge methods are required for environmental analysis.
- A total environmental study paradigm is designed for impact analysis of fracking.

GRAPHICAL ABSTRACT



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ABSTRACT

Fracking has become a hot topic in the media and public discourse not only because of its economic benefit but also its environmental impacts. Recently, scientists have investigated the environmental impacts of fracking, and most studies focus on its air and ground water pollution. A systematic research structure and an overall evaluation of fracking's impacts on the environment are needed, because fracking does not only influence ground water but most environmental elements including but not limited to air, water, soil, rock, vegetation, wildlife, human, and many other ecosystem components. From the standpoint of the total environment, this communication assesses the overall impacts of fracking on the environment and then designs a total environmental study paradigm that effectively examines the complicated relationship among the total environment. Fracking dramatically changes the anthroposphere, which in turn significantly impacts the atmosphere, hydrosphere, lithosphere, and biosphere through the significant input or output of water, air, liquid or solid waste disposals, and the complex chemical components in fracking fluids. The proposed total environment study paradigm of fracking can be applied to other significant human activities that have dramatic impacts on the environment, such as mountain top coal mining or oil sands for environmental studies.

1. Introduction

Fracking has become one of the hot topics in both the media and science. Fracking has been discussed from “revolutionary” to “disastrous”, and in reality it is blessing and curse. Fracking generates income, creates new jobs, and could reduce air pollution and even water use compared

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with coal (Jackson et al., 2014). Fracking has become a fast growing industry, experienced a rapid expansion, yielded more than one-half of US natural gas supply, and is transforming energy supplies in USA (Jackson et al., 2013; Meng and Ashby, 2014). Hydraulic fracturing is a geochemical engineering process by which huge volumes of water combined with chemicals and sand proppant is injected into tight formations with high pressure to fracture and facilitate recovery of unconventional reserves of oil and gas. In USA, it is often called the high-volume horizontal hydraulic fracturing process (HVHFP) with horizontal drilling technique applied in order to maximize retrieval of oil/gas from shale plays (Meng, 2014), which directly or indirectly results in the impacts of fracking on the environment. Fracking has resulted in a so-called "shale gas revolution". For example, British Petroleum stated that global shale gas production could increase sixfold till 2030 (Hughes, 2013), and the natural gas is expected to be triple by 2030 in USA (Deutch, 2011). According to U.S. EIA (2011), there are 48 significant gas shale basins in 32 countries, which including about 70 shale gas formations trap almost the same amount of conventional natural gas. Fracking (i.e., the current exploitation of shale gas reserves) has resulted in lower energy prices, clean environment impacts, and local economic development.

Fracking poses benefit to the society but has caused environmental concerns about air and ground water degradation (Gregory et al., 2011; Howarth et al., 2011a; Petron et al., 2012; Jackson et al., 2013; Yan et al., 2017), human health problems caused by near fracking wells (Colborn et al., 2011; Mckenzie et al., 2012; Schmidt, 2011), and pollutants in groundwater and drinking water in proximity to fracking sites. For example, fracking in the Marcellus Shale region in the Northeastern United States has raised concerns of potential environmental pollution (Kerr, 2010; Kargbo et al., 2010). Methane tested in both ground water and well water suggests its migration from fracking wells to nearby drinking water wells, surface water, and atmosphere (Howarth et al., 2011a; Howarth et al., 2011b; Osborn et al., 2011; Jiang et al., 2011). Besides the surface air and ground water concerns, fracking's impacts on other components of anthroposphere are beginning to be analyzed and modeled, such as landscape changes modeling (Meng, 2014), the role of distance in general risk assessment (Meng and Ashby, 2014), and population and the environment at risk due to fracking (Meng, 2015).

Employing cutting-edge technologies, fracking now means the combination of advanced high-pressure, high-volume hydraulic fracturing, and often horizontal drilling, and it has been used worldwide (Meng, 2016). From the standpoint of the total environment, the impacts of fracking on the environment are much broader than the current studies have attempted to observe. It is time to design and develop a systematic study paradigm to assess the overall environmental effects caused by fracking. From the view point of the total environment, this commentary will provide a conceptual summary of the impacts that fracking has had on the anthroposphere, atmosphere, biosphere, hydrosphere, and lithosphere, to show the need for a total study paradigm.

2. Fracking and the total environment

2.1. Fracking changes the anthroposphere

Fracking changes anthrophosphere by removing initial land cover types, creating large concrete fracking pads, and developing new transportation networks (Meng, 2014, 2015, 2016). Fracking has become a common part of the landscape in shale gas regions (Meng, 2014). A conventional gas/oil drilling site often occupies less than 3 acres, but current fracking sites typically needs about 5 acres (2 ha). These fracking pads as industrial landscapes intrude into original urban, rural, and forest landscapes, which are connected by newly created transportation networks (Fig. 1). People working at fracking sites often move and aggregate into a nearby city or town, in which the communities are influenced and changed by these strangers (Jacquet, 2014) who often move to other places as the drilling and fracking are completed and new fracking tasks are needed away from their current locations.

As the fracking pad is established, the vertical and horizontal drilling processes are going to be completed, and then a fracking well is hydraulically fractured. Before the fracking operation starts, the control van, pump truck, sand haulers, water tanks and water-hauling trucks, and blender arrive on site. Too much noise and truck traffic then becomes the most noticeable sign of fracking sites (Meng, 2014).

2.2. Fracking impacts on biosphere

The fracking sites often intrude into forest lands, agricultural lands, and grass lands. Each fracking pad looks like a small town at mountaintop gas fracking pad sites, where are typically clear cut, paved with tons of gravel, and inhabited by dozens of huge instruments and equipment (Meng, 2014). Besides the fracking pads, there are also lined pits to contain wastewater from the drilling and fracturing operations, and the social and environmental properties near the pad area can be severely impacted (Pipenberg, 2012; Johnson et al., 2010).

Deforestation caused by fracking (Drohan et al., 2012) or converting grassland into fracking pads has deep effects on the environment, such as a loss of habitats for animal and plant species (Kiviat, 2013), and could be a critical factor driving climate change locally and regionally. Soils in forest lands are typically moist, but they quickly dry out and become barren deserts after clear-cut. After clear-cut, the sun's rays cannot be blocked during the day, and the land surface is quickly heated during days and cooled down at night. This disruption in a region can lead to changes of local extreme temperatures, which can harm microorganisms, plants, animals, and even human. Thus, ecological niches change, and invasive species become easily to be intruded and established in the changed terrestrial environment, which further impact and change the species selection and evolution in the long run.

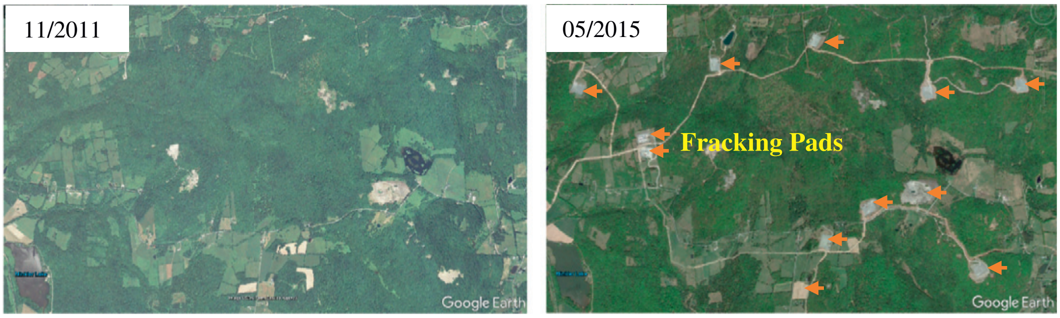

Fig. 1. 12 fracking sites have been established in a 3.5 × 5 km area in northwest Susquehanna County, Pennsylvania, USA by May 2015. The left image was observed in November 2011; the right image was observed in May 2015, in which the arrow points to the 12 fracking sites. Google Earth is used to portray the images.

2.3. Fracking impacts on atmosphere

Fracking impacts on atmosphere are mainly through two approaches. First, fracking deforestation reduces forests as discussed above. Methane emission from fracking is another major contribution to fracking impacts on atmosphere. Methane is the second most prevalent greenhouse gas. Methane is more efficient at trapping radiation than CO_2, although its lifetime is much shorter than that of carbon dioxide in atmosphere. In the USA, the largest source of CH_4 emission is natural gas and petroleum systems. Regional level methane leakages have been detected by recent atmospheric studies. About 55,000 ± 15,000 kg CH_4 per hour leaking into the atmosphere was detected in the Uinta Basin (Karion et al., 2013), which is about 6.2–11.7% of the total natural gas production in this region; in the Denver Basin, Colorado measured about a 4% leakage has been estimated (Pétron et al., 2014).

According to US Environmental Protection Agency (U.S. EPA, 2016), electricity production contributes about 30% greenhouse gas emission in USA, and natural gas for electricity generation at a plant level produces only about 50% greenhouse gas emissions compared with a coal power plant. However, the Intergovernmental Panel on Climate Change (IPCC) reports that methane is much more a potential greenhouse gas than scientists recognized before. If the GWP of carbon dioxide is 1, the GWP of CH_4 is 86 and 34 respectively in the time horizon of 20 and 100 years (Stocker et al., 2013).

2.4. Fracking impacts on hydrosphere

Although water consumption is relatively low compared to other fossil fuels, water withdrawals can be locally substantial (Mielke et al., 2010). Typically, one fracking well needs about 2–20 million gal of water with proppants of sand and chemicals to be pumped into impermeable rocks (Jackson et al., 2014). While conventional gas without consumption of water, the water consumption of shale gas extraction is 1.3 gal/MMBtu (Mielke et al., 2010). Now, there are more than 7000 fracking wells in the state of Pennsylvania (Meng, 2015). The high density concrete construction of fracking sites can significantly change the landscape and deforestation as described above (Meng, 2014), and local throughflow, surface runoff, streamflow, as well as therefore the local hydrologic cycle. Fracking in USA was poorly regulated at the federal level, its wastes and wastewater are not managed as hazardous waste by the Resource Conservation and Recovery Act, and the Safe Drinking Water Act has no rules about fracking wells (Osborn et al., 2011). Fortunately, the U.S. Department of the Interior (2015) recently issued the fracking regulation that is effective on June 24, 2015.

2.5. Fracking impacts on lithosphere

Fracking directly and indirectly influences the lithosphere. Mountaintop fracking pads and fracking pads within agricultural lands and grassland change the landform and other geomorphological characteristics, such as weathering, slope process, and mass movement. Mechanical and chemical translocation of soil materials and organic activity in soil can be significantly changed on the local level due to deforestation or converting crop fields or grassland into fracking pads. A typical HVHFP with a pressure of 10,000–20,000 psi could cause seismic wave changes and induce small earthquakes (Seismosoc.org, 2015). Fluid injection into deep wells is related to recorded seismicity (Ellsworth et al., 2012), and recently the significant spatiotemporal association between fracking and seismicity is observed in USA, Canada, and Poland (e.g., Atkinson et al., 2016; Petersen et al., 2015; Schultz et al., 2015a, 2015b; Skoumal et al., 2015). Generally, about 2–20 million gal of water and proppants of sand and chemicals are pumped into impermeable rocks; accordingly in volume 0.123% acid, 0.088% friction reducer, 0.085% surfactant, 0.06% salt, 0.043% scale inhibitor, 0.011% pH-adjusting agent, 0.004% iron control, 0.002% corrosion inhibitor, and 0.001% biocide are injected (Gregory et al., 2011), most of them left in the rocks, and in short, fracking could change the rock chemical composition and physical structure.

3. A total environmental study paradigm

Centering on the fracking, a total environmental study paradigm is developed, and a total of 26 fields across anthroposphere, atmosphere, lithosphere, hydrosphere, and biosphere are impacted by and associated with fracking (Fig. 2). Fracking directly changes the anthroposphere including the 10 aspects of fracking pads: land cover change, land use change, air pollution, water pollution, soil pollution, noise, labor migration, community change, and economic growth. As a result of huge amounts of methane emissions into atmosphere, fracking significantly changes the effect of current greenhouse gases, and the author would assume it has changed land surface temperatures and local and regional climates. Fracking influences five aspects of lithosphere including landform, weathering and soil, erosion and deposition, rock composition, and seismicity and earthquakes. Fracking also results in significant effects on hydrosphere including freshwater consumption, wastewater pollution, evaporation and transpiration, and local hydrologic cycle. Lastly, fracking is changing the biosphere, and four aspects would be affected apparently including biogeochemical cycling, species distribution and diversity, ecological niches, and terrestrial biomes.

Fracking's impacts on the environment is a typical interdisciplinary study. It is a complicated human-environment interaction process; landscape sciences, environment study, sociology and demography, economy, atmosphere and climatology, geology and geomorphology, geoengineering and geochemical engineering, hydrology, and ecological systems could make important contribution to the environment study of fracking. On the one hand, this proposed paradigm provides a conceptual understanding of a total environmental study of fracking, which could be implemented in case studies at a shale gas place by considering the environmental elements that are suggested in Fig. 2. Scientists from different academic fields including but not limited to anthroposphere, atmosphere, biosphere, lithosphere, hydrosphere need to be brought together to work on the complicated interactions between fracking and the environment in order to enlarge the public understanding of the total environmental impacts of fracking. On the other hand, it does not mean every study of fracking's impacts must be a multidisciplinary research, but any considerations and incorporations of knowledge or techniques from the related disciplines could make significant complementary to research specified by an individual field. For example, the combination of advances in geochemical and geophysical engineering techniques (e.g., smart magnetic markers used in fracking (Zawadzki and Bogacki, 2016)) and geospatial sciences (e.g., geographic information systems including geodatabases, remote sensing, and cartography and computer mapping) will not only efficiently identify and map fracking ranges but also accurately analyze, track, and update its environment impacts underground, in soil, in surface water, and potentially in methane life cycle in the atmosphere. Another example is geodatabase and spatiotemporal database of fracking's effects on the environment, which need to be established so that scientists may have the opportunity to analyze and understand its impacts on the total environment in a long run (Meng, 2016).

This total environmental study paradigm is different from the "whole-system thinking" risk assessment approach proposed for fracking in UK (Hammond et al., 2015; Pidgeon et al., 2014; UK-DECC, 2014), in which the engagement of stakeholders and citizen is emphasized. Specifically, Hammond et al. (2015) summarized that six aspects of socio-economic and market issue, induced seismicity, water use and contamination, environmental impacts, public and stakeholder engagement, and planning, regulation and monitoring should be included in an energy technology assessment of fracking in UK in order to provide balanced information and policy framings. Local communities and the stakeholders (oil and gas companies) can participate in environmental study of fracking, and balanced opinions or information could be

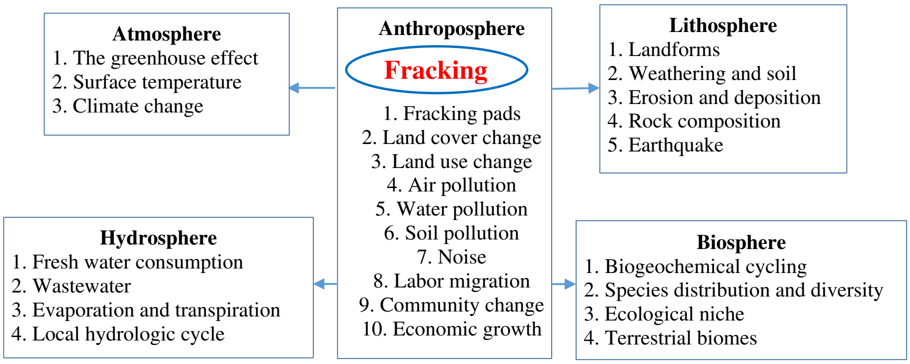

Fig. 2. A total environmental study paradigm of fracking.

combined; however, a biased assessment can be easily obtained by local communities or the stakeholders because of the obvious and significant conflicts of interest. An environmental risk assessment of fracking must be based on scientific evidence base (Prpich et al., 2015). The systematic relationship between fracking and the total environmental systems have not been recognized, and the environment aspects or elements affected or potentially affected by fracking are needed to be input in a total environmental study model, which are the primary and most important steps before an environmental risk assessment of fracking could be conducted. The objective of the total environmental study paradigm proposed in this study is to provide an overall conceptual model and a neutral scientific thinking prototype for pure environmental impact study of fracking, which is not limited by a country or region.

This total environmental study paradigm reveals that there are many other environmental aspects and elements that are affected by fracking, the current research of fracking's impacts on the environment is just a start, and besides the study of air and water, scientific research including but not limited to soil erosion and weathering, land forms, species invasion, ecological niches, climate change, and terrestrial biomes (e.g., the total 26 fields in Fig. 2) is also critical and needed for scientists from environmental sciences, geosciences, engineering, and other disciplinary to conduct pure environmental assessment and at the same time avoid conflicts of interest; and thereafter, a neutral, unbiased, and overall assessment of the impacts of fracking on the environment and society could be provided to the public.

References

Atkinson, G.M., Eaton, D.W., Ghofrani, H., Walker, D., Cheadle, B., Schultz, R., Shcherbakov, R., Tiampo, K., GU, J., Harrington, R.M., Liu, Y., van der Baan, M., Kao, H., 2016. Hydraulic fracturing and seismicity in the Western Canada Sedimentary Basin. Seismol. Res. Lett. 87 (3), 1–17.

Colborn, T., Kwiatkowski, C., Schultz, K., Bachran, M., 2011. Natural gas operations from a public health perspective. Hum. Ecol. Risk. Assess. 17, 1039–1056.

Deutch, J., 2011. The good news about gas: the natural gas revolution and its consequences. Foreign Aff. 90, 82–93.

Drohan, P.J., Brittingham, M., Bishop, J., et al., 2012. Early trends in landcover change and forest fragmentation due to shale-gas development in Pennsylvania: a potential outcome for the Northcentral Appalachians. Environ. Manag. 49:1061. http://dx.doi.org/10.1007/s00267-012-9841-6.

Ellsworth, W.L., Hickman, S.H., Llesons, A.L., Mcgarr, A., Michael, A.J., Rubinstein, J.L., 2012. Are seismicity rate changes in the midcontinent natural or manmade? US Geological Survey (Menlo Park, CA)

Gregory, K.B., Vidic, R.D., Dzombak, D.A., 2011. Water management challenges associated with the production of shale gas by hydraulic fracturing. Elements 7, 181–186.

Hammond, G.P., O'Grady, A., Packham, D.E., 2015. Energy technolgy assessment of shale gas 'Frakcing' - A UK perspective. Energy Procedia 75, 2764–2771.

Howarth, R.W., Ingraffea, A., Engelder, T., 2011a. Natural gas: should fracking stop? Nature 477, 271–275.

Howarth, R.W., Santoro, R., Ingraffea, A., 2011b. Methane and the greenhouse-gas footprint of natural gas from shale formations. Clim. Chang. 106, 679–690.

Hughes, J.D., 2013. A reality check on the shale revolution. Nature 494 (308).

Jackson, R.B., Vengosh, A., Darrah, T.H., Warner, N.R., Down, A., Poreda, R.J., Osborn, S.G., Zhao, K., Karr, J.D., 2013. Increased stray gas abundance in a subset of drinking water wells near Marcellus shale gas extraction. Proc. Natl. Acad. Sci. U. S. A. 110, 11250.

Jackson, R.B., Vengosh, A., Carey, W., Davies, R.J., Darrah, T.H., O'Sullivan, F., Petron, G., 2014. The environment costs and benefits of fracking. Annu. Rev. Environ. Resour. 39, 327–362.

Jacquet, J.B., 2014. Review of risks to communities from shale energy development. Environ. Sci. Technol. 48 8321-8333.

Jiang, M., Griffin, W.M., Hendrickson, C., Jaramillo, P., VanBriesen, J., Venkatesh, A., 2011. Life cycle greenhouse gas emissions of Marcellus shale gas. Environ. Res. Lett. 6, 034041.

Johnson, N., Gagnolet, T., Zimmerman, E., Eichelberger, B., Tracey, C., Kreitler, G., Orndorff, S., Tomlinoson, J., Bearer, S., Sargent, S., 2010. Pennsvlvania Energy Impacts Assessment. http://www.nature.org/media/pa/tnc_energy_analysis.pdf (Accessed on 12/01/2016).

Kargbo, D.M., Wilhelm, R.G., Campbell, D.J., 2010. Natural gas plays in the Marcellus Shale: challenges and potential opportunities. Environ. Sci. Technol. 44, 5679–5684.

Karion, A., Sweeney, C., Pétron, G., Frost, G., Hardesty, R.M., et al., 2013. Methane emissions estimate from airborne measurements over a western United States natural gas field. Geophys. Res. Lett. 40, 4393–4397.

Kerr, R.A., 2010. Natural gas from shale bursts onto the scene. Science 328, 1624–1626.

Kiviat, E., 2013. Risks to biodiversity from hydraulic fracturing for natural gas in the Marcellus and Utica shales. Ann. N. Y. Acad. Sci. 1286, 1–14.

Mckenzie, L.M., Witter, R.Z., Newman, L.S., Adgate, J.L., 2012. Human health risk assessment of air emissions form development of unconventional natural gas resources. Sci. Total Environ. 424, 79–87.

Meng, Q., 2014. Modeling and prediction of natural gas fracking pad landscapes in the Marcellus Shale region, USA. Landsc. Urban Plan. 121, 109–116.

Meng, Q., 2015. Spatial analysis of environment and population at risk of natural gas fracking in the state of Pennsylvania, USA. Sci. Total Environ. 515–516, 198–206.

Meng, Q., 2016. Fracking. In: Chen, W.-Y., Suzuki, T., Lackner, M. (Eds.), Handbook of Climate Change Mitigation and Adaptation, pp. 1–14.

Meng, Q., Ashby, S., 2014. Distance: a critical aspect for environmental impact assessment of hydraulic fracking. Ext. Ind. Soc. 1, 124–126.

Mielke, E., Anadon, L.D., Narayanamurti, V., 2010. Water Consumption of Energy Resource Extraction, Processing, and Conversion. (http://belfercenter.ksg.harvard.edu/files/ETIP-DP-2010-15-final-4.pdf. Accessed on 11/16/2016).

Osborn, S.G., Vengosh, A., Warner, N.R., Jackson, R.B., 2011. Methane contamination of drinking water accompanying gas-well drilling and hydraulic fracturing. Proc. Natl. Acad. Sci. U. S. A. 108, 8172.

Petersen, M., Mueller, C., Moschetti, M., Hoover, S., Rubinstein, J., Llenos, A., Michael, A., Ellsworth, W., McGarr, A., Holland, A., Anderson, J., 2015. Incorporating induced seismicity in the 2014 United States National Seismic Hazard Model. Results of the 2014 Workshop and Sensitivity Studies, U.S. Geol. Surv. Open-File Rept. 2015-XXXX.

Petron, G., Frost, G., Miller, B.R., Hirsch, A.I., Montzka, S.A., Karion, A., Trainer, M., Sweeney, C., Andrews, A.E., Miller, L., Kofler, J., Bar-Ilan, A., Dlugokencky, E.J., Patrick, L.T., Moore Jr., C.T., Ryerson, T.B., Siso, C., Kolodzey, W., Lang, P.M., Conway, T., Novelli, P., Masarie, K., Hall, B., Guenther, D., Kitzis, D., Miller, J., Welsh, D., Wolfe, D., Neff, W., Tans, P., 2012. Hydrocarbon emissions characterization in the Colorado Front Range: a pilot study. J. Geophys. Res. 117 (D4), D04304.

Pétron, G., Karion, A., Sweeney, C., Miller, B.R., Montzka, S.A., et al., 2014. A new look at methane and nonmethanehydrocarbon emissions from oil and natural gas operations in the Colorado Denver-Julesburg Basin. J. Geophys. Res. 119 (11), 6836–6852.

Pidgeon, N., Demski, C., Butler, C.C., Parkhill, K., Spence, A., 2014. Creating a national citizen engagement process for energy policy. Proc. Natl. Acad. Sci. (Suppl. 4), 13606–13613.

Pipenberg, N., 2012. Gas drilling destroying Pennsylvania forests. http://wtfrackorg.blogspot.com/2012/02/gas-drilling-destroying-pennsylvania.html. (Accessed on 12/01/2016).

Prpich, G., Coulon, F., Anthony, E.J., 2015. Review of the scientific evidence to support environmental risk assessment of shale gas development in the UK. Sci. Total Environ. 563–564, 731–740.

Schmidt, C.W., 2011. Blind rush? Shale gas boom proceeds amid human health questions. Environ. Health Perspect. 119 (8), A348–A353.

Schultz, R., Mei, S., Pana, D., Stern, V., Gu, Y., Kim, A., Eaton, D., 2015a. The Cardston earthquake swarm and hydraulic fracturing of the “Alberta Bakken” play. Bull. Seismol. Soc. Am. 105, 2871–2884.

Schultz, R., Stern, V., Novakovic, M., Atkinson, G., Gu, Y., 2015b. Hydraulic fracturing and the Crooked Lake Sequences: insights gleaned from regional seismic networks. Geophys. Res. Lett. 42, 2750–2758.

Seismosoc.org, 2015. Fracking confirmed as cause of rare “felt” earthquake in Ohio. http://www.seismosoc.org/society/press_releases/BSSA_105-_Skoumal_et_al_Press_Release.pdf (Accessed on 4/13/2016).

Skoumal, R., Brudzinski, M., Currie, B., 2015. Earthquakes induced by hydraulic fracturing in Poland township, Ohio. Bull. Seismol. Soc. Am. 105, 189–197.

Stocker, T.F., Qin, D., Plattner, G., Tignor, M.B., Allen, S.K., Boschung, J., Nauels, A., Xia, Y., Bex, V., Midgley, P.M., 2013. Climate change 2013: working group I: the physical science basis. https://www.ipcc.ch/pdf/assessment-report/ar5/wg1/WG1AR5_SummaryVolume_FINAL.pdf (Accessed on 11/17/2016).

U.S. Department of the Interior, 2015. Oil and gas, hydraulic fracturing on federal and Indian Lands. https://www.gpo.gov/fdsys/pkg/FR-2015-03-26/pdf/2015-06658.pdf (Accessed on December 1, 2016).

U.S. EIA, 2011. World Shale Gas Resources: an Initial Assessment of 14 Regions Outside the United States. U.S. Department of Energy, Washington, DC.

U.S. EPA, 2016. Sources of greenhouse gas emissions. https://www.epa.gov/ghgemissions/sources-greenhouse-gas-emissions (Accessed on 11/16).

UK-DECC, 2014. Guidance on the preparation of an environmental risk assessment of shale gas operations in Great Britain involving the use of hydraulic fracturing. https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/305884/Guidance:on_the_preparation_of_an_environmental_risk_assessment_of_shale_gas_operations_in_Great_Britain_involving_the_use_of_hydraulic_fracturing.pdf (Accessed on December 1, 2016).

Yan, B., Stute, M., Panettieri Jr., R.A., Ross, J., Mailloux, B., Neidell, M.J., Soares, L., Howarth, M., Liu, X., Saberi, P., Chillrud, S.N., 2017. Association of groundwater constituents with topography and distance to unconventional gas wells in NE Pennsylvania. Sci. Total Environ. 577, 195–201.

Zawadzki, J., Bogacki, J., 2016. Smart magnetic markers use in hydraulic fracturing. Chemosphere 162, 23–30.