

2016

# The environmental and political ecology of natural gas

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BOSTON UNIVERSITY  
GRADUATE SCHOOL OF ARTS AND SCIENCES

Dissertation

**THE ENVIRONMENTAL AND POLITICAL ECOLOGY OF NATURAL GAS**

by

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Submitted in partial fulfillment of the  
requirements for the degree of  
Doctor of Philosophy

2016

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## ACKNOWLEDGMENTS

I would like to extend my deepest gratitude to the multitude of people who have supported and encouraged me throughout the development of my dissertation. First and foremost, my heartfelt thanks go to my advisor, Nathan Phillips, who has expertly guided me for five and half years while also allowing me the creative space to craft a dissertation for which I am immensely proud. Thank you, Nathan, for the opportunity to work with you at Boston University and break into climate change science in such a significant and meaningful way that has exceeded all of my expectations! Many thanks to my committee: Lucy Hutyra, Anne Short Gianotti, Suchi Gopal, and Shanna Cleveland. I have learned so much from all of you, and I feel extremely fortunate for the opportunity to have worked with you over the course of my doctoral program. My sincerest thanks also go to Bob Ackley who has taught me everything I could possibly want to know about natural gas distribution systems. Thanks, Bob, for taking me under your wing and showing me a few tricks of the trade!

Many, many thanks to all of the professors that I've had the pleasure of working with and learning from over the course of my graduate program – you've made my time at Boston University incredibly rewarding. Thanks also to my fellow graduate students for inspiring me, offering support in solidarity, and for the many lasting friendships built over the course of my time in the Earth and Environment Department. I would like to specifically thank my cohort who have been with me since the beginning: Kira Sullivan-Wiley, Chris Holden, Ha Nguyen, Dan Gianotti, Jared Woollacott, and Zhan Li. I'd also

like to thank all my graduate friends across the Geography, Earth Science, and Biogeoscience programs: Rebecca Sanders-DeMott, Val Pasquarella, Conor Gately, Marta Ribera, Eli Melaas, Britt Briber, Xiaojing Tang, Bahare Sanaie-Movahed, Ann Dunlea, Kasey Aderhold, Rohan Kundargi, Ken Takagi, and Alistair Hayden. Thanks also to Joel Sparks for keeping our lab running smoothly and safely. I'd like to thank my undergraduate mentees, Emily Korman and Annie Lissandrello – it was wonderful to work with you during such an important time in your careers and I wish you all the best. Thanks also to Tony Janetos, Cynthia Barakatt, and Theresa White at the Frederick S. Pardee Center for the Study of the Longer-Range future, where I spent a wonderful and productive summer as a graduate summer fellow.

I have been extremely fortunate to have had the opportunity to work with and learn from all of the Gas Allies at Clean Water Action (Joel Wool and Becky Smith), Conservation Law Foundation (David Ismay and Veronica Eady), the Sierra Club (David Zeek and Ed Woll), HEET (Audrey Schulman), Boston Climate Action Network (Mike Prokosch, Dick Clapp, and Paula Georges), and Mother's Out Front (Ania Camargo and Debbie New). You have shown me what climate change policy in action looks like and I am grateful to have been able to contribute my expertise in a small way to affect larger action in Massachusetts. Many thanks to Austin Blackmon and Carl Spector at the City of Boston for inviting Boston University researchers to contribute to climate preparedness measures in the City of Boston. And finally, thank you to State Representative Ehrlich, State Senators Eldridge and Creem, and Boston City Councilor Matt O'Malley for their

interest in my research and their tireless work towards a sustainable and just future for all Massachusetts residents.

Thanks to my parents and family for their interest, support, and encouragement along my long and winding academic journey. And finally, my sincerest thanks go to my partner, Ash, who has read countless drafts, listened to most every talk that I've delivered, and shown me limitless support and tolerance throughout this journey. This degree would not be possible without her, and I am forever grateful for her belief in me. I love you.

# **THE ENVIRONMENTAL AND POLITICAL ECOLOGY OF NATURAL GAS**

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Boston University Graduate School of Arts and Sciences, 2016

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## **ABSTRACT**

Methane (CH<sub>4</sub>) is the primary constituent of natural gas and a significant contributor to global climate change, accounting for 11% of all U.S. greenhouse gas emissions. With the advent of hydraulic fracturing technology, production of natural gas from shale gas reserves has increased by 35% from 2005 to 2013. Fugitive CH<sub>4</sub> emissions attributed to venting or leakage across the life cycle of natural gas systems have also increased, making the climate benefits ascribed to natural gas questionable when compared to oil and coal. This dissertation reports the results of three studies that improve our knowledge of the environmental and political ramifications of continued investment in and consumption of natural gas fuels. Using bottom-up flux chamber techniques we made direct measurements of CH<sub>4</sub> emissions from 100 natural gas leaks in cast iron distribution mains within Metro Boston, MA in order to assess the nature of the distribution of gas leak size and constrain estimates of fugitive CH<sub>4</sub> emissions across

leak-prone urban distribution infrastructure. We find that the distribution of leak size is skewed, a small fraction of ‘superemitter’ leaks contribute disproportionate CH<sub>4</sub> emissions, and CH<sub>4</sub> flux at leak sites is not an indicator of safety. Next, we use the lens of urban natural gas infrastructure systems and apply an ecological analytical framework to identify dysfunctions in and opportunities for coordinated urban infrastructure management in Boston, MA. We find that there are real physical and fiscal constraints to retrofitting and expanding aging, urban infrastructure in U.S. cities. Achieving sustainable, resilient urban infrastructure requires active participation by all stakeholders as well as coordination within and between stakeholder groups. Finally, we introduce the term ‘unleakable carbon’ to refer to the uncombusted carbon-based gases associated with fossil fuel systems and demonstrate that in particular the unleakable carbon associated with natural gas constitutes a potentially large and heretofore unrecognized factor in estimating usable portions of Earth’s fossil fuel reserves. We demonstrate that unless unleakable carbon is curtailed, roughly 80 – 100% of our global natural gas reserves must remain underground if we hope to limit warming to 2 °C from 2010 to 2050.

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## CHAPTER 1 – INTRODUCTION

Atmospheric methane (CH<sub>4</sub>) concentrations have more than doubled in the past 150 years in conjunction with global industrialization and urbanization (NOAA, 2015). Methane, the primary constituent of natural gas, accounts for 11% of all U.S. greenhouse gas (GHG) emissions, approximately 33% of which are attributable to natural gas and petroleum systems (U.S. Environmental Protection Agency, 2015). Methane is a potent GHG whose global warming potential is 34 and 86 times greater than carbon dioxide (CO<sub>2</sub>) over 100 and 20-year time horizons, respectively (IPCC, 2013). In terms of anthropogenic CH<sub>4</sub> emissions by source, emissions from natural gas systems are the highest (U.S. Environmental Protection Agency, 2015). As the U.S. shifts away from oil and coal, production of natural gas from shale gas reserves has increased by 35% from 2005 to 2013 (U.S. Energy Information Administration, 2015). Elucidating CH<sub>4</sub> emissions from natural gas systems will facilitate responsible management in keeping with national GHG mitigation goals (U.S. Global Change Research Program, 2014). A majority of research to date has sought to constrain estimates of upstream and midstream fugitive CH<sub>4</sub> emissions (Allen et al., 2013, 2015; Brantley et al., 2014; Mitchell et al., 2015; Subramanian et al., 2015). However, downstream emissions associated with the processing and distribution of natural gas remain poorly characterized.

Aged natural gas distribution infrastructure is prone to leakage, and urban mapping studies now reveal that densely populated Eastern U.S. cities contend with thousands of natural gas leaks stemming from outdated mains (Phillips et al., 2013;

Jackson et al., 2014; Environmental Defense Fund and Google Earth Outreach, 2015; Gallagher et al., 2015). Leak-prone pipelines also present an explosive risk. In 2014 alone, there were 113 gas distribution pipeline incidents reported across the U.S., with 18 fatalities, 94 injuries, and almost \$75 M in property damage (PHMSA, 2016), exceeding the national 5-year average (2010-2014) reported for all categories. Urban infrastructure is often taken for granted by city dwellers as much of it travels through cables strung high above roadways or is distributed through pipes buried deep below impervious surface, as is the case with natural gas. It is only when infrastructure fails that we acknowledge the inherent vulnerability of these systems and the depth of our dependence on the services they provide. The greatest challenge, however, lies in the capacity of networked private and public stakeholders to develop a coordinated model for transforming crumbling infrastructure. The state of aging U.S. natural gas distribution infrastructure typifies this conundrum.

At a global scale, the release of CH<sub>4</sub> across the natural gas process chain is now cited as the largest contributor to fossil fuel-related fugitive emissions (IPCC, 2013).

Advances in extraction technology have encouraged a shift to natural gas, but the advantage of fuel switching depends strongly on mitigating current levels of uncombusted carbon-based gases associated with fossil fuel systems, otherwise referred to as ‘fugitive,’ ‘leaked,’ ‘vented,’ ‘flared,’ or ‘unintended’ emissions. Here, we introduce the new concept of, ‘unleakable carbon,’ to refer to these emissions and draw attention to the fact that they play a potentially large and heretofore unrecognized factor in determining use of Earth’s remaining fossil fuel reserves. At present, global levels of

unleakable carbon can be substantial enough to offset any climate benefit relative to oil or coal. It is imperative that companies, investors, and world leaders considering capital expenditures and policies towards continued investment in natural gas fuels do so with a complete understanding of how dependent the ultimate climate benefits are upon increased regulation of unleakable carbon. Continued focus on combustion emissions alone undermines the importance of assessing the full climate impacts of fossil fuels, leading many stakeholders to support near-term mitigation strategies that rely on fuel switching from coal and oil to cleaner burning natural gas. The current lack of transparent accounting of unleakable carbon represents a significant gap in the understanding of what portions of the Earth's remaining global fossil fuel reserves can be utilized while still limiting global warming to 2 °C.

Successful climate change mitigation requires that stakeholders understand the entire carbon footprint of natural gas systems as well as the policies governing management of these systems at municipal to global scales. This dissertation reports the results of three core research articles that improve our understanding of the environmental and political impacts of fugitive CH<sub>4</sub> emissions in urban environments, the state of networked stakeholder decision-making towards management of aged natural gas distribution infrastructure in American cities, and the carbon accounting that determines utilizable portions of the Earth's remaining global fossil fuel reserves. The first research chapter, Chapter 2, reports on a bottom-up survey of fugitive CH<sub>4</sub> emissions across leak-prone distribution infrastructure in Metro Boston, MA. Direct measures of CH<sub>4</sub> flux from 100 individual leaks revealed that the distribution of leak size is skewed, a small fraction

of ‘superemitter’ leaks contribute disproportionate CH<sub>4</sub> emissions, and CH<sub>4</sub> flux at leak sites is not an indicator of safety. The second research chapter, Chapter 3, presents an analysis of the natural gas infrastructure stakeholder ecosystem in Boston, MA. The application of a novel ecological analytical framework reveals that funding infrastructure revitalization, increasing stakeholder participation, and enhancing communication and coordination within and between stakeholder groups are important steps to take towards sustainable management of aging U.S. natural gas distribution infrastructure. The final research chapter, Chapter 4, introduces the term ‘unleakable carbon’ to refer to the uncombusted carbon-based gases associated with fossil fuel systems, and demonstrates that in particular the unleakable carbon associated with natural gas constitutes a potentially large and heretofore unrecognized factor in estimating usable portions of Earth’s fossil fuel reserves.

The body of research reported in this dissertation presents novel results that improve our understanding of the global warming contribution of fugitive CH<sub>4</sub> emissions across natural gas systems, with special attention paid to distribution systems in urban environments. It also elucidates best practices for managing aging natural gas infrastructure systems as well as informs policies that govern continued investment in and consumption of natural gas fuels. As the energy supply sector is the largest contributor to global GHG emissions, it is imperative that policy makers, stakeholders, and investors understand the full warming consequences of near-term strategies that rely on fuel switching from coal and oil to natural gas as we work towards a long-term shift to scalable renewable energy.

**CHAPTER 2 – FUGITIVE METHANE EMISSIONS FROM LEAK-PRONE  
NATURAL GAS DISTRIBUTION INFRASTRUCTURE IN URBAN  
ENVIRONMENTS**

Fugitive emissions from natural gas systems are the largest anthropogenic source of the greenhouse gas methane (CH<sub>4</sub>) in the U.S. and contribute to the risk of explosions in urban environments. Here, we report on a survey of CH<sub>4</sub> emissions from 100 natural gas leaks in cast iron distribution mains in Metro Boston, MA. Direct measures of CH<sub>4</sub> flux from individual leaks ranged from 4.0 – 2.3 x 10<sup>4</sup> g CH<sub>4</sub> • day<sup>-1</sup>. The distribution of leak size is positively skewed, with 7% of leaks contributing 50% of total CH<sub>4</sub> emissions measured. We identify parallels in the skewed distribution of leak size found in downstream systems with midstream and upstream stages of the gas process chain. Fixing ‘superemitter’ leaks will disproportionately stem greenhouse gas emissions. Fifteen percent of leaks surveyed qualified as potentially explosive (Grade 1), and we found no difference in CH<sub>4</sub> flux between Grade 1 leaks and all remaining leaks surveyed ( $p = 0.24$ ). All leaks must be addressed, as even small leaks cannot be disregarded as ‘safely leaking.’ Key methodological impediments to quantifying and addressing the impacts of leaking natural gas distribution infrastructure involve inconsistencies in the manner in which gas leaks are defined, detected, and classified. To address this need, we propose a two-part leak classification system that reflects both the safety and climatic impacts of natural gas leaks.

## 2.1 Introduction

Atmospheric methane CH<sub>4</sub> concentrations have more than doubled in the past 150 years in conjunction with global industrialization and urbanization (NOAA, 2015).

Methane, the primary constituent of natural gas, accounts for 11% of all U.S. greenhouse gas (GHG) emissions, approximately 33% of which are attributable to natural gas and petroleum systems (U.S. Environmental Protection Agency, 2015). Methane is a potent GHG whose global warming potential is 34 and 86 times greater than carbon dioxide (CO<sub>2</sub>) over 100 and 20-year time horizons, respectively (IPCC, 2013). In terms of anthropogenic CH<sub>4</sub> emissions by source, emissions from natural gas systems are the highest (U.S. Environmental Protection Agency, 2015). As the U.S. shifts away from oil and coal, production of natural gas from shale gas reserves has increased by 35% from 2005 to 2013 (U.S. Energy Information Administration, 2015). Elucidating CH<sub>4</sub> emissions from natural gas systems will facilitate responsible management in keeping with national GHG mitigation goals (U.S. Global Change Research Program, 2014).

With the recent increase in hydraulic fracturing and horizontal drilling, carbon emissions associated with the upstream, midstream, and downstream sectors of the natural gas industry have become the subject of growing research interest (Alvarez et al., 2012; Miller et al., 2013; Brandt et al., 2014). Fugitive CH<sub>4</sub> emissions, attributed to venting or leakage across the life cycle of natural gas, make the climate benefits ascribed to natural gas questionable when compared to oil and coal. A majority of research to date has sought to constrain estimates of upstream and midstream fugitive CH<sub>4</sub> emissions (Allen et al., 2013, 2015; Brantley et al., 2014; Mitchell et al., 2015; Subramanian et al.,

2015). However, downstream emissions associated with the processing and distribution of natural gas remain poorly characterized. Given the strain that increased production and consumption of natural gas places on aged U.S. distribution infrastructure (American Society of Civil Engineers, 2013; U.S. Department of Energy, 2015), this study assesses the impact of fugitive CH<sub>4</sub> emissions associated with leak-prone distribution infrastructure in urban environments.

Leak-prone distribution infrastructure is composed of outdated pipe material such as cast iron, wrought iron, and unprotected steel, often dating back to the mid 1800s and early 1900s (U.S. Environmental Protection Agency and Gas Research Institute, 1996). Iron mains make up 2.4% of the natural gas distribution system in the U.S. (PHMSA, 2015) yet contribute a majority of total pipeline emissions (U.S. Environmental Protection Agency and Gas Research Institute, 1996; Lamb et al., 2015). Leak-prone mains constitute up to 34% of natural gas distribution infrastructure in Eastern U.S. states (PHMSA, 2015). Urban mapping studies reveal that densely populated Eastern U.S. cities have thousands of natural gas leaks (Phillips et al., 2013; Jackson et al., 2014; Environmental Defense Fund and Google Earth Outreach, 2015; Gallagher et al., 2015). Despite progress made towards leak identification and mapping, quantification of fugitive CH<sub>4</sub> emissions from leak-prone distribution infrastructure remains poorly characterized. Bottom-up approaches are limited by small sample sizes (U.S. Environmental Protection Agency and Gas Research Institute, 1996; Lamb et al., 2015), while top-down approaches (Townsend- Small et al., 2012; McKain et al., 2015) are not designed to resolve point source attribution.

Further, very little is known about the nature of the statistical distribution of sizes of gas leaks in distribution pipeline systems in terms of CH<sub>4</sub> flux. Current industry practice is to use emissions factors that carry an implicit assumption of an average leak size based on a normal distribution (U.S. Environmental Protection Agency and Gas Research Institute, 1996). However, results from midstream and upstream studies increasingly show evidence for a skewed distribution of leak size (Brandt et al., 2014; Brantley et al., 2014; Allen et al., 2015; Mitchell et al., 2015; Subramanian et al., 2015). There also remains a lack of consensus regarding the volume of fugitive CH<sub>4</sub> emissions lost from leak-prone distribution infrastructure, the frequency of leaks per road mile, and the severity of the safety hazard posed by potentially explosive (Grade 1) natural gas leaks in urban environments.

In this study we made direct measurements of CH<sub>4</sub> emissions from 100 natural gas leaks in cast iron distribution mains within Metro Boston, MA in order to assess the nature of the distribution of gas leak sizes, in particular whether they are characterized by a normal or skewed distribution. We took flux chamber measurements at individual leak sites to constrain estimates of fugitive CH<sub>4</sub> emissions from leak-prone distribution infrastructure. We resampled a subset of these leaks in summer and winter to evaluate seasonal variation in CH<sub>4</sub> flux. We assessed the hazard potential of each leak surveyed, reporting those that qualified as Grade 1 to local utility companies. These results can be used to prioritize pipeline repair and replacement, stem GHG emissions, safeguard against pipeline explosions, and efficiently distribute and consume natural gas.

## 2.2 Materials and Methods

To estimate CH<sub>4</sub> emissions from leak-prone natural gas distribution infrastructure we made direct measures of 100 natural gas leaks in cast iron distribution mains within Metro Boston, MA [Table A1; see Field Sampling section of Appendix A for details]. We selected sampling sites based on three criteria: 1) cast iron pipe material, 2) a proportion of pipeline operating pressures representative of the total distribution network, and 3) detection of elevated atmospheric [CH<sub>4</sub>] (Figure A1). We obtained the location, age, operating pressure, and diameter of buried cast iron mains from natural gas distribution infrastructure maps provided by National Grid (2013). We identified 45 natural gas leaks using the results of our 2011 on-road atmospheric CH<sub>4</sub> survey (Phillips et al., 2013) and an additional 55 leaks in Boston, Brookline, and Newton through real-time on-road atmospheric CH<sub>4</sub> surveys following the same methodology. We checked the calibration on the mobile Picarro G2301 Cavity Ring-Down Spectrometer (Picarro, Inc., Santa Clara, CA) with 0 and 5 ppm CH<sub>4</sub> test gas (Balance: air; Spec Air Specialty Gases, Auburn, ME; reported precision  $\pm 10\%$ ) periodically throughout our sampling campaign. We sampled leaks over cast iron distribution mains operating at 0.5 (n = 93), 2 (n = 3), 22 (n = 3), and 60 (n = 1) pounds per square inch gage (PSIG; see Pipeline Operating Pressure section of Appendix A for details).

We defined a leak as any detected atmospheric [CH<sub>4</sub>] above a threshold of 2.5 ppm, consistent with Phillips et al. (2013), Jackson et al. (2014), and Gallagher et al. (2015). We further defined a leak as 1) at least 3.7 m (12 ft) in distance from adjacent leaks emanating from the same distribution main; 2) spatially distinct from leaks in

parallel distribution mains; 3) spatially distinct from leaks in associated service lines; and 4) attributable to natural gas due to a recognizable odor of mercaptan. Distribution main segments are 3.7 m in length, attached by joints at either end (U.S. Environmental Protection Agency and Gas Research Institute, 1996). Applying a horizontal 3.7 m buffer reduces the risk of double counting leaks on the same distribution main. We avoided double counting leaks from parallel distribution mains running under the same street by excluding leaks that we could not confidently assign to one main or the other. Natural gas leaks also arise from service lines, which attach directly to the distribution main. We similarly excluded leaks that we could not confidently assign to either the distribution main or the service line.

We surveyed leaks in June and December of 2012, September and November of 2013, January of 2014, and June – September of 2014. We used a flame ionization unit (FIU; Dafarol A500 Flame Ionization Unit, Dafarol Inc., Hopedale, MA) to determine the spatial extent of each leak and the location of individual gas escape points within a sampling site (e.g., manhole, utility access point, road or sidewalk crack, curb, tree well, urban lawn, roadway drill hole). We checked the calibration on the FIU daily using 50 ppm CH<sub>4</sub> test gas (Balance: air; Spec Air Specialty Gases, Auburn, ME; reported precision ±5%). After taking flux chamber measurements at all gas escape points we used a combustible gas indicator (CGI; Gas Sentry®, model CGI-201, Bascom-Turner Instruments, Inc., Norwood, MA) to measure [CH<sub>4</sub>] in soil gas and in the headspace of voids under manholes, gas and water valve boxes, electrical access points, and storm water drains. The CGI was calibrated every 30 days with 2.5% CH<sub>4</sub> test gas (MC-105

Methane & CO Calibration Gas; Bascom-Turner Instruments, Inc., Norwood, MA; reported precision  $\pm 2\%$ ). We reported all leaks that qualified as potentially explosive (Grade 1) to local utility providers.

The Pipeline and Hazardous Materials Safety Administration (PHMSA, 2015), a U.S. Department of Transportation agency, classifies natural gas leaks into three grades, Grade 1 through 3 with Grade 1 being the most dangerous, based on their proximity to persons and property and the concentration of CH<sub>4</sub> gas detected in nearby air samples (Table A4; see Leak Grading section of Appendix A for details). The lower explosive limit (LEL) and upper explosive limit (UEL) for natural gas in air are five and 15%, respectively. Natural gas is flammable at 5 – 15% in open air and explosive at 5 – 15% when found in a confined space. If a natural gas leak is proximate to people or property, where gas may accumulate to explosive levels (80% LEL) in confined spaces or migrate inside or around buildings, it is considered unsafe. Alternatively, a natural gas leak that occurs in a well-ventilated area removed from people and high-value property is considered relatively low risk. Here, we follow the leak classification standards published by PHMSA and classify leaks as Grade 1 if we detected  $\geq 4\%$  natural gas in the air sampled from confined, person-sized spaces (e.g. manholes), or 80% LEL (Table 2.1; Table A4; PHMSA, 2002). We also classify leaks as Grade 1 if we detected any gas within 1.5 m (5 ft) or less of a building (Table 2.1; Table A4; PHMSA, 2002).

**Table 2.1** We report the conditions found at fifteen sites that qualify for Grade 1 leak classification that were identified during leak surveys of cast iron distribution mains in Boston, Brookline, and Newton, MA in column one (Table A4; PHMSA, 2002). The Environmental Defense Fund (EDF) and Google Earth Outreach also identified fourteen of the same leaks during street mapping in March and June of 2013, but deemed all of them nonhazardous (Roston, 2014; Wong, 2014). The Environmental Defense Fund and Google Earth Outreach assessed leaks according to low (700-9,000 L CH<sub>4</sub> • day<sup>-1</sup>), medium (9,000-60,000 L CH<sub>4</sub> • day<sup>-1</sup>), or high (>60,000 L CH<sub>4</sub> • day<sup>-1</sup>) column two (Environmental Defense Fund and Google Earth Outreach, 2015).

| Leak Assessment                                  |                               | Leak Location                                 |                             |
|--|-------------------------------|---|-----------------------------|
| Boston University                                | EDF and Google Earth Outreach | Block Address                                 | Lat Long                    |
| 9% CH <sub>4</sub> in manhole                    | Low                           | 400 block Dudley St., Boston, MA 02119        | 42°19'30.94"N 71°04'30.09"W |
| >30% CH <sub>4</sub> in three manholes           | Medium                        | 800 block Centre St., Boston, MA 02130        | 42°18'33.24"N 71°07'13.78"W |
| 13% CH <sub>4</sub> in manhole                   | Low                           | 4100 block Washington St., Boston, MA 02131   | 42°17'19.01"N 71°07'32.93"W |
| 6% CH <sub>4</sub> in manhole                    | Low                           | 1900 block Columbus Ave., Boston, MA 02119    | 42°18'54.76"N 71°06'00.47"W |
| 7% CH <sub>4</sub> in manhole                    | Low                           | 4300 block Washington St., Boston, MA 02131   | 42°17'04.73"N 71°07'50.28"W |
| 8% CH <sub>4</sub> in manhole                    | Medium                        | 400 block Hyde Park Ave., Boston, MA 02131    | 42°17'12.70"N 71°07'07.29"W |
| 5% CH <sub>4</sub> in manhole                    | Not detected                  | 100 block Mt. Pleasant Ave., Boston, MA 02119 | 42°19'36.37"N 71°04'46.92"W |
| 42% CH <sub>4</sub> in soil ≤ 1.5m from building | Low                           | 600 block Centre St., Boston, MA 02130        | 42°19'15.37"N 71°07'21.04"W |
| 6% CH <sub>4</sub> in manhole                    | Low                           | 1900 block Dorchester Ave., Boston, MA 02124  | 42°16'58.95"N 71°03'54.21"W |
| 25% CH <sub>4</sub> in soil ≤ 1.5m from building | Low                           | 1900 block Dorchester Ave., Boston, MA 02124  | 42°16'59.52"N 71°03'53.54"W |
| 25% CH <sub>4</sub> in soil ≤ 1.5m from building | Low                           | 0 block Lanark Rd., Boston, MA 02135          | 42°20'23.64"N 71°08'45.28"W |
| 6% CH <sub>4</sub> in manhole                    | Low                           | 100 block Lochstead Ave., Boston, MA 02130    | 42°19'04.39"N 71°06'54.26"W |
| 17% CH <sub>4</sub> in manhole                   | Low                           | 100 block Tappan St., Brookline, MA 02445     | 42°20'00.50"N 71°08'03.17"W |
| 66% CH <sub>4</sub> in manhole                   | Low                           | 100 block Claflin Rd., Brookline, MA 02445    | 42°20'14.35"N 71°08'10.43"W |
| 5% CH <sub>4</sub> in manhole                    | Medium                        | 200 block Hammond St., Newton, MA 02467       | 42°19'51.61"N 71°10'12.15"W |

We made direct measures of CH<sub>4</sub> efflux from gas leaks using a chamber-based method (see Chamber Measurements section of Appendix A for details). Natural gas is lighter than air and migrates up and away from the leak origin (Okamoto and Gomi, 2011). As distribution pipes are buried under impervious surface (i.e., roads and sidewalks), leaked natural gas migrates underground along paths of least resistance for escape. We designed four chambers (55.6, 17.2, 16.1, and 14.0 L) to quantify CH<sub>4</sub> emissions escaping from manholes, utility access structures, curbs, soil, and cracks in asphalt and cement (Figure A2; Table A2; Table A3). Two Swagelok-fitted vent holes located at the top of each chamber facilitated gas sampling from the chamber headspace via 1/4 in plastic tubing. We fit a third vent hole with a ‘pigtail’ extension to reduce pressure anomalies resulting from wind turbulence (Bain et al., 2005). We equipped the chambers with plastic skirts, which were weighted down with gravel- filled burlap tubes to create a seal with the sampling surface. To ensure that the sample air was well mixed, we placed battery- operated fans inside each chamber. We fit a simple linear regression to plotted chamber data and used the slope of this line ( $[\text{CH}_4] \cdot \text{sec}^{-1}$ ) to approximate CH<sub>4</sub> flux at gas escape points.

We utilized a closed dynamic chamber method (Bain et al., 2005) for quantifying CH<sub>4</sub> emissions from relatively low flux gas escape points (where flux was  $\leq 96 \text{ g CH}_4 \cdot \text{day}^{-1}$ ). Of 535 individual chamber measurements made over the course of this study, 26% employed this chamber methodology (capturing 11% of all CH<sub>4</sub> emissions sampled). For these measurements, we used a Picarro G2301 Cavity Ring-Down Spectrometer to collect CH<sub>4</sub> flux data. As this analyzer resolves [CH<sub>4</sub>] the nearest parts per billion and has an

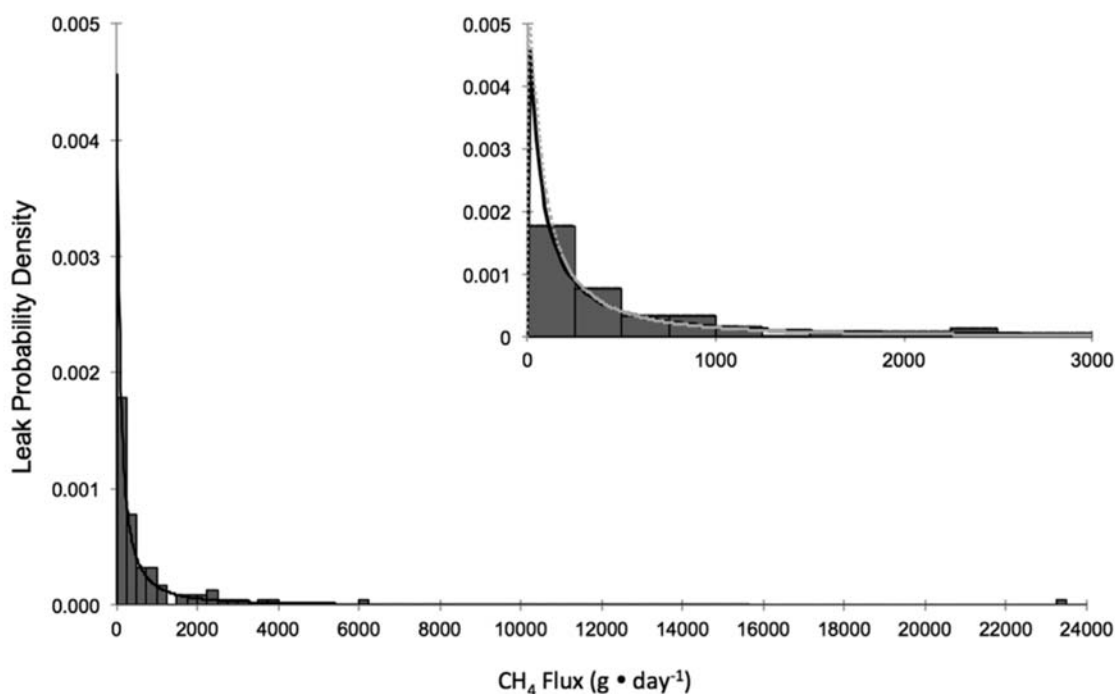
upper [CH<sub>4</sub>] limit of ~40 ppm, it is particularly well suited for quantifying CH<sub>4</sub> emissions from relatively low flux gas escape points.

We utilized a modified closed dynamic chamber method (Bain et al., 2005) for quantifying CH<sub>4</sub> emissions from relatively high flux gas escape points (where flux was  $\leq 1.6 \times 10^4$  g CH<sub>4</sub> • day<sup>-1</sup>). A majority (74%) of the chamber measurements made during this study employed this technique (capturing 89% of all CH<sub>4</sub> emissions sampled). For these measurements, we used a CGI to collect CH<sub>4</sub> flux data. This analyzer is less precise than the Picarro G2301 Cavity Ring-Down Spectrometer, but it is capable of measuring up to 100% CH<sub>4</sub> gas. The CGI collects [CH<sub>4</sub>] data at 0.01% gas intervals (100 ppm), making it particularly well suited for quantifying CH<sub>4</sub> emissions from relatively high flux gas escape points.

## **2.3 Results and Discussion**

### ***2.3.1 Leak size is skewed***

Direct measures of CH<sub>4</sub> flux from 100 natural gas leaks originating from cast iron distribution infrastructure in Metro Boston, MA ranged from 4.0 – 2.3 x 10<sup>4</sup> g CH<sub>4</sub> • day<sup>-1</sup> (Table A1). The distribution of leak size is positively skewed, with a long right-hand tail anchored by a few superemitter leaks that contribute a large proportion of fugitive CH<sub>4</sub> emissions (Figure 2.1). The left-hand mass of the distribution is composed of many small flux leaks. The log-normal mean leak rate is 1.2 x 10<sup>3</sup> g CH<sub>4</sub> • day<sup>-1</sup> for all leaks surveyed. We found no significant difference in CH<sub>4</sub> flux between leaks sampled in the winter versus summer seasons (n = 13, p = 0.56).



**Figure 2.1.** The distribution of leak size is skewed ( $n = 99$ ; Pearson's coefficient of skewness for flux data = 7.5). The black line represents a fitted, log-normal distribution (main and inset plot;  $\mu = 5.4$ ,  $\sigma = 1.8$ , log-normal mean =  $1.2 \times 10^3$  g  $\text{CH}_4 \cdot \text{day}^{-1}$ ). The distribution of leak size is skewed even when superemitter leaks are excluded (grey dotted line in inset plot represents all leaks excluding the top 7% that contribute 50% of total  $\text{CH}_4$  emissions;  $\mu = 5.2$ ,  $\sigma = 1.7$ , log-normal mean =  $7.4 \times 10^2$  g  $\text{CH}_4 \cdot \text{day}^{-1}$ ,  $n = 92$ , Pearson's coefficient of skewness for flux data = 1.8). See Leak Size Distribution section of Appendix A for details.

A positively skewed distribution of leak size across leak-prone distribution infrastructure in Metro Boston, MA is inconsistent with earlier work that implicitly assumes a normal distribution of leak size (U.S. Environmental Protection Agency and Gas Research Institute, 1996), but consistent with the distribution of direct measures of natural gas leaks made by Lamb et al. (2015) within local distribution systems in the U.S. The emission factor reported for cast iron mains by Lamb et al. (2015;  $1.3 \times 10^3$  g  $\text{CH}_4 \cdot$

day<sup>-1</sup>) is also consistent with the log-normal mean leak rate that we report for our survey. A positive skew in fugitive CH<sub>4</sub> emissions across leak-prone distribution infrastructure, with many small leaks and few superemitter leaks, is also analogous to findings on CH<sub>4</sub> leakage from natural gas equipment in the upstream and midstream sectors of the natural gas industry (Brandt et al., 2014; Brantley et al., 2014; Allen et al., 2015; Mitchell et al., 2015; Subramanian et al., 2015).

Our survey makes progress on improving our understanding of the distribution of leak size across leak-prone natural gas distribution infrastructure by virtue of its enhanced sample size of 100. Previous research by the U.S. Environmental Protection Agency and Gas Research Institute (1996) and Lamb et al. (2015) reported on 21 and 14 leaks, respectively, across cast iron distribution mains. A larger sample size increases the likelihood of capturing the furthest extent of a positively skewed leak distribution with bottom-up sampling approaches. Lamb et al. (2015) report a 95% upper confidence limit of  $4.8 \times 10^3 \text{ g} \cdot \text{CH}_4 \text{ day}^{-1}$  for an emission factor for cast iron distribution mains, while the largest leak surveyed in Metro Boston, MA was  $2.3 \times 10^4 \text{ g} \cdot \text{CH}_4 \text{ day}^{-1}$ . Notably, our reported natural gas leakage rates are likely an underestimate of actual leakage rates across natural gas distribution pipelines as subsurface leaks from distribution mains in urban environments are highly complex. The heterogeneous patchwork of pervious and impervious surfaces and the abundance of buried, collocated non- gas utility structures make it unlikely that we have captured all natural gas emissions during our sampling events.

### ***2.3.2 Top 7% of leaks contribute 50% of total CH<sub>4</sub> emissions***

We found that seven superemitter leaks contributed 50% of all fugitive CH<sub>4</sub> emissions captured in this survey. Of these superemitter leaks, five were sampled over mains operating at 0.5 PSIG, including the largest leak surveyed. The two remaining superemitter leaks were sampled over mains operating at 22 and 60 PSIG, respectively. Mean CH<sub>4</sub> flux appeared to correlate positively with pipeline operating pressure ( $R^2 = 0.85$ ,  $p = 0.03$ ,  $n = 5$ ). Nevertheless, leak size data remain skewed even when leaks sampled over mains operating at pressures greater than 0.5 PSIG are excluded ( $\mu = 5.4$ ,  $\sigma = 1.8$ , log-normal mean =  $1.0 \times 10^3 \text{ g} \cdot \text{CH}_4 \text{ day}^{-1}$ ,  $n = 92$ , Pearson's coefficient of skewness for flux data = 8.0). Further, the distribution of leak size remains skewed even when all superemitter leaks are excluded (Figure 2.1). Resolving the relationship between leak size and pipeline operating pressure remains an open area of research for future studies of natural gas distribution systems.

The positively skewed distribution of leak size across aged distribution infrastructure has important policy implications. Fixing superemitter leaks will stem a large fraction of fugitive CH<sub>4</sub> emissions from natural gas infrastructure that are known to contribute to the GHG profile of urban centers (Brandt et al., 2014; McKain et al., 2015). Many cities, including Boston, MA, do not currently factor in CH<sub>4</sub> emissions from natural gas systems when accounting for citywide GHG emissions, or when setting specific GHG reduction goals (City of Boston, 2014). However, awareness of the issue is growing, in part due to research published on the topic. Understanding how leak size is distributed allows urban stakeholders to prioritize leak repair towards meeting climate

change goals, improving efficiency in urban energy systems, and reducing utility rate inflation associated with lost and unaccounted for (LAUF) gas.

Top-down measurements of fugitive CH<sub>4</sub> emissions in the Boston urban region estimate that the average annual loss rate from all downstream components of the natural gas system is 2.7%, or roughly \$90 million worth of natural gas fuel (McKain et al., 2015). Addressing superemitter leaks is an effective way to revitalize aged infrastructure while still meeting energy needs and adhering to GHG reduction targets. To the extent that the cost of both LAUF gas and pipeline repair are folded into natural gas utility rates, as they currently are in MA, fixing superemitter leaks will benefit consumers by reducing LAUF gas through relatively high benefit-to- cost pipeline repair projects.

### ***2.3.3 Flux is not an indicator of safety***

Of the 100 natural gas leaks surveyed, 15% qualified as potentially explosive (Grade 1; Table 2.1). Notably, we found no significant difference in CH<sub>4</sub> flux between Grade 1 leaks and all remaining leaks surveyed based on the result of a two-tailed, heteroscedastic t-test. Here, we compare CH<sub>4</sub> flux from fifteen Grade 1 leaks to all remaining leaks surveyed (n = 85) and find that CH<sub>4</sub> flux is not significantly different between the two sample populations (p = 0.24).

Further, we found 10 cases of small leaks ( $<1.2 \times 10^3 \text{ g} \cdot \text{CH}_4 \text{ day}^{-1}$ ) that qualified as potentially explosive (Grade 1). As small leaks have the potential to be hazardous, CH<sub>4</sub> flux is not an indicator of safety. Addressing superemitter leaks will stem GHG emissions, but all leaks must be assessed as small leaks cannot be disregarded as ‘safely

leaking.’ This result has important implications for human health and safety, as well as for the future of leak detection and classification.

While good progress has been made towards revitalizing aged infrastructure, with 15% of remaining leak-prone distribution mains replaced in the U.S. since 2010, local utilities still rely on 29,359 miles of cast and wrought iron mains to distribute natural gas to consumers (PHMSA, 2015). As these pipes continue to age, the U.S. sees an average of 110 gas distribution pipeline incidents per year (2010 – 2014; PHMSA, 2015). Significant distribution pipeline incidents are characterized by a fatality or injury requiring in-patient hospitalization, or causing \$50,000 or more in total costs (PHMSA, 2015). In 2014 alone, there were 113 gas distribution pipeline incidents reported across the U.S., with 18 fatalities, 94 injuries, and almost \$75 M in property damage (PHMSA, 2015), exceeding the national 5-year average (2010 – 2014) reported for all categories. Since 2010, there have been 23 gas distribution pipeline incidents reported across Massachusetts, with one fatality, 18 injuries, and almost \$6 M in property damage (PHMSA, 2015). Most recently, a house explosion caused by a natural gas leak in Dorchester, MA on April 16, 2014 injured 12 people and destroyed a two-and-a-half story residence in an ensuing three-alarm fire. Although costly, our results indicate that reducing pipeline incidents requires fully revitalizing leak-prone distribution infrastructure and improving leak detection and monitoring.

Utility companies currently detect natural gas leaks following similar on-road driving surveys of elevated atmospheric [CH<sub>4</sub>] as those employed by Phillips et al. (2013), Jackson et al. (2014), and Gallagher et al. (2015), yet do not employ additional

equipment to measure meteorological conditions (e.g. wind speed and direction, boundary layer stability, mixing layer height, atmospheric pressure). Utilities also perform walking surveys of mains and service lines, although at less frequent intervals relative to driving surveys, and rely on the public to directly report suspected natural gas leaks in their vicinity in real-time. Grade 1 leaks detected by or reported to natural gas utility companies are currently prioritized for expedited repair (Table A4; PHMSA, 2002). As utility companies can only repair a finite number of leaks per year, a surplus of Grade 2 and predominantly Grade 3 leaks are monitored less frequently. Grade 2 and Grade 3 leaks are classified as non-hazardous at the time of detection and do not require reevaluation for another six and 15 months following the time of detection, respectively (Table A4; PHMSA, 2002). This leak management model is worrisome because there is no evidence to support a correlation between on-road atmospheric [CH<sub>4</sub>] readings and CH<sub>4</sub> flux at leak sites (Table 2.1, Figure A3), CH<sub>4</sub> flux is not an indicator of leak safety, and lesser leaks can quickly transform into Grade 1 leaks via mechanical disruption or as the result of frost heaves associated with prevalent winter freeze-thaw cycles in Northeastern states. A lesser gas leak may also be upgraded to a Grade 1 leak if 1) existing corrosion intensifies, leading to an increase in CH<sub>4</sub> flux; 2) operating pressure is increased, leading to an increase in CH<sub>4</sub> flux; 3) natural gas begins, or continues, to accumulate in a closed space to 80% LEL; and 4) natural gas begins, or continues, to spread into or around buildings.

#### ***2.3.4 Universal leak detection and classification methodology is required***

There is currently no universal definition of what constitutes a natural gas leak, no universal leak detection methodology, and no universal standard for how leaks are classified according to severity. This lack of agreement amongst stakeholders poses a problem as urban environments are heterogeneous and natural gas leaks can be complex. For example, what is the relationship between individual gas escape points at the road's surface and the number of fissure points in the underlying pipeline? Leaks are now detected using on-road driving or walking surveys of atmospheric [CH<sub>4</sub>], but academic (Phillips et al., 2013; Jackson et al., 2014; Gallagher et al., 2015), utility (PHMSA, 2002), and environmental advocacy groups (Environmental Defense Fund and Google Earth Outreach, 2015) utilize different leak detection instruments and employ different leak detection methods. Leaks are also classified in a variety of ways, including via direct measurements of CH<sub>4</sub> flux (Lamb et al., 2015), estimated CH<sub>4</sub> flux based on 'controlled releases' (Environmental Defense Fund and Google Earth Outreach, 2015), and a combination of FIU and CGI readings (PHMSA, 2002).

The lack of universal leak detection and classification methodology amongst natural gas stakeholders limits our understanding of the magnitude of safety and climate concerns associated with aged natural gas distribution infrastructure. Current estimates of the total number of leaks within a particular region, or the frequency of leaks per road mile or pipe mile within that region, are ambiguous without universal leak detection and reporting criteria (Table 2.2). Further, the results of this study indicate that on-road driving surveys are not sufficient to classify leak severity. There is no reliable evidence to

indicate that atmospheric [CH<sub>4</sub>] correlate to CH<sub>4</sub> flux at a leak site (Figure A3; see On-Road Driving Surveys vs. Flux Measurements section of Appendix A for details) and CH<sub>4</sub> flux itself is not a reliable indicator of leak safety (Table 2.1). While mobile CH<sub>4</sub> surveys provide excellent information towards leak detection and location, small leaks may still go undetected during mobile surveys and all leaks require additional FIU and CGI readings to determine safety classifications (Table 2.1).

**Table 2.2** Street leak frequency reported for Boston, MA since 2005.

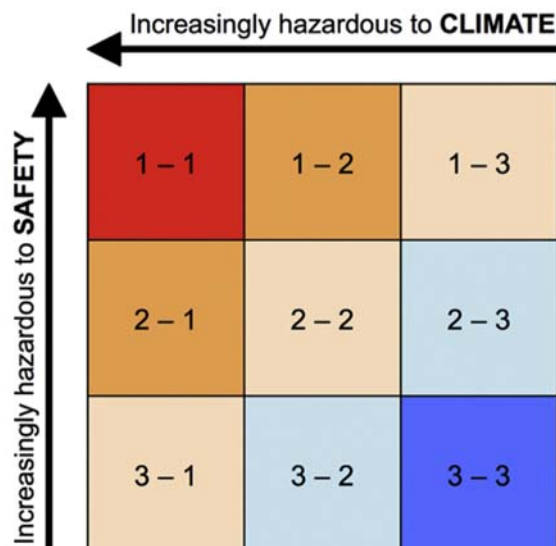
| <b>Leaks/<br/>Road Mile</b> | <b>Pipe Material</b> | <b>Survey<br/>Year(s)</b> | <b>Data Source</b>                                   |
|-----------------------------|----------------------|---------------------------|--|
| 2.7                         | All Materials        | 2005                      | Keyspan Corporation (now National Grid), 2005        |
| 4.3                         | All Materials        | 2011                      | Phillips et al., 2013                                |
| 1.0                         | All Materials        | 2013                      | Environmental Defense Fund and Google Earth Outreach |
| 2.2                         | All Materials        | 2014                      | National Grid, 2015                                  |

This issue is as relevant for aged natural gas distribution infrastructure as it is for relatively ‘young’ natural gas systems. Currently 38% of U.S. natural gas distribution mains are composed of protected steel and 55% are composed of plastic (PHMSA, 2015). Even though protected steel and plastic pipes are not considered leak-prone, proposed increases in operating pressure associated with increased supply and demand for natural gas fuels does place strain on even the most robust distribution systems. We report that mean CH<sub>4</sub> flux appears to correlate positively with pipeline operating pressure, suggesting that resolving the relationship between leak size and pipeline operating pressure is a vital next step for future studies of natural gas distribution systems.

Improving distribution pipeline safety and mitigating associated greenhouse gas emissions, regardless of the age of the distribution network, requires that U.S. regulators mandate that all public utilities companies adopt 1) a universal definition of what constitutes a natural gas leak; 2) universal leak detection methodology that employs both driving and walking surveys in order to detect and assess leaks of all sizes; 3) universal standards for how leaks are classified; and 4) universal action criteria for how leaks are addressed within appropriate timelines.

## **2.4 Conclusions**

We report on a survey of CH<sub>4</sub> emissions from 100 natural gas leaks in cast iron distribution mains in Metro Boston, MA. This study has three results: 1) the distribution of leak size is skewed, 2) a small fraction of leaks contribute disproportionate CH<sub>4</sub> emissions, and 3) CH<sub>4</sub> flux at leak sites is not an indicator of safety. Key methodological impediments to quantifying and addressing this problem involve inconsistencies in the manner in which gas leaks are defined, detected, and classified. While leak definition and detection are beyond the scope of this research, here we propose one key advance in leak classification.



**Figure 2.2** A two-part leak classification system accounts for both the safety and climatic impacts of natural gas leaks (safety-climate). Warm colors indicate hazardous leaks with increasing explosive potential and large volumes of LAUF gas lost. Cool colors indicate non-hazardous leaks with a reduced safety risk and limited LAUF gas lost.

Natural gas leaks are now classified according to a three-tiered system that reflects explosive potential, with Grade 1 leaks posing the most serious threat to life and property and Grade 3 leaks posing no threat at the time of detection. Missing from this classification system is an assessment of the climatic and monetary consequences of LAUF gas. To address this need, we propose a two-part leak classification system that better reflects the full impacts of natural gas leaks (Figure 2.2). This classification system accounts for both the explosive potential (1 to 3, most to least dangerous) and climatic consequence (1 to 3, most to least LAUF gas lost) of natural gas leaks. For example, a Grade ‘3-1’ leak is non-hazardous to life and property but emits large quantities of LAUF gas, while a Grade ‘3-3’ leak is non-hazardous to life and property and emits little LAUF

gas. With regard to a Grade ‘3-1’ leak, the current leak classification system misses what may be called the ‘Climatic Grade 1’ designation of an otherwise non-hazardous Grade 3 leak. We propose improvements to leak classification in part to also encourage similar progress towards development of a universal leak definition and universal leak detection methodology.

**Acknowledgements:** The Barr Foundation and Conservation Law Foundation supported this research. This publication was developed under STAR Fellowship Assistance Agreement no. F13F31263 awarded by the U.S. Environmental Protection Agency (EPA). It has not been formally reviewed by the EPA. Additional support was provided by the U.S. National Science Foundation ULTRA-ex program (DEB 0948857). Shanna Cleveland, Lucy Hutyra, Anne Short Gianotti, and Sucharita Gopal provided helpful comments on the manuscript. Annie Lissandrello provided support in the field.

**Appendix A** contains detailed methodology, additional figures, and additional tables.

## **CHAPTER 3 – AGING NATURAL GAS INFRASTRUCTURE IN THE UNITED STATES: DEVELOPING A COORDINATED AND SUSTAINABLE URBAN INFRASTRUCTURE ECOSYSTEM**

### **3.1 Introduction**

Critical urban infrastructure plays an integral role in sustaining life in metropolitan areas yet age and years of deferred maintenance now render these infrastructure systems vulnerable in many U.S. cities. The American Society of Civil Engineers awarded U.S. infrastructure a grade of D+ in 2013, estimating that an investment of \$3.6 trillion is required to adequately revitalize critical infrastructure systems by 2020 (ASCE, 2013). While decrepit roads, bridges, and waterways have garnered modest attention over the course of the 2016 U.S. election cycle (Soergel, 2016), lesser known infrastructure systems, like natural gas distribution networks, remain out of the spotlight. Mains dating back to the mid 1800s and early 1900s (U.S. Environmental Protection Agency and Gas Research Institute, 1996) constitute up to 34% of natural gas distribution infrastructure in Eastern U.S. states (PHMSA, 2016). These mains run underneath roads in densely populated cities making maintenance, let alone improvement and expansion, tactically demanding and enormously expensive. The greatest challenge, however, lies in the capacity of networked private and public stakeholders to develop a coordinated model for transforming crumbling infrastructure.

Aged natural gas distribution infrastructure is prone to leakage, and urban mapping studies now reveal that densely populated Eastern U.S. cities contend with

thousands of natural gas leaks stemming from outdated mains (Phillips et al., 2013; Jackson et al., 2014; Environmental Defense Fund and Google Earth Outreach, 2015; Gallagher et al., 2015). Gas leaks emit methane (CH<sub>4</sub>), the main constituent of natural gas, whose global warming potential is 34 and 86 times greater than carbon dioxide (CO<sub>2</sub>) over 100 and 20-year time horizons, respectively (IPCC, 2013). Leak-prone pipelines also present an explosive risk. In 2014 alone, there were 113 gas distribution pipeline incidents reported across the U.S., with 18 fatalities, 94 injuries, and almost \$75 M in property damage (PHMSA, 2016), exceeding the national 5-year average (2010-2014) reported for all categories. Urban infrastructure is often taken for granted by city dwellers as much of it travels through cables strung high above roadways or is distributed through pipes buried deep below impervious surface, as is the case with natural gas. It is only when infrastructure fails that we acknowledge the inherent vulnerability of these systems and the depth of our dependence on the services they provide. The state of aging U.S. natural gas distribution infrastructure typifies this conundrum.

As the U.S. shifts away from oil and coal, production of natural gas from shale gas reserves has increased by 35% from 2005 to 2013 (U.S. Energy Information Administration, 2015), resulting in a preponderance of proposed natural gas expansion projects across the country (FERC, 2016). Utilities must now consider increasing the volume and pressure of natural gas distributed through pipeline networks within older urban centers that are struggling to maintain existing infrastructure already straining under current demands. Outdated mains make up 7% of the natural gas distribution system in the U.S. (PHMSA, 2016) yet contribute a majority of total pipeline emissions

(U.S. Environmental Protection Agency and Gas Research Institute, 1996; Lamb et al., 2015). Research on urban natural gas distribution systems suggests that increasing the volume and pressure of natural gas distributed across outdated mains will also increase in the volume of CH<sub>4</sub> emitted to the atmosphere from gas leaks (Hendrick et al., 2016). This scenario is in contravention of federal, state, and municipal greenhouse gas (GHG) mitigation policies (The President's Climate Action Plan, 2013; Compact of Mayors, 2016). Stakeholders must now devise a model for how to expedite the repair and revitalization of aged natural gas distribution infrastructure while also meeting our nation's energy demands.

In an age when urban infrastructure must be efficient, reliable, and cost-effective to meet the needs of residents and the environmental pressures of climate change, the U.S. currently lacks a strategy for revitalizing aged urban infrastructure. The importance of high-functioning urban infrastructure has never been greater as nearly 81% of Americans now reside in urban centers, a near doubling of the urban population since 1900 (USCB, 2010). In order to understand how to successfully adapt urban infrastructure for the future, a careful analysis of the current state of networked infrastructure management is required. In the U.S., this network is both complex and balkanized. Here, we employ leak-prone natural gas distribution networks as a lens to examine the challenges of managing and revitalizing aged U.S. infrastructure in order to 1) reveal the limitations of current stakeholder decision-making networks; 2) inform future management policies towards increasing resilience, reducing inefficiencies, and

enhancing coordination; and 3) inform urban expansion in both the U.S. and developing nations forecast to experience the brunt of rural-to-urban migration.

We begin this article by reviewing the stakeholders, infrastructure systems, and analytical frameworks inherent to urban environments and their corresponding fields of study. Next, using the lens of urban natural gas infrastructure systems we apply an ecological analytical framework to identify dysfunctions in and opportunities for coordinated urban infrastructure management in U.S. cities through a series of qualitative stakeholder interviews. We conclude by discussing opportunities for enhancing coordination and efficiency in the management and revitalization of aged natural gas distribution infrastructure in U.S. cities, and the corresponding implications for all critical infrastructure systems in the U.S.

### ***3.1.1 Critical infrastructure and the urban ecosystem***

The state of critical urban infrastructure in the U.S. has important ramifications for the economy, national security, disaster resilience, and global economic competitiveness (National Research Council, 2009; Lange, 2011). Subpar infrastructure engenders fiscal and environmental inefficiency, hampering economic growth and innovative development. In order to remain competitive, infrastructure stakeholders must pioneer new technologies and management practices that yield efficient and resilient infrastructure. Infrastructure stakeholders operate in complex, multi-scale networks consisting of dynamic social, political, and physical systems (Boyle et al., 2010). The infrastructure stakeholder community marks the unique intersection of cultural and

political human systems and built infrastructure systems. This intersection of social and physical networks is referred to as a ‘socio-technical system’ (Barrett et al., 2004). The processes of urbanization and globalization have rendered this intersection particularly complex due to the increasingly heterogeneous nature of U.S. urban populations (Boyle et al., 2010; Xu et al., 2012). The urgent need to revitalize degraded urban infrastructure systems adds yet another layer of complexity. This large and highly diverse network of infrastructure stakeholders is responsible for the design, management, economics, safety, and resilience of urban infrastructure.

The major players that compose urban infrastructure stakeholder communities include federal, state, and municipal government agencies, private- and municipally-owned utilities, infrastructure support services within the private, academic, and nonprofit sectors, and utility rate payers (Table 3.1). While urban residents sometimes perceive infrastructure systems as ‘public goods,’ ownership of physical infrastructure and regulation of associated activities is actually distributed amongst a mix of private and public sector entities depending on the infrastructure system of interest (National Research Council, 2009). In general, water and wastewater systems are owned and managed at the municipal level, and power and telecommunication systems are owned and managed by private companies. Publically- and privately-owned utilities are both regulated at the federal and state levels, but municipally-owned utilities are managed primarily at the municipal level. A mix of federal, state, and municipal government entities manage a majority of roads, highways, and bridges, while a mix of both public and private organizations manage subways, ports, and airports.

Structures of power and money strongly dictate the efficacy of decision-making and degree of connectivity amongst stakeholders within socio-technical systems (Pincetl, 2012). Power and money are not allocated equally amongst stakeholders. Federal and state agencies dictate safety and regulatory policy governing infrastructure condition, and by default, the entities that own the infrastructure systems in question. Municipal governments control access to distributed infrastructure systems within their jurisdiction through permitting systems that sanction all maintenance or construction work conducted by infrastructure stakeholders (Public Works Department, 2016). However, there are state-mandated regulations that allow privately-owned utility companies to access buried infrastructure without a city permit when that utility system poses a danger to persons or property (Cleveland, 2012). Utilities can often offset their maintenance budgets by passing the cost of maintaining and replacing infrastructure onto the consumer through rate adjustments, raising the specter of rate inflation in the face of widespread infrastructure decline (Cleveland, 2012; Analysis Group, Inc., 2013; Markey, 2013). The current model of infrastructure management is designed to support routine annual maintenance of physical systems, but not the degree of expansion and revitalization necessary to transform aged infrastructure systems. A collaborative approach to infrastructure management across siloed stakeholder entities is often stymied by disparate agendas and operating budgets.

**Table 3.1** Key stakeholders operating within the urban infrastructure ecosystem, their economic sectors, and the roles they perform.

| <b>Stakeholder</b>     | <b>Sector</b>                    | <b>Role</b>  |
|------------------------|----------------------------------|--|
| Federal Government     | Public                           | <ul style="list-style-type: none"> <li>• Set guidelines for infrastructure quality</li> <li>• Create policy affecting extraction/production of energy/water, price of utility</li> <li>• Set environmental/climate change standards</li> </ul>   |
| State Government       | Public                           | <ul style="list-style-type: none"> <li>• Maintain just and reasonable utility rates, protect utility rate payers from rate inflation</li> <li>• Set standards for public safety, infrastructure quality</li> <li>• Set funding allocated for infrastructure maintenance, improvement</li> <li>• Create policy regulating utility companies towards provision of safe/just distributed utility services</li> <li>• Set environmental/climate change standards</li> </ul>                                    |
| Municipal Government   | Public                           | <ul style="list-style-type: none"> <li>• Manage municipally-owned utility infrastructure systems</li> <li>• Manage road resurfacing and reconstruction</li> <li>• Control permitting for utility maintenance within municipal boundaries</li> <li>• Set standards for public safety, infrastructure quality</li> <li>• Coordinate road and utility maintenance projects</li> <li>• Provide police detail for utility maintenance projects</li> <li>• Set environmental/climate change standards</li> </ul> |
| Utility Companies      | Private                          | <ul style="list-style-type: none"> <li>• Manage privately-owned utility infrastructure systems</li> <li>• Provide distributed utility service to ratepayers</li> <li>• Satisfy shareholders</li> </ul>   |
| Infrastructure Support | Private<br>Academic<br>Nonprofit | <ul style="list-style-type: none"> <li>• Contractors for road construction, pipeline repair/replacement</li> <li>• Environmental/energy monitoring, infrastructure assessment</li> <li>• Academia in studies of urban ecology, urban planning</li> </ul>   |
| Utility Rate Payer     | Public                           | <ul style="list-style-type: none"> <li>• Pay rates for utility product consumed</li> <li>• Pay utility rates and taxes to support infrastructure maintenance and improvement</li> <li>• Grass roots advocacy</li> </ul>  |

### ***3.1.2 Urban infrastructure: Collocated and interdependent***

Critical urban infrastructure is spatially collocated and highly interdependent (Slaughter, 2007; Barrett et al., 2004; Xu et al., 2012). Water, sewer, natural gas, electric, and telecommunications distribution infrastructure systems are all located under streets, in close proximity to one other. Similarly, overhead cable strung along telephone poles or between buildings carries both phone and electric service. Interdependencies amongst infrastructure systems arise as a result of this collocation. For example, the quality and longevity of roads is dependent on how underground infrastructure is maintained. Utility companies must ‘open’ the road, or excavate, in order to access buried pipes and cables. This process requires acquisition of permits, use of heavy equipment, and obstruction of the right of way. Roads are then patched with asphalt, which leaves transportation infrastructure vulnerable to frost heaves, potholes, and accelerated degradation. As disparate governmental and private entities own and manage utility infrastructure, repeated road excavation is a common contributing factor in the decline of roads and the delay of maintenance and revitalization of underlying utility infrastructure systems (ASCE, 2013).

Interdependencies amongst infrastructure systems are also a result of the networked nature of urban infrastructure. For example, the functionality of many infrastructure systems depends on the status of the electric grid. The Northeast blackout of 2003, which affected an estimated 55 million Americans and Canadians living in Ontario and the northeastern U.S. (Barron, 2003), was a stark reminder of this fact. The blackout, which was ultimately caused by a software bug and poor cable maintenance,

had downstream effects on water, sewer, transportation, and communication infrastructure. Without electricity, water and sewer pumps stopped working, leaving sewage spilling into waterways and residents without fresh water. Transportation infrastructure was severely impacted when trains and airports lost power. Gas station pumps and traffic lights also went down, triggering gas shortages and gridlocked road congestion. Unfortunately, the networked interdependency between critical infrastructure systems and the electric grid remains a serious source of vulnerability in the U.S. today due to years of deferred maintenance and a lack of investment by stakeholders in revitalizing aged infrastructure (ASCE, 2013).

### ***3.1.3 What is sustainable urban infrastructure?***

Existing urban infrastructure in the U.S. is falling into disrepair before completing its design life (Sohail et al., 2005). As such, deteriorating infrastructure has become a significant contributing factor in establishing cities as a primary source of GHG emissions and the site of massive landscape restructuring (Pickett et al., 2011). According to the National Resource Council (2009), sustainable and efficient urban infrastructure can only be achieved through a paradigm shift in how the nation thinks about, builds, operates, and invests in critical infrastructure systems. Before adopting new models of management, however, it is important to first define what is meant by *sustainable urban infrastructure*. Simply put, sustainability is the capacity to endure. Sustainable urban infrastructure, therefore, is broadly defined as a system that is able to meet the needs of current and future generations by being physically resilient, cost-effective,

environmentally viable, and socially equitable (Sahely et al., 2005; National Research Council, 2009; Baird, 2010).

Achieving sustainable urban infrastructure requires weighing the cost of action against inaction. Do we invest in innovative solutions now to adapt to the social, environmental, and political challenges of the future, or do we forego investment and risk paying for the failures of an unsustainable and vulnerable system further down the line? Most urban planners argue that the status quo of replacing broken parts is no longer sufficient; we must revitalize our infrastructure system as a whole, and in doing so, invest in the future (Slaughter, 2007). Rendering aging infrastructure sustainable for future generations is admittedly a difficult task. Experts agree that progress towards this goal requires research and development in three categories; global warming, engineering, and management (Boyle et al., 2010). Sustainable infrastructure must mitigate global warming and reduce vulnerability in the face of associated environmental pressures. These systems must incorporate sustainable materials, techniques, and technologies to enhance resiliency. Finally, management of infrastructure must transition to an integrated and coordinated model to meet the needs of large, high-density populations.

#### ***3.1.4 The ecosystem approach to network analysis***

In order to parse the current state of urban infrastructure management, it is essential to understand how social and physical systems interact (Boyle et al., 2010). Researchers have proposed frameworks to facilitate such an analysis, many involving analogies of cities with ‘living systems’ or ‘organisms’ and notions of urban ‘ecosystems’

and ‘metabolism’ (Bettencourt et al., 2007). These biologically influenced frameworks are powerful analytical tools because they capture the flow of energy, resources, and materials in and out of a system, while also parsing the role of organisms, or groups of organisms, in affecting these flows (Pickett et al., 2001). When characterizing complex urban systems, such as infrastructure stakeholder decision-making networks, an ecological analytical framework best captures their inherent interdependencies, feedback mechanisms, and emergent properties (Pickett et al., 2011; Boyle et al., 2010; Pincetl, 2012; Xu et al., 2012).

The term ‘ecosystem’ describes a community of organisms and their abiotic environment, interacting as a system (Tansley, 1935). For the purpose of the current analysis, an ecosystem approach dictates that infrastructure stakeholders are the ‘organisms’ and the urban landscape, their ‘abiotic environment.’ An urbanized area is defined as a region containing at least 2,500 inhabitants residing at a minimum density of 1,000 persons per square mile (USCB, 1995). Urban environments are not only densely populated, they are also highly built, with much of the land covered by impervious surface, structures, and infrastructure (Pickett et al., 2011). Urbanites, therefore, are inextricably linked to their built environment. Here, the scale of analysis is restricted to established metropolitan boundaries, while the scale of participating infrastructure stakeholders ranges from the individual household to the entire federal government. The urban abiotic environment is not only characterized by built structures, impervious surface, and infrastructure, but also by the environmental pressures it experiences: weather, natural disasters, sea-level rise, and the urban heat island effect. Energy,

resources, and materials flowing through this system include money, power, distributed utilities, and physical infrastructure materials.

Evolutionary theory dictates that organisms are motivated to compete for resources in a drive towards reproduction (Conner and Hartl, 2004). Human behavioral patterns are far more complex. Humans operate within highly complex communities governed by layers of social structures and differentiated by spatial, social, and temporal factors (Pickett et al., 2001). Human ecological systems are characterized by five types of sociocultural hierarchies; wealth, power, status, knowledge, and territory (Burch and DeLuca, 1984). The disconnections and inefficiencies inherent to the infrastructure stakeholder ecosystem arise by virtue of the complexity of these governing powers and the often-competing interests of individual stakeholders. An ecological analytical framework is a unique and especially powerful tool in its ability to integrate physical, biological, and social sciences (Pickett et al., 2001). An ecosystem analysis of infrastructure decision-making networks will afford valuable insight into the current climate of management and elucidate the roles, motives, and incentives of participating stakeholders. These results will reveal shortcomings in the current infrastructure management model and identify new avenues towards greater fiscal and environmental sustainability.

### **3.2 A case study of the natural gas infrastructure stakeholder ecosystem in Boston, Massachusetts**

Boston is a quintessential American city, making it an ideal subject for our case study of a representative U.S. urban natural gas infrastructure stakeholder ecosystem. Boston is both an old city, with aged natural gas distribution infrastructure straining under a growing population, and a global city, with significant technological, social, and political parallels to other large, international cities. Founded in 1630 by Puritan colonists, Boston is one of the oldest cities in the U.S. and the largest city in New England. Boston is ranked 10<sup>th</sup> in the country for most populated urban areas, with 4.7 million residents (World Population Review, 2016). Boston grew dramatically in size between the early 1800s and the early 1900s, transitioning from the ‘Town of Boston’ to the ‘City of Boston’ in 1822. During this period, Boston annexed many adjacent towns, extending its gas, water, sewer, railway, electric, and phone infrastructure down established country roads (Warner, 1978). Massachusetts achieved an urban majority in 1850. In recent years, many political, academic, and environmental stakeholders have published reports that have begun to parse the ramifications of aged natural gas distribution infrastructure in the state (Cleveland, 2012; Markey, 2013; Phillips et al., 2013; Environmental Defense Fund and Google Earth Outreach, 2015; McKain et al. 2015; Hendrick et al., 2016), providing a rich comparative context for our investigation.

Like many cities in the U.S., a majority of Boston’s infrastructure is over half a century old. Leak-prone mains composed of outdated materials including cast iron, wrought iron, and unprotected steel, many of which were originally installed in the mid

1800s and early 1900s, still make up roughly one third of the natural gas distribution infrastructure system in Massachusetts (Cleveland, 2012). Lost and unaccounted for natural gas that has escaped from leaks in decrepit infrastructure across the state of Massachusetts over the past decade is now estimated to be worth up to \$1.5 billion (Markey, 2013), and roughly \$90 million per year in the Boston urban region, alone (McKain et al., 2015). Some experts estimate that fugitive CH<sub>4</sub> emissions associated with leak-prone natural gas infrastructure account for 10% of Massachusetts' entire GHG inventory (Phillips, 2015). Aging infrastructure jeopardizes Boston's economic competitiveness, contributes to global warming, and renders Boston vulnerable to changing climatic conditions and natural disasters. An analysis of the natural gas infrastructure stakeholder ecosystem of Boston will shed light on how infrastructure is managed in the U.S. today, and how we can develop policies to manage it sustainably for the long-term future.

### ***3.2.1 Methods***

We characterized the natural gas infrastructure stakeholder ecosystem of Boston via a series of qualitative stakeholder interviews with individuals working in the private, public, academic, and nonprofit sectors to parse the inherent interdependencies, feedback mechanisms, and emergent properties of stakeholder interactions. In the summer of 2013 and winter of 2014 we conducted 14 semi-structured interviews with employees of the State of Massachusetts (n = 4), City of Boston (n = 3), Town of Brookline (n = 1), local academic institutions (n = 3), and the nonprofit (n = 1) and private sectors (n = 2). In

2015, we conducted six informal interviews during policy meetings, academic conferences, and academic seminars with employees of the City of Boston (n = 3), local academic institutions (n = 1), and the public (n = 1) and private sectors (n = 1). All interviews were conducted in person, over the phone, or over Skype. As many of our sources requested to remain anonymous, we have grouped stakeholders by broad categories to avoid identifying specific departments, offices, and individuals (Table 3.1). Here, we look through the lens of urban natural gas infrastructure systems and apply an ecological analytical framework to identify dysfunctions in, and opportunities for, coordinated infrastructure management with the goal of enhancing urban sustainability.

### ***3.2.2 Results: The current ecosystem***

#### ***3.2.2.1 Federal Government: The United States***

The current Administration has been forthright in acknowledging that the security and resilience of American infrastructure are essential to a strong American economy, the safety of U.S. citizens, and our capacity to adapt to the environmental pressures of climate change. The President is keenly aware of the limitations of current infrastructure management practices in the U.S. and has worked to develop a number of infrastructure funding initiatives. In August of 2012 and again in March of 2016, the U.S. Department of Transportation (USDOT) released \$470 million and \$2 billion of ‘earmarked’ funds, respectively, to be used by states to improve transportation infrastructure across the country (Foxx et al., 2016). Similarly, the President took executive action to create the Built America Investment Initiative, described as a government-wide initiative to

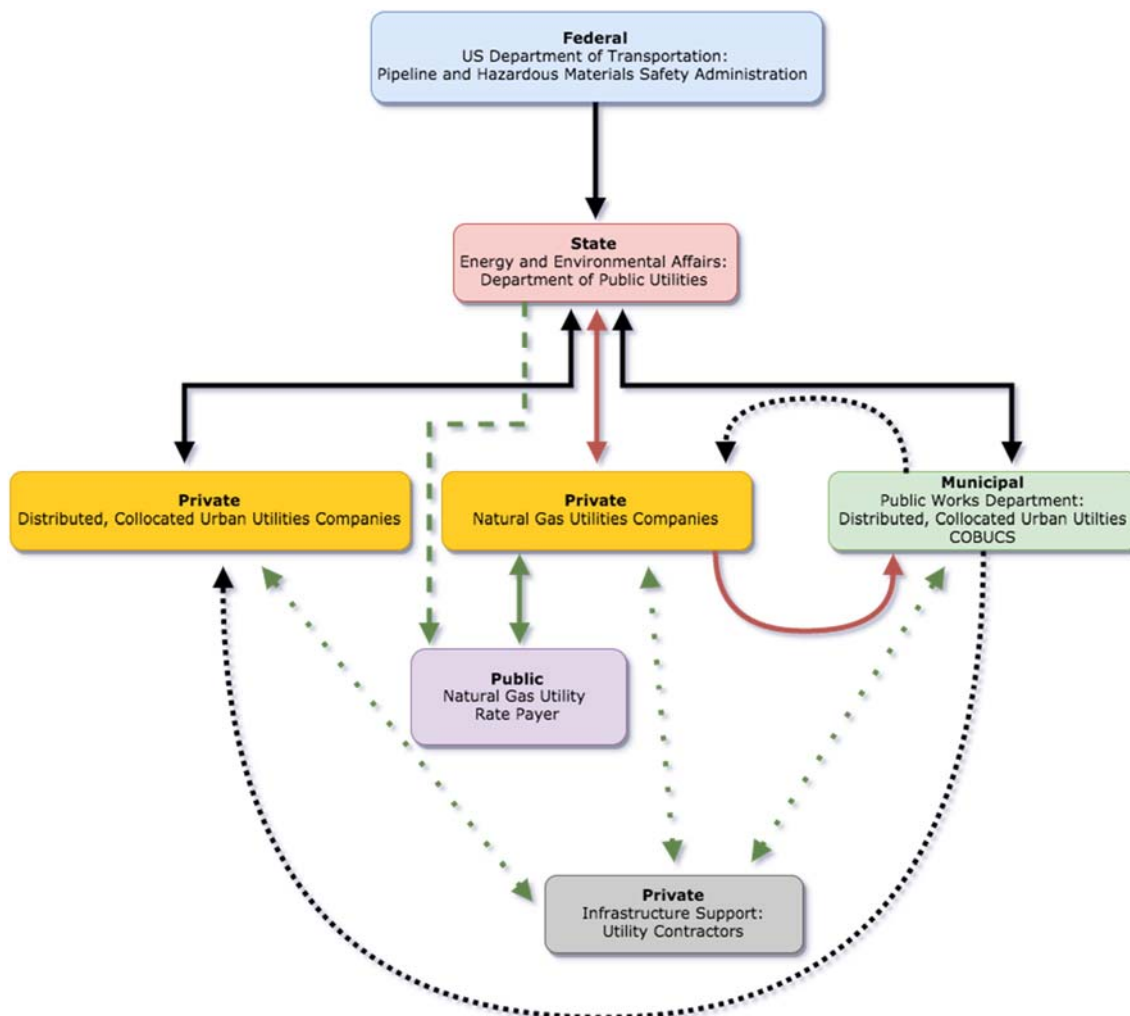
increase infrastructure investment, economic growth, and public-private partnerships (Office of the Press Secretary, 2014). Most recently the White House proposed the 21st Century Clean Transportation System, which will increase investment in transportation systems funded through a fee levied on oil companies (Office of the Press Secretary, 2016). However, approval of permits for federally funded projects can take up to a decade or more, leaving vast room for improvement (Common Good, 2015). Notably, federal infrastructure initiatives to date focus primarily on funding the revitalization of U.S. transportation systems and the electric grid, with no mention of aged U.S. natural gas infrastructure systems.

While the White House has been effective in raising public awareness of infrastructure vulnerability, allocation of federal funds towards natural gas infrastructure revitalization projects has not materialized. This is due in large part to the designation of natural gas as a hazardous material and to the fact natural gas infrastructure is privately owned and operated. The Natural Gas Pipeline Safety Act of 1968 gives the USDOT the authority to regulate pipeline transportation of natural gas, which is classified as a flammable, toxic, and corrosive material (Natural Gas Pipeline Act of 1968, 1968). The Pipeline and Hazardous Materials Safety Administration (PHMSA), housed within the USDOT, executes this regulatory authority (PHMSA, 2016; Figure 3.1). PHMSA is responsible for developing and enforcing federal regulations that aim to ensure the safe, reliable, and environmentally sound operation of the nation's 2.6 million mile pipeline transportation system (PHMSA, 2016). Local distribution companies operate and maintain urban natural gas distribution infrastructure including network piping,

regulators, and meters that service residential and commercial customers. While these companies must comply with federally mandated safety regulations, which are generally enforced at the state level, they are unlikely to receive federal funding for infrastructure revitalization projects as the cost of pipeline maintenance, pipeline replacement, and lost and unaccounted for gas are built into utility rates that are collected from urban rate payers (Cleveland, 2012; Figure 3.1).

An important feedback that is currently missing from the urban natural gas infrastructure ecosystem is an assessment of how the carbon footprint of aged U.S. natural gas infrastructure contributes to the nation's GHG profile. The mitigation of fugitive CH<sub>4</sub> emissions is a cornerstone of the President's Climate Action Plan (Executive Office of the President, 2013) as well as the U.S.' GHG reduction pledge towards the United Nation's Framework Convention on Climate Change in Paris (UNFCCC COP, 2015). While the U.S., Canada, and Mexico have just pledged to cut CH<sub>4</sub> emissions by 40 to 45 per cent by 2025 (U.S.-Canada Joint Statement on Climate, Energy, and Arctic Leadership, 2016), the EPA's newly updated inventory of GHG emissions does not fully account for all fugitive CH<sub>4</sub> emissions from natural gas systems, nor does it adequately evaluate the warming potential of these emissions (EPA, 2016). Natural gas leaks that contribute disproportionate CH<sub>4</sub> emissions, which are referred to as 'superemitters' in peer-reviewed scientific literature, are not currently accounted for in the 1990-2014 U.S. GHG inventory (Zimmerle et al. 2015; EPA, 2016). Great uncertainty still surrounds national estimates of all fugitive CH<sub>4</sub> emissions associated with extractive industry, which is exacerbated by the fact that an outdated uncertainty

analysis from 2009 is applied to estimate CH<sub>4</sub> emissions spanning through 2014 (EPA, 2016). Further, the EPA employs an outdated Global Warming Potential (GWP) value of 25 evaluated over a 100-year time horizon (EPA, 2016) to estimate the warming contribution from fugitive CH<sub>4</sub> emissions, despite recommendations by the Intergovernmental Panel on Climate Change that the most conservative GWP value to apply over this timeframe is 28 (IPCC, 2013). Federal climate change mitigation benchmarks influence state and municipal climate action plans yet inventories of GHGs at all levels of government fail to fully account for fugitive CH<sub>4</sub> emissions from aged natural gas infrastructure systems. Increased accuracy in carbon accounting and appropriate attribution of CH<sub>4</sub> emissions specifically to aged natural gas distribution infrastructure would provide federal and state regulators with a novel policy lever to facilitate accelerated pipeline replacement and GHG mitigation.



**Figure 3.1** The current natural gas infrastructure stakeholder ecosystem in Boston, MA. Black solid lines represent regulatory policy regarding distributed utilities; red solid lines represent regulatory policy regarding distributed utilities classified as hazardous materials; black dotted lines represent permits granted for utility maintenance projects; green dotted lines represent contracted construction work performed by private sector businesses; the green solid line represents utility services rendered and paid; and green dashed lines represent rate payer protection from rate inflation.

### ***3.2.2.2 State Government: The Commonwealth of Massachusetts***

According to the Massachusetts government officials working within the Departments of Public Utilities, Energy Resources, and Environmental Protection interviewed here, all of which are housed within the state's Energy and Environmental Affairs offices, the issue of aged urban natural gas infrastructure is concerning and one that many are interested in addressing. Reflecting the high stakes, bureaucratic nature of the political realm, however, all of the state officials interviewed for this piece declined to be identified. Here, we refer to our interviewees simply as 'Energy and Environmental Affairs officials' in order to respect their request for anonymity.

One Energy and Environmental Affairs official conceded that both electric and gas infrastructure systems are struggling in Massachusetts, further stating that officials are increasingly aware of natural gas pipeline leaks and failures, and the aged, subpar state of natural gas infrastructure materials. There is less consensus amongst officials within the Massachusetts state government, however, regarding the current state of coordination amongst infrastructure stakeholders within the stakeholder ecosystem. A second Energy and Environmental Affairs official described both long-lived and recently formed working relationships within and across the City of Boston, privately-owned utility companies, and environmental consulting agencies in the private sector, indicating a high degree of established coordination amongst stakeholder groups. A third Energy and Environmental Affairs official expressed a different outlook on the current state of the natural gas infrastructure stakeholder ecosystem, stating that the current system is not as coordinated as it should be and that there is a growing need to focus on strategic

coordination between stakeholders in the future. This official pointed out that interaction between the state and municipalities occurs on a ‘case by case basis.’ A fourth Energy and Environmental Affairs official described the interactive role of state government as limited to setting gas and electric infrastructure policy, and not micromanaging privately-owned utility companies. According to this official it is the role of municipalities to implement the state’s policy and coordinate with utilities.

The state’s role in the current urban natural gas infrastructure ecosystem resides predominantly with the Department of Public Utilities. Stakeholders at the Department of Public Utilities strive to meet two competing goals: improve infrastructure safety and functionality and assure just and fair rates for consumers. Department of Public Utilities officials interpret and enforce federally mandated safety regulations set by PHMSA in order to address this first goal (Figure 3.1). As for the second goal, the current funding paradigm for improvement of natural gas utility distribution infrastructure in Massachusetts includes a ‘cost of service’ rate regulation (Cleveland, 2012). This dictates that the cost of maintenance performed by privately-owned natural gas utility companies on the distribution infrastructure systems that they own is incorporated into the rate that the company then charges to the consumer (Figure 3.1). All Energy and Environmental Affairs officials interviewed agree that figuring out a way to solve the problem of aging infrastructure without inflating rates and bringing urban life to a halt is the greatest hurdle to increasing efficiency, accountability, and long-term viability of urban infrastructure. The logistics of avoiding rate shock, while also providing an incentive for utility companies to change maintenance and improvement procedures, present the state with a

significant challenge. These concerns are clearly acknowledged in the recently commissioned Electric Grid Modernization proposal, which represents the state's first push for electric infrastructure improvement (Raab Associates, Ltd. and Synapse Energy Economics, Inc., 2013). State agencies are still trying to discern what mix of tools to employ to incentivize infrastructure improvement in a timely manner, both in terms of rates and regulation. The modernization proposal recognizes that the state currently lacks a sufficient framework for regulatory review and cost recovery (Raab Associates, Ltd. and Synapse Energy Economics, Inc., 2013).

The state has made progress in implementing a regulatory framework to address some of these issues with natural gas utilities. Here, the 'cost of service' rate regulation also includes a 'cost-of-gas adjustment clause,' which allows privately-owned natural gas utility companies to pass along the cost of gas lost from leaking infrastructure to consumers (Cleveland, 2012). As environmental nonprofits and politicians have now shown, this cost amounts to as much as \$1.5 billion over the last decade in the state of Massachusetts (Cleveland, 2012; Markey, 2013). Utility companies buy gas from a supplier at the same rate that they charge the consumer. There is no markup on the price of natural gas, but the price of the product is locked in before the gas leaves the transmission hub and enters distribution pipes (Cleveland, 2012). Therefore, the cost of any gas that is lost between the transmission hub and the meter is paid by the consumer, leaving little monetary incentive for privately-owned natural gas utility companies to fix gas leaks or replace aging infrastructure (Markey, 2013). In order to incentivize faster action in infrastructure improvement by natural gas companies, above and beyond the

annual maintenance covered by the ‘cost of service’ rate regulation, the state has implemented Targeted Infrastructure Replacement Factors (TIRF; Cleveland, 2012; Analysis Group, Inc., 2013; Markey, 2013).

TIRF allows privately-owned natural gas utility companies to increase their rates to finance infrastructure upgrades that are proven to be used and useful (Analysis Group, Inc., 2013). Currently, utility companies track infrastructure upgrades performed during one year, and then apply for a TIRF to increase rates in the following year to earn back the previous year’s investment (Cleveland, 2012). In theory, these rate adjustments are allocated in order to decrease the financial risk assumed by the utility company, therefore incentivizing proactive renovation of infrastructure (Analysis Group, Inc., 2013). The Department of Public Utilities maintains the power to cap the level of TIRF compensation in order to avoid runaway rate hikes. In 2012 the state legislature raised the limit on how much money the Department of Public Utilities can fine utility companies for poor performance during storms in order to further incentive improved management of infrastructure and increased accountability. Citing ‘poor coordination’ with municipalities and other infrastructure stakeholders, the Department of Public Utilities fined National Grid, NSTAR, and Western Massachusetts Electric Company a combined \$24.8 million for their botched responses in 2011 to Tropical Storm Irene and Snowstorm Alfred (Moore, 2012).

Two Energy and Environmental Affairs officials pointed to the Electric Grid Modernization proposal, recently commissioned from Raab Associates, Ltd. and Synapse Energy Economics, Inc. (2013), as an example of collaboration between the state,

privately-owned electric utility companies, and private-sector energy consultants in improving urban infrastructure. The goals of the proposal are to enhance the reliability of electricity services, reduce electricity costs, empower customers to better manage their use of electricity, develop a more efficient electricity system, promote clean energy resources, and provide new customer service offerings (Raab Associates, Ltd. and Synapse Energy Economics, Inc., 2013). However, the same ‘cost of service’ rate regulation conundrum that affects natural gas utility rates also informs the degree to which stakeholders can simultaneously enhance grid reliability and reduce electricity costs. Another example of coordination between state government entities and the infrastructure stakeholder community is the execution of the Massachusetts’ Global Warming Solutions Act, which is overseen by the Executive Office of Energy and Environmental Affairs (Massachusetts Global Warming Solutions Act, 2008). The Global Warming Solutions Act implementation advisory committee includes representatives from the State of Massachusetts, the City of Boston, energy and environmental consultants in the private and nonprofit sectors, academia, urban and regional planners, and the privately-owned natural gas utility company, National Grid. As is the case with federally mandated GHG reduction strategies (Executive Office of the President, 2013; UNFCCC COP, 2015), there is currently a disconnect between the substantial carbon footprint of aged U.S. natural gas infrastructure and the GHG reduction goals outlined in Massachusetts’ Global Warming Solutions Act. It remains to be seen how well these stakeholders can coordinate and compromise to achieve a minimum 80% reduction in

GHG emissions from 1990 levels by 2050, and a 25% reduction from 1990 levels by 2020 (Massachusetts Global Warming Solutions Act, 2008).

### ***3.2.2.3 Municipal Government: The City of Boston***

All stakeholders interviewed within the City of Boston's government identified aging natural gas infrastructure as an issue of concern. Further, these stakeholders all indicated that it is in municipalities' best interests to begin to utilize resources more efficiently in order to decrease the stress placed on urban infrastructure systems. All stakeholders interviewed within the City of Boston's government also cited the discrepancy in regulatory power at the state versus city level as a hurdle to enacting a comprehensive, sustainable management plan. An official in the Environment and Energy Services Cabinet pointed out that when it comes to privately owned and operated natural gas utilities; the city doesn't have a lot of 'levers' to influence change, the Department of Public Utilities holds all of the regulatory power at the state level. The state regulates the privately utility companies that own and operate the infrastructure network, while the city manages zoning, development, and other municipal procedures. All stakeholders interviewed within the City of Boston's government indicated that there is a shared sentiment amongst municipal officials across all branches of city government that the current state of coordination amongst infrastructure stakeholders is less than optimal. Different branches of the Boston city government have different priorities, however, in seeking to increase connectivity in the stakeholder network.

All city and state government officials that were interviewed identified the ongoing ‘battle’ between road and utility maintenance projects as a major source of inefficiency in urban infrastructure management. The Public Works Department is responsible for managing Boston’s annual road reconstruction and resurfacing program (Figure 3.1). Every year, from April 1<sup>st</sup> to November 30<sup>th</sup>, the city selects roads to be resurfaced or reconstructed. The Public Works Department publishes a list of these roads at the beginning of the construction season, along with a service announcement urging affected residents to act quickly if they are planning to install a new utility service or upgrade an existing service (The City of Boston Public Works Department, 2016). This announcement reflects the city’s policy of applying a ‘guaranteed’ status to roads after they have been resurfaced or reconstructed. A guaranteed street cannot be opened to access underground utilities for five years following reconstruction - the city enforces this policy by refusing to issue permits for road construction until the guaranteed status has been lifted.

In order to coordinate between utility companies, private contractors, and other agencies that rely on road excavation, the Public Works Department developed the City of Boston Utility Coordination Software (COBUCS) as a centralized database coordination tool (Public Works Department, 2016). COBUCS is an online reservation database that seeks to limit roadwork conflicts while facilitating work by infrastructure stakeholders prior to applying guaranteed status to a street. The city will only issue permits for roadwork if the project is first registered on COBUCS. According to the Public Works Department, COBUCS has allowed the city to avoid 1,700 conflicting

utility projects that would have otherwise caused excavation on newly paved streets (Public Works Department, 2016). Despite its apparent success, all stakeholders interviewed at both the city and state levels of government outside of the Boston Public Works Department were unfamiliar with the COBUCS program.

COBUCS represents a major step forward in coordination between stakeholders to accomplish a higher degree of efficiency in urban infrastructure management, making the Public Works Department the most influential municipal stakeholder within the current natural gas infrastructure stakeholder ecosystem (Figure 3.1). The efficacy of COBUCS is compromised, however, by state-mandated regulations that allow privately-owned utility companies to access buried infrastructure without a city permit when that utility system poses a danger to persons or property (PHMSA, 2002). This policy allows excavation of a guaranteed street in the case of a utility emergency. Utility emergencies are defined as presenting a human health risk and include explosive Grade 1 natural gas leaks (PHMSA, 2002), phone failure, and water/sewer line rupture. According to a City of Boston Public Works Department official, the predominant utilities approved for excavation on guaranteed streets are also those with the most extensive infrastructure systems; water, sewer, and natural gas. The large proportion of leak-prone natural gas distribution pipes in Massachusetts (Cleveland, 2012) and high frequency of gas leaks stemming from these pipes (Phillips et al., 2013) coupled with state regulated safety policies aimed at deterring natural gas explosions (PHMSA, 2002) have made avoiding repeated excavation of municipal roads difficult despite the Public Works Department's best efforts. While officials within state and municipal governments cite road-utility

coordination as one of the greatest barriers to infrastructure efficiency, municipal Public Works Department stakeholders cannot solve this problem alone.

The City of Boston is now spearheading a number of infrastructure improvement initiatives in collaboration with private infrastructure support stakeholders. The Greenovate Boston initiative, launched by the Environment and Energy Services Cabinet in 2010, is a community-driven movement born from late Mayor Thomas M. Menino's plan to reduce Boston's GHG emissions 25% by 2020, and 80% by 2050 (City of Boston, 2014). The initiative focuses on generating public awareness and participation in increasing energy efficiency, using renewables, and adapting for climate change. While these initiatives strive to reduce demands currently placed on urban infrastructure, they do not yet include explicit acknowledgement of the GHG emissions associated with aging infrastructure. According to one city official, the status quo of infrastructure management is not a GHG issue, it's an issue of day-to-day management - as the city has no regulatory authority over privately owned utility companies, it is up to the Department of Public Utilities and privately owned utility companies to manage these emissions. However, up to 10% of Massachusetts' annual GHG emissions are attributable to methane lost from natural gas infrastructure, alone (Phillips, 2015). Aging natural gas distribution infrastructure is therefore very much entwined with both the city and state's GHG mitigation goals.

#### ***3.2.2.4 The Utilities***

Natural gas utility companies own and maintain natural gas infrastructure systems, are subject to government regulation at both the federal and state levels, and provide a service to rate payers (Figure 3.1). Privately-owned natural gas utility companies are also beholden to their shareholders' interests. The current paradigm for utility rate structuring reflects the notion that urban infrastructure is a 'public good,' and should therefore be financially supported at least in part by the public (National Research Council, 2009). As described above, the cost of routine infrastructure maintenance as well as the cost of lost and unaccounted for gas is incorporated into the natural gas utility rates charged to consumers through the state's 'cost of service' policy. Investments on large infrastructure upgrades are not included in this 'cost of service,' they must be factored into what is called a 'rate base.' The 'rate base' accounts for all of the expenses a utility company accumulates for infrastructure upgrades in a single year (Cleveland, 2012). This 'rate base' is established during a 'test year,' or a baseline year, in which a utility company documents how much they invest in infrastructure beyond 'cost of service' maintenance. According to one nonprofit sector infrastructure stakeholder, in order to lock in the most advantageous 'rate base' possible, a utility company will choose a 'test year' in which they have invested significantly in infrastructure upgrades. Natural gas utility rates are currently established in Massachusetts by the Department of Public Utilities based on this regulatory paradigm (Analysis Group, Inc., 2013).

This rate-structuring framework does not incentivize natural gas utility companies to invest in infrastructure upgrades beyond those covered by their 'rate base' (Cleveland,

2012). In order to address this issue, TIRF programs have been proposed and adopted in a number of states including Massachusetts, Rhode Island, and Ohio (Analysis Group, Inc., 2013). TIRF programs allow utilities to track all of the infrastructure upgrades they perform over the course of a single year beyond those established in their ‘rate base,’ and then apply for a TIRF to increase rates in the following year to earn back the previous year’s investment (Analysis Group, Inc., 2013). In theory these rate adjustments incentivize proactive renovation of infrastructure. In practice, however, one state government infrastructure stakeholder stated that natural gas utility companies do not find this rate structuring entirely satisfactory. Utility companies must wait for an entire year, sometimes longer, to increase rates to reflect the work performed in previous years. The time lag on recouping infrastructure investment requires the utility company to shoulder the financial burden until rates are increased, after which they must wait another year to fully earn back their investment. According to a second state government infrastructure stakeholder, utility companies are not inclined to take on financial risk because they are accountable to their shareholders for maintaining the ‘bottom line.’ As such, natural gas utility companies do not utilize TIRF towards investment in much needed innovative technological advances for infrastructure improvement.

The relationship between natural gas utility companies and municipal stakeholders is also complex. Utility companies must apply for work permits through the city’s Public Works Department in order to perform infrastructure maintenance or upgrades (Figure 3.1). Permitting is contingent on road resurfacing and reconstruction programs and the status of streets: guaranteed or not. Although permitting and

coordination through the COBUCS system restricts utilities from freely accessing their infrastructure systems, it does represent a successful framework for facilitating communication between the city and all critical utilities. This coordination breaks down when ‘utility emergencies,’ such as a potentially explosive Grade 1 natural gas leak, require utility companies to override city-level regulation to access buried natural gas distribution infrastructure. According to a Boston Public Works Department official, all of the road resurfacing and reconstruction projects that the city schedules for an upcoming year are communicated to the natural gas utility companies before work begins. This official claims that the city coordinates with the utilities to replace underlying leak-prone distribution pipes beneath scheduled road projects, but that this pipeline replacement coordination is often unsuccessful. This is due in part because the utilities cannot keep up with the city’s annual road project schedule given the work required to maintain and/or replace the preponderance of remaining leak-prone pipes across Boston’s distribution network. The Public Works Department official also points to a mismatch in timing for available funding for the Public Works Department and the utilities through their municipal budgets and capital plans, respectively.

### ***3.2.2.5 Infrastructure Support***

Infrastructure support stakeholders in the private, academic, and nonprofit sectors are instrumental in facilitating natural gas infrastructure maintenance and improvement, monitoring of infrastructure performance, and identification of and capitalization on new avenues for infrastructure innovation. Stakeholders specializing in infrastructure

performance include consulting firms that monitor environmental and energy impacts, as well as firms that generate vulnerability assessments. Stakeholders spearheading infrastructure innovation include urban ecologists, planners, and informaticians working within private, academic, and nonprofit sectors. All of the infrastructure stakeholders interviewed from the private, academic, and nonprofit sectors, here, identified aging natural gas infrastructure as a serious concern, and also shared the perspective that established state and municipal governmental entities are unlikely to change the current state of infrastructure management without outside pressure from non-governmental stakeholders. Similarly, these same stakeholders expressed a perceived lack of political will on the part of government officials in setting the tone for bold action towards addressing aging natural gas distribution infrastructure in urban environments.

The most prominent infrastructure support stakeholders in the current natural gas infrastructure stakeholder ecosystem are the private utility contractors that facilitate maintenance, repair, and replacement of natural gas infrastructure systems (Figure 3.1). Natural gas utilities companies hire private utility contractors to install natural gas transmission, distribution, and service pipelines, assist with pipeline repairs, and often provide 24-hour emergency repair services to fix gas leaks (Feeney Brothers Utility Services, 2016; New England Utility Constructors, Inc., 2016). The relationship between these two private stakeholder entities is based on an abundance of opportunities for repair and replacement of aged natural gas distribution infrastructure. One academic stakeholder specializing in public policy suggested that expedited pipeline replacement through enhanced stakeholder coordination may actually be perceived as destabilizing by one or

both stakeholder entities over concerns of job loss and wage reductions. This stakeholder cautioned that in order to incentive improved efficiency and coordination within the natural gas infrastructure stakeholder ecosystem, the current and future roles of all stakeholders must be considered. According to this stakeholder, this is especially true for unionized natural gas utility workers and private utility contractor employees, as these entities both play an important role in maintaining public safety (American Gas Association, 2016) and contribute to state and municipal economies (MA Executive Office of Labor and Workforce Development, 2016).

Academic researchers also play an important supporting role in the natural gas infrastructure stakeholder ecosystem. As evidenced by the ecosystem framework inherent to the current analysis, urban ecology integrates the social sciences and the urban landscape through the lens of ecological theory. While the field is fairly young, first emerging in the late 1970s, it has produced a community of highly motivated scientists interested in characterizing the biotic and abiotic processes inherent to the urban landscape. Urban ecologists have developed new protocols and equipment for monitoring GHG emissions, evaluating ecosystem services, and parsing urban inputs and outputs such as energy and waste, respectively (Pickett et al., 2011; Pincetl, 2012). These scientists are elucidating urban processes by generating long-term, robust datasets. In fact, the National Science Foundation now funds the Dynamics of Coupled Natural and Human Systems program, which supports coordinated research of coupled human-environment systems, social-ecological systems, ecological-economic systems, and population-environment systems (CHANS-Net, 2016). The Dynamics of Coupled Natural

and Human Systems program sponsors an international network of research that strives to identify sustainable solutions that benefit both the environment and its human inhabitants (CHANS-Net, 2016). The data, equipment, and monitoring protocols inherent to the field of urban ecology have great potential to inform innovation in urban infrastructure management.

Environmental and energy consulting organizations also help to inform companies, neighborhoods, universities, cities, and states in managing their day-to-day operations towards optimizing resource use efficiency and minimizing environmental impact. These organizations may be housed within academic institutions (e.g. The Center for Urban Science and Progress at New York University), managed privately (e.g. Linnean Solutions, LLC), or function as nonprofit entities (e.g. Conservation Law Foundation). They strive to reduce the demand placed on infrastructure through educating private and public consumers on resource use efficiency (Cleveland, 2012), and they propose infrastructure modernization solutions with both environmental and economic benefits at heart (Linnean Solutions, 2016). Collaboration between these organizations and public sector infrastructure stakeholders helps to establish a new framework for urban infrastructure utilization and promotes adoption of sustainable urban policy (Boston Green Ribbon Commission, 2016). It is important that the results of these collaborations be communicated to all stakeholders within the infrastructure stakeholder ecosystem, however. For example, according to the non-state governmental stakeholders interviewed, here, the results of a report on lost and unaccounted for gas in Massachusetts commissioned by the Department of Public Utilities from ICF International were not

shared with stakeholders beyond the Energy and Environmental Affairs Agencies (ICF International, 2014).

### ***3.2.2.6 Utility Rate Payer***

Utility rate payers consume resources distributed through privately-owned natural gas infrastructure pipelines. They also pay for infrastructure maintenance and improvement through state and federal taxes, in addition to their utility rates. There is currently a fundamental lack of understanding amongst most urbanites regarding the condition of urban natural gas distribution infrastructure, the way it is managed, and the manner in which it is financed, especially in terms of their individual contributions (Markey, 2013). According to one environmental nonprofit stakeholder interviewed, private citizens are some of the least informed stakeholders within the urban natural gas infrastructure ecosystem and the most poorly represented during stakeholder negotiations. As the public bears a significant financial burden under the current utility rate-structuring paradigm and suffers greatly when infrastructure is compromised (Fox, 2014), they stand poised to become a stronger player within the urban infrastructure ecosystem. Growing public awareness of climate change, energy systems, and the risk of urban natural gas explosions has begun to shift this paradigm (Resist the Pipeline, 2016), but utility rate payers still shoulder a great financial burden for infrastructure maintenance and improvement as well as lost and unaccounted for gas (Analysis Group, Inc., 2013).

Some public ratepayer advocacy groups have formed in response to this apparent vacuum. The Associated Industry of Massachusetts (AIM) is a consortium of

Massachusetts' employers who advocate for public policy that supports economic growth and opportunity, including fair and just utility rates (Associated Industry of Massachusetts, 2016). According to the Attorney General's Office, public participation in the ratemaking process is encouraged (Attorney General Maura Healey, 2016).

According to an environmental nonprofit stakeholder familiar with the ratemaking process, when a utility company wants to raise rates they must first file the rate hike with the Department of Public Utilities, publish a legal notice of the proposed rate change in local newspapers, and then, 'in most cases,' the Department of Public Utilities will hold a public hearing. While advocacy groups like AIM attend these hearings, it is unclear if utility rate payer stakeholders themselves are also represented and/or if their position is afforded the same clout as other natural gas infrastructure stakeholders at the bargaining table. For example, one academic stakeholder interviewed indicated that AIM has a demonstrated history of lobbying for natural gas fuels and against expansion of wind and solar. The Attorney General has made 'promoting transparency and open government' a priority since 2007 (Attorney General Maura Healey, 2016). However, one environmental nonprofit stakeholder interviewed suggested that because most utility rate payer stakeholders are not aware of 'cost of service' rate regulation and may not understand the legalese of rate hike announcements, this results in a lack of transparency in public proceedings that may hinder genuine public participation in ratemaking.

The safety of urban residents is compromised when aged infrastructure systems fail (Fox, 2014), and natural gas explosions in the U.S. are numerous and can be deadly (PHMSA, 2016). Environmental pressures associated with climate change such as rising

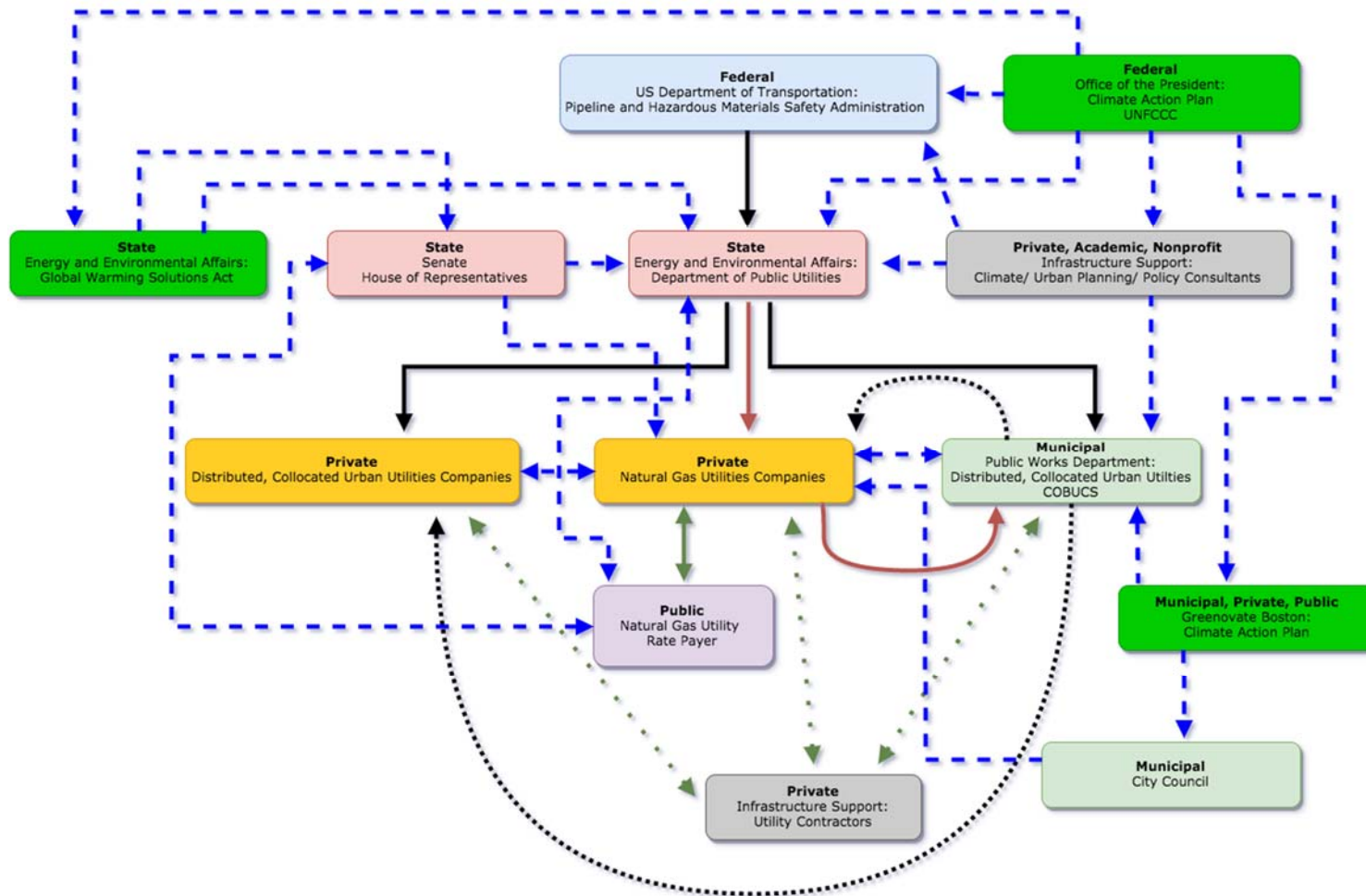
sea level, changes in precipitation regimes, and amplification of the urban heat island effect threaten to further compromise aged infrastructure systems (IPCC, 2014). In order to adapt to changing climate urban residents require resilient, sustainable infrastructure (IPCC, 2014). However, there are currently no policies that specify how long pipeline materials used in infrastructure maintenance and upgrades should last (PHMSA, 2016). This means that in an effort to strike a balance between quality versus price, utility companies will often opt for less expensive, less durable infrastructure materials. For example, when leak-prone cast iron distribution pipes are replaced, it is often with polyethylene plastic pipes that have a shelf life of only 50 years (PHMSA, 2002). Additionally, much of the infrastructure grid maps for extensive utilities are considered ‘proprietary information’ as a matter of public safety. All of the governmental infrastructure stakeholders interviewed, here, reported that public officials at both the city and state level do not possess maps of where underground infrastructure is buried - utility companies are the only stakeholders privy to this information. State-level Department of Public Utilities and municipal-level Public Works Departments must therefore rely on private natural gas utility companies to communicate where buried natural gas infrastructure systems are located.

### ***3.2.3 Discussion: Towards an ideal ecosystem***

Analysis of the natural gas infrastructure stakeholder ecosystem in Boston, MA reveals that there are real physical and fiscal constraints to retrofitting and expanding aging natural distribution infrastructure under the current management framework. In the

short term, utility rate structuring limitations render maintaining the current pace of infrastructure repairs financially advantageous for natural gas utility companies and private utility contractors as compared to the systematic replacement of aged components. A conundrum arises, however, when the timeline to replace aged natural gas distribution infrastructure is mismatched with the timeline under which proposed natural gas expansion projects will test the resiliency of this aged infrastructure. For example, natural gas utility providers in Boston estimate that it will take another 20 years for all leak-prone infrastructure to be replaced under the current management framework (Boston City Council Hearing, 2016). In spite of this timeline, Spectra Energy expects to complete their proposed West Roxbury Lateral Project that will expand pipeline operating capacity by delivering more domestic natural gas to the Northeast by November 2016 (Spectra Energy, 2016). This conundrum has safety, climate change, and economic implications as recent research now suggests that increasing pipeline operating pressure across leak-prone pipes will result in an increased loss of natural gas from thousands of existing leak sites (Phillips et al., 2013; Hendrick et al., 2016). In order to meet the challenges ahead, the natural gas infrastructure stakeholder community must consider shifting the current management paradigm to one where investment in urban infrastructure is embraced as a means of stimulating economic growth, increasing the safety of urban residents, and mitigating greenhouse gas emissions. Achieving sustainable, resilient urban infrastructure will require active participation by all stakeholders as well as coordination within and between stakeholder groups. Based on the extensive stakeholder interviews described here, we suggest that an ideal framework

for the natural gas infrastructure stakeholder ecosystem might look more like Figure 3.2 (c.f. Figure 3.1).



**Figure 3.2** The ideal natural gas infrastructure stakeholder ecosystem in Boston, MA features additional stakeholders, new stakeholder relationships (blue dashed lines), and improved regulatory oversight. Representation of stakeholder groups and coordination within and between these groups is enhanced in an ideal natural gas infrastructure stakeholder ecosystem as compared to the current ecosystem (Figure 3.1).

### ***3.2.3.1 Funding Infrastructure Revitalization***

The American Society of Civil Engineers estimates that the U.S. must invest \$3.6 trillion by 2020 to ensure that American infrastructure is able to adequately serve the public (ASCE, 2013). The current condition of American infrastructure is so poor, and the price tag for revitalization so high, that determining how to fund infrastructure upgrades is a formidable challenge. One natural gas infrastructure stakeholder within state government suggested that improving the TIRF program by expediting the release of funds towards natural gas infrastructure repair and revitalization is an important first step in the right direction. According to this stakeholder, closing the year-long time lag time between when natural gas utility companies invest in infrastructure upgrades and when the cost of those upgrades are reimbursed through rate base adjustments would reduce the financial risk placed on utility companies when embarking on extensive infrastructure upgrades. In order to do this, the same stakeholder indicated that the state has suggested adjusting the rate base at the beginning of a service year, before any work has been completed. Further, the size of the rate adjustment would be based on a proposed set of infrastructure upgrades presented by the utility company to the Department of Public Utilities. In order to ensure accountability in completing these proposed upgrades, this stakeholder indicated that service quality benchmarks and performance metrics would be attached to TIRF adjustments. Failure to meet these metrics would result in the loss of TIRF funding.

A second infrastructure stakeholder within state government agreed that improving the timeline for release of TIRF funding is necessary, but also pointed out that

the current TIRF funding paradigm still does not address the large financial burden placed on utility rate payers through the ‘cost of service’ rate adjustment. This second state-level infrastructure stakeholder indicated that private utilities and their shareholders must begin to shoulder some of the financial burden of revitalizing aging infrastructure. This stakeholder suggested that one way to incentivize both the closure of the TIRF funding time gap and the restructuring of the ‘cost of service’ rate adjustment is to tie the issue of natural gas infrastructure revitalization to global warming. As the Supreme Judicial Court of Massachusetts ruled in May of 2016, state regulators have failed to issue sufficient regulations to cut GHG emissions towards meeting the benchmarks outlined in the Global Warming Solutions Act (Abel, 2016), this strategy may prove fruitful to state utility regulators in the near future.

Funding natural gas infrastructure revitalization is also strongly tied to increasing transparency and accountability within the infrastructure stakeholder ecosystem. State and municipal legislators are key infrastructure stakeholders that stand poised to play a larger role in affecting these changes (Figure 3.2). State representatives and senators work to protect citizen consumers from exorbitant utility rates, serious environmental hazards, and taxes that fund natural gas pipeline expansion projects. For example, the landmark passage of Bill H.4164, ‘An Act relative to natural gas leaks,’ now requires expedited repair of gas leaks that pose a threat to public safety and property, enhanced communication between municipalities and gas utility companies, and annual reporting of comprehensive leak data by gas utility companies to the Department of Public Utilities (Downing, 2014).

State lawmakers also propose and pass legislation that affects the mix of fossil fuel and renewable energy sources that supply Massachusetts' electricity. The 2016 legislative session produced Bill H.4568, 'An Act to promote energy diversity,' which contains language that requires natural gas utility companies to develop methods to identify and fix 'environmentally significant' natural gas leaks that contribute disproportionate CH<sub>4</sub> emissions (Gibbons, 2016). As such, state legislatures in particular are well positioned to highlight the disconnect between the climate change risks associated with leak-prone urban natural gas infrastructure and the rapidly approaching GHG mitigation deadlines inherent to the United Nation's Framework Convention on Climate Change, the President's Climate Action Plan, the Global Warming Solutions Act, and the Greenovate Boston Climate Action Plan (Massachusetts Global Warming Solutions Act, 2008; Executive Office of the President, 2013; City of Boston, 2014; UNFCCC COP, 2015). Municipal city councilors are also well positioned to employ climate change mitigation and protection of public safety as policy levers to enact city ordinances that address management of urban natural gas distribution infrastructure, like the 'ordinance regarding elimination of gas leaks in the City of Boston' that is now under consideration by the Boston's City Council (Boston City Council Hearing, 2016).

### ***3.2.3.2 Coordination***

Achieving sustainable and resilient urban natural gas infrastructure ecosystem requires active participation by all stakeholders and coordination within and between stakeholder groups (Figure 3.2). While the Public Works Department officials

interviewed, here, attest that software tools like Boston's COBUCS program have made great strides in coordinating road and utility maintenance, more work is still required to further enhance communication between stakeholders and encourage coordinated management of interdependent and collocated infrastructure systems. Map-based software platforms that integrate road, utility, and environmental data represent a viable solution to the current lack of coordination amongst urban infrastructure stakeholders. A map-based program pioneered by the company, ENVISTA, has proven successful in efficiently and effectively coordinating amongst stakeholders in many American and Canadian cities (ENVISTA, 2016). Similar to COBUCS, the ENVISTA program allows stakeholders to input maintenance data into an online platform such that all concurrent initiatives are visualized. The ENVISTA program is also capable of compiling and visualizing myriad pre-existing datasets from public and private stakeholders to streamline a comprehensive management plan. Inclusion of infrastructure monitoring data from other stakeholders in the private sector, such as the natural gas leak and fugitive CH<sub>4</sub> emission data collected by academic institutions and environmental nonprofits, would further increase efficiency in maintenance procedures (Phillips et al., 2013; Environmental Defense Fund and Google Earth Outreach, 2015; McKain et al. 2015; Hendrick et al., 2016). According to ENVISTA representatives, the map-based program now saves the City of Baltimore \$900,000 annually (ENVISTA, 2016).

### 3.3 Conclusions

An ecosystem analytic framework proved useful in elucidating the roles, limitations, and key relationships within the natural gas infrastructure stakeholder ecosystem of Boston, MA. This stakeholder community is not often analyzed holistically, which obscures important interdependencies and feedbacks amongst stakeholders. Characterization of the stakeholder ecosystem of Boston, MA reveals the current state of networked decision-making in many American urban centers that are currently grappling with aging infrastructure systems. Funding infrastructure revitalization, increasing stakeholder participation, and enhancing communication and coordination within and between stakeholder groups are important steps to take towards sustainable management of aging natural gas distribution infrastructure. State and municipal legislatures also stand poised to employ novel policy levers that connect the current state of aged natural gas infrastructure systems to the public safety risks posed by natural gas leaks and the contribution to global climate change made through pervasive fugitive CH<sub>4</sub> emissions. Raising public awareness of the financial burden born by utility rate payers and encouraging participation and representation of all stakeholders has the potential to enhance connectivity, equity, and efficiency within the stakeholder ecosystem. The condition of critical urban infrastructure systems has declined in the U.S. over the last century, but it is not too late to develop and implement coordinated, innovative management policies that will increase infrastructure resilience and reduce inefficiencies. Our analysis of the natural gas infrastructure stakeholder ecosystem in Boston, MA

elucidates the many ways in which American cities may optimize stakeholder ecosystem functionality and improve vital infrastructure systems for the long-term future.

**Acknowledgements:** The Frederick S. Pardee Center for the Study of the Longer-Range Future supported this research through a Pardee Graduate Summer Fellowship. This publication was developed under STAR Fellowship Assistance Agreement no. F13F31263 awarded by the US Environmental Protection Agency (EPA). It has not been formally reviewed by the EPA. Shanna Cleveland, Lucy Hutyra, Anne Short Gianotti, and Sucharita Gopal provided helpful comments on the manuscript. We are grateful to all of the individuals who agreed to be interviewed for this work.

## CHAPTER 4 – UNLEAKABLE CARBON

Unleakable carbon, or the uncombusted methane and carbon dioxide associated with fossil fuel systems, constitutes a potentially large and heretofore unrecognized factor in determining use of Earth's remaining fossil fuel reserves. Advances in extraction technology have encouraged a shift to natural gas, but the advantage of fuel switching depends strongly on mitigating current levels of unleakable carbon, which can be substantial enough to offset any climate benefit relative to oil or coal. To illustrate the potential warming effect of methane emissions associated with utilizable portions of our remaining natural gas reserves, we use recent data published in peer-reviewed journals to estimate the impact of these emissions. We demonstrate that unless unleakable carbon is curtailed, roughly 80 – 100% of our global natural gas reserves must remain underground if we hope to limit warming to 2 °C from 2010 to 2050. Successful climate change mitigation depends on improved quantification of current levels of unleakable carbon and a determination of acceptable levels of these emissions within the context of international climate change agreements.

### 4.1 Policy Relevance

It is imperative that companies, investors, and world leaders considering capital expenditures and policies towards continued investment in natural gas fuels do so with a complete understanding of how dependent the ultimate climate benefits are upon increased regulation of unleakable carbon, the uncombusted carbon-based gases

associated with fossil fuel systems, otherwise referred to as ‘fugitive,’ ‘leaked,’ ‘vented,’ ‘flared,’ or ‘unintended’ emissions. Continued focus on combustion emissions alone, or unburnable carbon, undermines the importance of assessing the full climate impacts of fossil fuels, leading many stakeholders to support near-term mitigation strategies that rely on fuel switching from coal and oil to cleaner burning natural gas. The current lack of transparent accounting of unleakable carbon represents a significant gap in the understanding of what portions of Earth’s remaining global fossil fuel reserves can be utilized while still limiting global warming to 2 °C. Successful climate change mitigation requires that stakeholders confront the issue of both unburnable and unleakable carbon when considering continued investment in and potential expansion of natural gas systems as part of a climate change solution.

#### **4.2 Main Text**

‘Unburnable carbon’ refers to the vast majority of the world’s fossil fuel reserves that must remain underground—and unburned—to achieve at least a 50% chance of keeping global warming below 2 °C throughout the 21<sup>st</sup> century (Carbon Tracker Initiative, 2011; McGlade & Ekins, 2015). The term was first coined in a report produced by the Carbon Tracker Initiative in 2011, and McGlade and Ekins were the first to quantify specific portions of coal, oil, and natural gas that must remain undeveloped in a letter to *Nature* in 2015. Since this time unburnable carbon has become a dominant frame by which stakeholders discuss global warming mitigation strategies, including fuel switching to cleaner burning natural gas (Figure 4.1). But unburnable carbon is an

incomplete metric and concept. It does not account for the uncombusted carbon-based gases that are also associated with the extraction, distribution, and consumption of fossil fuel reserves, otherwise referred to as ‘fugitive,’ ‘leaked,’ ‘vented,’ ‘flared,’ or ‘unintended’ emissions. Here we introduce the term ‘unleakable carbon’ to refer to these non-combustion emissions, and demonstrate that in particular the unleakable carbon associated with natural gas constitutes a potentially large and heretofore unrecognized factor in estimating usable portions of Earth’s fossil fuel reserves.

Energy-related activities other than fuel combustion are known to intentionally and unintentionally release both methane (CH<sub>4</sub>) and carbon dioxide (CO<sub>2</sub>) to the atmosphere. In the U.S., as well as other countries that produce and rely on fossil fuels, these emissions consist primarily of fugitive CH<sub>4</sub> released during the production, transmission, storage, and/or distribution of coal, oil, and natural gas (EPA, 2016). The primary sources of non-combustion greenhouse gas (GHG) emissions across fossil fuel systems include but are not limited to coal seams, equipment leaks, evaporation and flashing losses, venting, flaring, incineration, and accidental releases (IPCC, 2006). Carbon dioxide emissions resulting primarily from fuel combustion make up the majority of energy-related GHG emissions, but non-CO<sub>2</sub> emissions from energy-related activities comprise a smaller yet highly potent portion of national emissions. In the U.S. methane accounts for 11% of annual GHG emissions, 42% of which can be traced to coal, oil, and natural gas systems (EPA, 2016). While the term unleakable carbon refers to both uncombusted CO<sub>2</sub> and CH<sub>4</sub>, it is the release of CH<sub>4</sub>, the main constituent of natural gas, which has the greatest potential to diminish our ability to meet GHG mitigation goals.

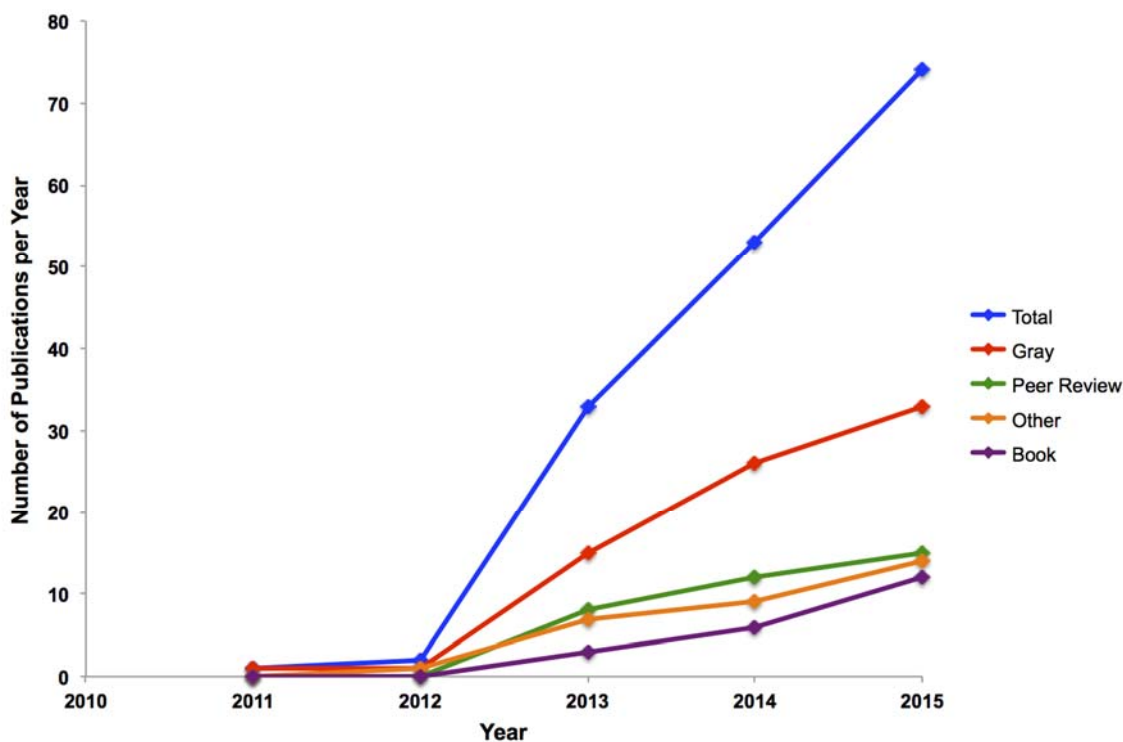
Here we discuss the warming contribution of uncombusted CH<sub>4</sub> emissions associated with natural gas systems to illustrate the importance of accounting for unleakable carbon when estimating usable portions of remaining global fossil fuel reserves.

Methane has a global warming potential 86 times greater than CO<sub>2</sub> over a 20-year time horizon, making it one of the most potent GHGs (IPCC, 2013). The release of CH<sub>4</sub> across the natural gas process chain is now cited as the largest contributor to fossil fuel related fugitive emissions (IPCC, 2013), intensifying the importance of the issue of unleakable carbon as we embark on a global shift away from coal and oil towards natural gas use. Advances in extraction technology have increased momentum for energy policies favoring fuel switching to natural gas, but they have also drawn greater attention to the associated non-combustion emissions from natural gas systems (Alvarez, Pacala, Winebrake, Chameides, & Hamburg, 2012). Growing awareness of the magnitude of these non-combustion emissions amongst stakeholders has not yet translated to inclusion within global ‘carbon budget’ negotiations that continue to focus solely on unburnable carbon (Gillis, 2015). As recently as five years ago, research estimating the magnitude of fugitive CH<sub>4</sub> emissions across the life cycle of conventional and shale gas was met with skepticism (Howarth, Santoro, & Ingraffea, 2011). Mounting evidence now demonstrates that CH<sub>4</sub> emissions across all sectors of the natural gas industry have the potential to be substantial enough to offset any climate benefit, as compared to oil or coal, for electric generation (World Resources Institute, 2013; Heath, O’Donoghue, Arent, & Bazilian, 2014; ICF International, 2015). Leaks like the 2015 blowout at the Aliso Canyon underground storage facility in California, which at its peak effectively doubled the CH<sub>4</sub>

emission rate for the entire Los Angeles basin, exemplify how aging infrastructure and lax enforcement of environmental and safety regulations render natural gas systems particularly vulnerable to the release of massive volumes of unleakable carbon (Conley et al., 2016).

The climate advantage of fuel switching to natural gas is strongly dependent on mitigating current levels of CH<sub>4</sub> emissions from natural gas systems, from the point of extraction to the point of consumption (Alvarez et al., 2102; Brandt et al., 2014). While the issue of CH<sub>4</sub> emissions across the natural gas process chain has now become well known, this recognition has not manifested itself as a category of unleakable carbon in studies estimating usable fossil fuel reserves. For example, McGlade and Ekins (2015) do not explicitly mention CH<sub>4</sub> emissions in their landmark study of utilizable fossil fuel reserves, whereas variations of the terms “combust” or “burn” appear 36 times. A subsequent study by Heede and Oreskes (2016) provides an alternative analysis of the same fossil fuel reserves, estimating the combustion emissions from proved reserves. Here the authors note that CH<sub>4</sub> emissions account for roughly 10% of total estimated emissions from the production, processing, and delivery of fossil fuels, yet these results are not folded into final carbon budget estimates and are only presented for context and future analysis. While extraordinarily important in terms of their contribution to our understanding of Earth’s remaining fossil fuel reserves, the overwhelming focus of literature to date that aims to parse usable portions of these reserves and/or discuss climate change mitigation strategies is clearly on combustion emissions.

A Google Scholar search of the term ‘unburnable carbon’ yields 165 publications over the past four years, with a roughly exponential increase in use since the term was first coined in 2011 (Figure 4.1, Appendix B). The concept of carbon budgeting through the mitigation of combustion emissions is not a new one, however. Analogous terms such as ‘fossil carbon emissions’ (Krause, Bach, & Koomey, 1989), ‘subprime carbon’ (Friends of the Earth, 2009), ‘carbon bubble’ (McKibben, 2012), and ‘combustion emissions’ and have all been used to describe the concept of unburnable carbon prior to 2011. The evolution and adoption of the term ‘unburnable carbon’ demonstrates the utility of a policy-relevant concept in facilitating an increasingly pragmatic approach to developing remaining fossil fuel reserves in the face of global climate change (Figure 4.1). As was the case with unburnable carbon there are currently many different terms used to describe the non-combustion emissions associated with fossil fuel systems, which can lead to confusion and a lack of consensus within policymaker and stakeholder communities. Just as the term ‘unburnable carbon’ has gained traction as a means of discussing combustion emissions associated with fossil fuel reserves that should remain untouched, we intend for ‘unleakable carbon’ to draw attention to and facilitate a discussion of non-combustion emissions across coal, oil, and natural gas systems.



**Figure 4.1** The number of publications per year that contain the term(s) ‘unburnable’ carbon, ‘unburnable’ reserves, or ‘unburnable’ coal/ oil/ natural gas recovered during a Google Scholar search for the term ‘unburnable carbon’ (total = all publications per year; gray = reports, dissertations or theses, conference abstracts or papers, non-peer reviewed journals; peer review = publications in peer reviewed journals; other = blogs, non-peer reviewed advocacy journals, select online or print newspaper articles, divestment materials; books = published books). As of December 2015, Google Scholar yields 165 publications that utilize the concept of unburnable carbon within the body of their text since the term was first coined by the Carbon Tracker Initiative in 2011. A comparatively less rigorous Google search for the term ‘unburnable carbon’ yields 24,300 results. When the term ‘unleakable carbon’ is queried using both Google and Google Scholar, however, zero results are recovered. See Appendix B for details.

Estimates of global CH<sub>4</sub> emissions from natural gas systems are as high as 5% of the world's produced gas (IPCC, 2014). In order to illustrate the potential warming effect of the volume of unleakable carbon associated with utilizable portions of our remaining natural gas reserves, we use recent data published in peer-reviewed journals to roughly estimate the impact of these emissions, assuming they continue unabated. According to McGlade and Ekins (2015), who provide the most current analysis to date, we can utilize 50% of our remaining global natural gas reserves from 2010 to 2050 and still keep warming below 2 °C. This assessment is predicated on the assumption that development of unconventional natural gas reserves will widely displace coal production in the coming years (McGlade & Ekins, 2015). The mass of half our total remaining gas reserves, when combusted, is estimated to be 179.5 Gt CO<sub>2</sub> (McGlade & Ekins, 2015). This value is reported in units of CO<sub>2</sub>, or combustion-only emissions, without yet factoring in the warming consequences of unleakable carbon. As global monitoring and reporting of CH<sub>4</sub> emissions remains poor and uncertainty surrounding these estimates remains high (Allen, 2014; IPCC, 2014), we assume that the relatively robust low (1.8%) and high (5.4%) estimates of CH<sub>4</sub> emissions for North American natural gas systems published by Brandt et al. (2014) function well as a conservative estimate of CH<sub>4</sub> emissions for global natural gas systems. If we assume that 3.2 Gt CO<sub>2</sub> and 9.7 Gt CO<sub>2</sub> of the utilizable portion of recoverable gas reserves are leaked under low and high leakage scenarios, respectively, we can then convert these emissions to equivalent CO<sub>2</sub> emissions (CO<sub>2</sub>e) to reflect uncombusted CH<sub>4</sub>.

Low estimates of CH<sub>4</sub> emissions evaluated over a centennial time horizon show that unleakable carbon enhances CO<sub>2e</sub> from the combustion of utilizable portions of remaining natural gas fuels by 30% (Table 4.1, Appendix B). This comprehensive carbon accounting demonstrates that stakeholders may need to prepare to leave 80% of remaining global natural gas reserves in the ground instead of just 50%. Alarming, high estimates of CH<sub>4</sub> emissions on decadal time scales increase CO<sub>2e</sub> emissions by 230% (Table 4.1, Appendix B). This worst-case leakage scenario indicates that stakeholders may not be able to afford to extract any remaining global natural gas reserves, and that even current, ongoing leakage across natural gas systems may present a challenge to limiting warming to 2 °C from 2010 to 2015. At present only a few countries have outlined specific goals for reducing CH<sub>4</sub> emissions from the natural gas systems in the future, and implementing proposed regulations remains challenging (Rhodium Group, 2015; U.S.-Canada Joint Statement on Climate, Energy, and Arctic Leadership, 2016). Scientists (Alvarez et al., 2012; Brandt et al., 2014; Zhang, Myhrvold, & Caldeira, 2014) and policy experts (Union of Concerned Scientists, 2013; Climate Council, 2015; Rhodium Group, 2015; The New Climate Economy & Stockholm Environment Institute, 2015) advocate for a pragmatic approach to assessing the climate risks of continued reliance on natural gas, while extractive industry underemphasizes the consequences of CH<sub>4</sub> emissions from natural gas systems and promotes fuel switching as a climate change solution (Lund et al., 2015). As it stands, many fossil fuel companies queried about the issue of Carbon Asset Risk have responded by pointing to increased weighting of their capital expenditures towards natural gas exploration and development (Carbon Tracker

Initiative & The Grantham Research Institute on Climate Change and the Environment at LSE, 2013). Yet, natural gas drillers continue to fight regulation of methane emissions despite growing evidence that supports the utility of environmental and safety regulations aimed at stemming ‘superemitter’ leaks, such as the Aliso Canyon blowout, which are responsible for releasing the largest proportion of unleakable carbon to the atmosphere (Conley et al., 2016; EPA, 2016; Hendrick et al., 2016; Lyon et al., 2016).

**Table 4.1** When low and high CH<sub>4</sub> leakage rates (Brandt et al., 2014) are applied to the combustion emissions associated with the utilizable portion of our remaining natural gas reserves, estimated to be 50% if we aim to meet a warming target of 2 °C from 2010-2050 (McGlade & Ekins, 2015), we find that the warming contribution of unleakable carbon is large enough to enhance CO<sub>2e</sub> between 30% and 230% over best and worst-case leakage and global warming potential (GWP) scenarios, respectively. Here combustion emissions are converted to CO<sub>2e</sub> to reflect uncombusted CH<sub>4</sub> using the most recent GWP data published for 20- and 100-year time horizons (IPCC, 2013). Stakeholders may need to prepare to leave 80% of remaining global natural gas reserves untouched in a best-case scenario, and all reserves untouched in a worst-case scenario where even current, ongoing CH<sub>4</sub> leakage may present a challenge to limiting warming to 2 °C from 2010-2050. See Appendix B for details.

| GWP | Time horizon (years) | 1.8% Leakage rate | 5.4% Leakage rate |
|-----|----------------------|-------------------|-------------------|
|     |                      | Low               | High              |
| 34  | 100                  | 80%               | 139%              |
| 86  | 20                   | 127%              | 280%              |

Unburnable carbon, alone, is currently informing global policymaking. Many extractive industry giants including BG Group, BP, Eni, Royal Dutch Shell, Statoil, and Total have appealed to policymakers to endorse natural gas and the role they believe it

should play in addressing climate change (Lund et al., 2015). Their argument proceeds from the premise that burning natural gas generates half of the carbon emissions as coal, thereby squandering less unburnable carbon while meeting the world's demand for energy. Of the world's remaining fossil fuel reserves, budgets of allowable natural gas use must include a new category of unleakable carbon, requiring companies, investors, and world leaders to make capital expenditures and policies towards extraction of natural gas with a complete understanding of how dependent the ultimate climate benefits are upon increased regulation of CH<sub>4</sub> emissions and improved monitoring, detection, and reporting of these emissions by all countries. The distribution of usable portions of remaining coal and oil reserves must also be reevaluated in light of the yet unaccounted for but significant warming consequences of unleakable carbon across the entire fossil fuel process chain, from the point of extraction to the point of consumption (Kort et al. 2016; Lyon et al. 2016). To this end, the term unleakable carbon provides a means of clearly designating a set of uncombusted carbon-based gases associated with the extraction, distribution, and consumption of fossil fuel reserves in the same unifying and policy relevant manner that unburnable carbon functions to draw attention to analogous combustion emissions. The concept also functions as a call to action for both policymakers and scientists to better quantify current levels of unleakable carbon and to determine acceptable levels of these emissions within the context of international climate change mitigation strategies moving forward.

The 2015 Paris Agreement marks an important shift in the global perception of climate change and the arrival of 195 nations at the consensus that immediate and

coordinated action must be taken to reduce carbon-based emissions (UNFCCC Conference of the Parties, 2015). Long-term mitigation strategies include utilization of carbon capture and storage (CCS) technologies and a shift to scalable renewable energy, but many stakeholders still support near-term strategies that rely on fuel switching from coal and oil to cleaner burning natural gas. In particular, countries like China, Russia, Argentina, Australia, Mexico, and Canada stand poised to develop their sizable unconventional natural gas reserves. Until CCS and renewable energy scale widely, the future of the world's investment in and consumption of natural gas fuels is poised to play a central role in GHG mitigation strategies. As the energy supply sector is the largest contributor to global GHG emissions, it is imperative that policymakers, stakeholders, and investors understand the full warming consequences of the extraction, distribution, and consumption of our remaining global fossil fuel reserves (International Energy Agency, 2015). Successful climate change mitigation requires that stakeholders confront the issue of *both* unburnable and unleakable carbon when considering continued investment in and potential expansion of natural gas systems as part of a climate change solution; otherwise we may be in for a much warmer future.

**Acknowledgements:** The Barr Foundation and Conservation Law Foundation supported this research. Lucy Hutyra, Anne Short Gianotti, and Sucharita Gopal provided helpful comments on the manuscript.

**Funding:** This publication was developed under STAR Fellowship Assistance Agreement [grant number F13F31263] awarded by the U.S. Environmental Protection Agency (EPA). It has not been formally reviewed by the EPA.

**Appendix B** contains detailed methodology and additional figures.

## CHAPTER 5 – CONCLUSION

This dissertation reports the results of three studies designed to improve our understanding of the global warming contribution of fugitive CH<sub>4</sub> emissions across natural gas systems, best practices for managing aging leak-prone natural gas distribution infrastructure, and policies that govern continued investment in and consumption of natural gas fuels. The overarching goal of this research was to produce policy relevant data that would inform stakeholders in the global discussion of the environmental and political ramifications of continued reliance on natural gas fuels. City and state legislators in Boston and Massachusetts, respectively, have already cited the findings published herein regarding the distribution of gas leak size in urban environments. They have pointed to these results in order to argue for accelerated replacement of leak-prone distribution mains and greater oversight of natural gas utility companies. These stakeholders have also recommended fixing superemitter leaks as a means of stemming urban greenhouse gas (GHG) emissions towards meeting the mitigation benchmarks outlined in both the Massachusetts Global Warming Solutions Act and the Greenovate Boston Climate Action Plan (Massachusetts Global Warming Solutions Act, 2008; City of Boston, 2014).

Characterization of the natural gas infrastructure stakeholder ecosystem in Boston, MA has also proved useful to stakeholders who seek to identify avenues for increasing efficiency across all distributed urban utilities. Legislators with the City of Boston and the State of Massachusetts have both introduced language that calls for

coordinated maintenance of collocated, buried utility infrastructure systems whenever a road has been excavated for road repair or reconstruction. This language is currently limited to fixing any natural gas leak detected at the time of excavation. While these initiatives represent good progress in increasing connectivity and accountability between urban infrastructure stakeholder groups, legislators must push harder for replacing entire segments of exposed leak-prone pipe rather than simply patching leaks. In order to replace aging natural gas distribution infrastructure quickly enough to meet GHG mitigation goals and decrease the risk of potentially fatal natural gas explosions, every opportunity to increase efficiency in the management of distributed urban utilities must be exploited. Stakeholders have pointed to the overwhelming financial burden currently born by utility rate payers, who still cover the cost of both lost and unaccounted for gas and pipeline repair with their natural gas utility rates, as an argument against levying further tariffs, taxes, or fees to support natural gas expansion projects in Massachusetts.

Finally, the need for transparent carbon accounting in determining usable portions of Earth's remaining fossil fuel reserves has never been greater. The concept of unleakable carbon stands poised to rally policymakers who have hedged their bets on meeting GHG mitigation goals by stemming fugitive CH<sub>4</sub> emissions towards stiffer safety and environmental regulations for the fossil fuel industry. The occurrence of superemitter leaks across the entire natural gas process chain presents a likely avenue for mitigating a large proportion of emissions quickly. However, moving away from fossil fuel energy sources entirely and working towards scalable renewable energy is the most sustainable manner in which we can hope to meet the 2 °C warming target outlined in the

United Nation's Framework Convention on Climate Change (UNFCCC COP, 2015).

Instituting a carbon tax and developing long-term GHG mitigation strategies like carbon capture and storage must also play a role in reducing the global warming impact of unleakable carbon. As countries like China, Russia, Argentina, Australia, Mexico, and Canada stand poised to develop their sizable unconventional natural gas reserves, it is time for the global community to acknowledge the full warming consequences of continued investment in and consumption of natural gas fuels.

## APPENDIX A

### Field Sampling

#### *Site Selection*

Sites for methane (CH<sub>4</sub>) emission sampling were determined by the coexistence of natural gas leaks and buried cast iron distribution infrastructure within Metro Boston, MA. We characterized 100 natural gas leaks emanating from cast iron distribution mains in Boston, Brookline, and Newton, MA (Table A1). We identified 45 natural gas leaks using the results of our on-road atmospheric CH<sub>4</sub> survey conducted in 2011 within the City of Boston (Phillips et al., 2013) and an additional 55 leaks in Boston, Brookline, and Newton through real-time on-road atmospheric CH<sub>4</sub> surveys following the same methodology. Using natural gas distribution infrastructure maps provided by National Grid, we obtained the location, age, operating pressure, and diameter of buried cast iron distribution mains (National Grid, 2013).

We selected sampling sites based on three criteria: 1) cast iron pipe material, 2) a proportion of pipeline operating pressures representative of the total distribution network, and 3) detection of elevated atmospheric [CH<sub>4</sub>] (Figure A1). We sampled leaks over cast iron distribution mains operating at 0.5 (n = 93), 2 (n = 3), 22 (n = 3), 60 (n = 1) pounds per square inch gage (PSIG). Since natural gas utility companies complete their own leak surveys and fix a number of leaks every year, we confirmed the presence of a gas leak at every sampling site. We defined a leak as any detected atmospheric [CH<sub>4</sub>] above a threshold of 2.5 ppm (Phillips et al., 2013; Jackson et al., 2014; Gallagher et al. 2015).

This threshold is conservative, as baseline atmospheric [CH<sub>4</sub>] is closer to 1.8 ppm (NOAA, 2015).

**Table A1.** Complete summary of natural gas leaks surveyed. We sampled 16 leaks in 2012, with eight sampled in June and eight in December. We sampled one leak in September 2013 and another 55 leaks from July to mid-September of 2014. We sampled the remaining 28 leaks in November 2013 and January 2014. We surveyed 13 leaks in both summer and winter months in order to characterize seasonal variation in CH<sub>4</sub> flux.

| Sampling Date | Block Address                                  | Lat Long                    | CH <sub>4</sub> Flux (g•day <sup>-1</sup> ) |
|---------------|--|-----------------------------|---|
| 06/01/12      | 1000 block Beacon St., Brookline, MA 02446     | 42°20'41.05"N 71°06'37.50"W | 1.6 x 10 <sup>3</sup>                       |
| 06/01/12      | 120 block Nonantum Rd., Newton, MA 02458       | 42°21'30.01"N 71°10'28.19"W | 6.1 x 10 <sup>3</sup>                       |
| 06/06/12      | 1200 block Washington St., Newton, MA 02465    | 42°20'58.33"N 71°13'31.41"W | 5.4 x 10 <sup>2</sup>                       |
| 06/06/12      | 400 block Washington St., Newton, MA 02458     | 42°21'33.52"N 71°11'27.16"W | 8.1 x 10 <sup>2</sup>                       |
| 06/06/12      | 1200 block Washington St., Newton MA 02465     | 42°20'58.38"N 71°13'31.26"W | 8.3 x 10 <sup>2</sup>                       |
| 06/06/12      | 1900 block Washington St., Newton, MA 02466    | 42°20'03.97"N 71°14'38.06"W | 9.1 x 10 <sup>2</sup>                       |
| 06/06/12      | 1200 block Washington St., Newton, MA 02465    | 42°20'56.94"N 71°13'34.76"W | 2.4 x 10 <sup>3</sup>                       |
| 06/06/12      | 2300 block Commonwealth Ave., Newton, MA 02466 | 42°20'39.55"N 71°15'32.82"W | 3.8 x 10 <sup>3</sup>                       |
| 12/27/12      | 100 block Ashford St., Boston, MA 02134        | 42°21'16.61"N 71°07'37.58"W | 2.8 x 10 <sup>3</sup>                       |
| 12/28/12      | 1600 block Beacon St., Brookline, MA 02446     | 42°20'23.30"N 71°08'07.10"W | 47  |
| 12/28/12      | 0 block Batchelder St., Boston, MA 02125       | 42°19'17.28"N 71°04'09.17"W | 3.4 x 10 <sup>2</sup>                       |
| 12/28/12      | 0 block E. Lenox St., Boston, MA 02119         | 42°19'58.12"N 71°04'34.06"W | 4.8 x 10 <sup>2</sup>                       |
| 12/28/12      | 0 block Calvin Rd., Boston, MA 02130           | 42°18'17.99"N 71°07'49.58"W | 5.7 x 10 <sup>2</sup>                       |
| 12/28/12      | 400 block Dudley St., Boston, MA 02119         | 42°19'30.94"N 71°04'30.09"W | 6.5 x 10 <sup>2</sup>                       |
| 12/28/12      | 1700 block Beacon St., Newton, MA 02468        | 42°19'34.76"N 71°14'03.18"W | 2.4 x 10 <sup>3</sup>                       |
| 12/28/12      | 0 block Claflin Rd., Brookline, MA 02445       | 42°20'14.44"N 71°08'10.48"W | 2.7 x 10 <sup>3</sup>                       |
| 09/25/13      | 0 block Pine Grove Ave., Newton, MA 02462      | 42°19'52.94"N 71°15'34.08"W | 2.4 x 10 <sup>2</sup>                       |
| 11/15/13      | 0 block Lakeville Rd., Boston, MA 02130        | 42°19'00.85"N 71°06'56.54"W | 20  |
| 11/19/13      | 0 block Lila Rd., Boston, MA 02130             | 42°18'18.80"N 71°07'48.54"W | 5.3   |
| 11/19/13      | 0 block Westchester Rd., Boston, MA 02130      | 42°18'14.17"N 71°07'43.16"W | 4.1 x 10 <sup>2</sup>                       |
| 11/20/13      | 0 block Theo Parker Rd., Boston, MA 02132      | 42°17'25.54"N 71°08'56.41"W | 4.0   |

| Sampling Date | Block Address                               | Lat Long                    | CH <sub>4</sub> Flux (g•day <sup>-1</sup> ) |
|---------------|---|-----------------------------|---|
| 11/20/13      | 0 block Theo Parker Rd., Boston, MA 02132   | 42°17'26.39"N 71°08'57.06"W | 11  |
| 11/20/13      | 100 block Russett Rd., Boston, MA 02132     | 42°17'30.41"N 71°09'03.90"W | 17  |
| 11/20/13      | 400 block Weld St., Boston, MA 02132        | 42°17'34.39"N 71°09'00.37"W | 18  |
| 11/20/13      | 200 block Church St., Boston, MA 02132      | 42°17'42.92"N 71°08'59.75"W | 3.4 x 10 <sup>2</sup>                       |
| 01/13/14      | 100 block Walworth St., Boston, MA 02131    | 42°16'47.04"N 71°08'13.40"W | 6.6   |
| 01/13/14      | 300 block Belgrade Ave., Boston, MA 02132   | 42°17'09.25"N 71°08'46.43"W | 12  |
| 01/13/14      | 100 block Walworth St., Boston, MA 02131    | 42°16'47.66"N 71°08'12.59"W | 21  |
| 01/13/14      | 0 block Belgrade Terrace, Boston, MA 02132  | 42°17'11.04"N 71°08'46.65"W | 36  |
| 01/13/14      | 0 block Anawan Ave., Boston, MA 02132       | 42°17'08.65"N 71°08'47.30"W | 1.3 x 10 <sup>2</sup>                       |
| 01/13/14      | 800 block Centre St., Boston, MA 02130      | 42°18'32.52"N 71°07'13.68"W | 2.3 x 10 <sup>4</sup>                       |
| 01/14/14      | 0 block Stoughton St., Boston, MA 02125     | 42°19'00.34"N 71°03'53.82"W | 91  |
| 01/15/14      | 900 block Parker St., Boston, MA 02130      | 42°19'30.74"N 71°06'04.35"W | 14  |
| 01/15/14      | 0 block Edge Hill St., Boston, MA 02130     | 42°19'26.85"N 71°06'25.31"W | 36  |
| 01/15/14      | 0 block Edge Hill St., Boston, MA 02130     | 42°19'27.67"N 71°06'24.28"W | 1.2 x 10 <sup>2</sup>                       |
| 01/15/14      | 0 block Edge Hill St., Boston, MA 02130     | 42°19'27.54"N 71°06'21.76"W | 3.7 x 10 <sup>2</sup>                       |
| 01/16/14      | 0 block Haverford St., Boston, MA 02130     | 42°18'42.95"N 71°06'10.04"W | 4.0   |
| 01/16/14      | 0 block Atherton St., Boston, MA 02119      | 42°19'00.67"N 71°05'58.69"W | 1.4 x 10 <sup>2</sup>                       |
| 01/16/14      | 0 block Gayhead St., Boston, MA 02130       | 42°19'26.01"N 71°06'20.08"W | 2.3 x 10 <sup>2</sup>                       |
| 01/17/14      | 200 block Arborway, Boston, MA 02130        | 42°18'17.18"N 71°07'09.66"W | 2.6 x 10 <sup>2</sup>                       |
| 01/17/14      | 200 block Arborway, Boston, MA 02130        | 42°18'21.86"N 71°07'08.74"W | 1.8 x 10 <sup>3</sup>                       |
| 01/20/14      | 500 block Canterbury St., Boston, MA 02130  | 42°17'16.65"N 71°06'33.09"W | 13  |
| 01/20/14      | 0 block Bickford St., Boston, MA 02130      | 42°19'26.31"N 71°06'07.25"W | 1.1 x 10 <sup>2</sup>                       |
| 01/20/14      | 3500 block Washington St., Boston, MA 02130 | 42°18'16.85"N 71°06'34.06"W | 4.3 x 10 <sup>2</sup>                       |
| 01/20/14      | 1900 block Columbus Ave., Boston, MA 02119  | 42°19'01.53"N 71°05'54.08"W | 7.0 x 10 <sup>2</sup>                       |
| 06/09/14      | 0 block Gayhead St., Boston, MA 02130       | 42°19'26.01"N 71°06'20.08"W | 4.8 x 10 <sup>2</sup>                       |

| Sampling Date | Block Address                                  | Lat Long                    | CH <sub>4</sub> Flux (g•day <sup>-1</sup> ) |
|---------------|--|-----------------------------|---|
| 06/09/14      | 0 block Edge Hill St., Boston, MA 02130        | 42°19'27.54"N 71°06'21.76"W | 7.0 x 10 <sup>2</sup>                       |
| 06/10/14      | 0 block Edge Hill St., Boston, MA 02130        | 42°19'26.85"N 71°06'25.31"W | 21  |
| 06/10/14      | 900 block Parker St., Boston, MA 02130         | 42°19'30.74"N 71°06'04.35"W | 66  |
| 06/10/14      | 0 block Edge Hill St., Boston, MA 02130        | 42°19'27.67"N 71°06'24.28"W | 2.7 x 10 <sup>2</sup>                       |
| 06/10/14      | 0 block Bickford St., Boston, MA 02130         | 42°19'26.31"N 71°06'07.25"W | 6.8 x 10 <sup>2</sup>                       |
| 06/16/14      | 0 block Theo Parker Rd., Boston, MA 02132      | 42°17'25.54"N 71°08'56.41"W | 19  |
| 06/16/14      | 400 block Weld St., Boston, MA 02132           | 42°17'34.39"N 71°09'00.37"W | 1.3 x 10 <sup>2</sup>                       |
| 06/16/14      | 200 block Arborway, Boston, MA 02130           | 42°18'17.18"N 71°07'09.66"W | 2.7 x 10 <sup>2</sup>                       |
| 06/16/14      | 200 block Arborway, Boston, MA 02130           | 42°18'21.86"N 71°07'08.74"W | 7.3 x 10 <sup>2</sup>                       |
| 06/25/14      | 0 block Batchelder St., Boston, MA 02125       | 42°19'17.28"N 71°04'09.17"W | 3.6 x 10 <sup>2</sup>                       |
| 06/25/14      | 0 block Stoughton St., Boston, MA 02125        | 42°19'00.34"N 71°03'53.82"W | 5.2 x 10 <sup>2</sup>                       |
| 06/25/14      | 1900 block Columbus Ave., Boston, MA 02119     | 42°19'01.53"N 71°05'54.08"W | 1.1 x 10 <sup>3</sup>                       |
| 06/25/14      | 4100 block Washington St., Boston, MA 02131    | 42°17'19.00"N 71°07'31.98"W | 2.1 x 10 <sup>3</sup>                       |
| 06/26/14      | 100 block Northampton St., Boston, MA 02118    | 42°20'11.87"N 71°04'42.37"W | 5.0 x 10 <sup>2</sup>                       |
| 06/26/14      | 500 block Columbus Ave., Boston, MA 02118      | 42°20'24.09"N 71°04'57.09"W | 9.3 x 10 <sup>2</sup>                       |
| 07/17/14      | 0 block Mellen St., Boston, MA 02124           | 42°17'08.70"N 71°04'04.82"W | 1.4 x 10 <sup>2</sup>                       |
| 07/17/14      | 200 block Norfolk St., Boston, MA 02124        | 42°17'08.15"N 71°04'49.12"W | 3.2 x 10 <sup>2</sup>                       |
| 07/17/14      | 0 block Ashmont St., Boston, MA 02124          | 42°17'06.30"N 71°04'13.99"W | 3.8 x 10 <sup>2</sup>                       |
| 07/17/14      | 200 block Norfolk St., Boston, MA 02124        | 42°17'04.84"N 71°04'49.62"W | 1.0 x 10 <sup>3</sup>                       |
| 07/17/14      | 0 block Helena Rd., Boston, MA 02122           | 42°17'12.33"N 71°03'20.58"W | 1.9 x 10 <sup>3</sup>                       |
| 07/17/14      | 1500 block Dorchester Ave., Boston, MA 02122   | 42°17'48.77"N 71°03'40.20"W | 2.4 x 10 <sup>3</sup>                       |
| 07/18/14      | 100 block Walnut Hill Rd., Brookline, MA 02467 | 42°18'19.06"N 71°09'26.49"W | 63  |
| 07/18/14      | 0 block Littledal St., Boston, MA 02131        | 42°16'24.69"N 71°07'29.35"W | 1.1 x 10 <sup>2</sup>                       |
| 07/18/14      | 0 block Drayton Ave., Boston, MA 02125         | 42°18'45.04"N 71°04'12.38"W | 1.5 x 10 <sup>2</sup>                       |
| 07/18/14      | 0 block Bodwell St., Boston, MA 02125          | 42°18'44.84"N 71°04'10.84"W | 1.5 x 10 <sup>2</sup>                       |

| Sampling Date | Block Address                                | Lat Long                    | CH <sub>4</sub> Flux (g•day <sup>-1</sup> ) |
|---------------|--|-----------------------------|---|
| 07/21/14      | 0 block Mt. Pleasant Ave., Boston, MA 02119  | 42°19'36.76"N 71°04'46.30"W | 0.0   |
| 07/21/14      | 100 block South St., Brookline, MA 02467     | 42°18'09.26"N 71°09'08.35"W | 2.6 x 10 <sup>2</sup>                       |
| 07/21/14      | 0 block Gannett St., Boston, MA 02121        | 42°18'51.70"N 71°04'52.94"W | 4.3 x 10 <sup>2</sup>                       |
| 07/21/14      | 4300 block Washington St., Boston, MA 02131  | 42°17'04.28"N 71°07'50.28"W | 6.6 x 10 <sup>2</sup>                       |
| 07/21/14      | 400 block Hyde Park Ave., Boston, MA 02131   | 42°17'12.23"N 71°07'07.29"W | 1.0 x 10 <sup>3</sup>                       |
| 07/22/14      | 0 block Upland Rd., Brookline, MA 02445      | 42°19'44.74"N 71°07'11.25"W | 30  |
| 07/22/14      | 100 block Babcock St., Brookline, MA 02446   | 42°20'58.20"N 71°07'15.32"W | 3.0 x 10 <sup>2</sup>                       |
| 07/22/14      | 100 block Mason Ter., Brookline, MA 02446    | 42°20'33.94"N 71°07'44.58"W | 8.7 x 10 <sup>2</sup>                       |
| 07/23/14      | 0 block Empire St., Boston, MA 02134         | 42°21'30.99"N 71°07'34.47"W | 72  |
| 07/23/14      | 0 block Abby Rd., Boston, MA 02135           | 42°21'41.11"N 71°08'30.22"W | 1.9 x 10 <sup>2</sup>                       |
| 07/23/14      | 0 block Mapleton St., Boston, MA 02135       | 42°21'07.73"N 71°08'58.64"W | 5.5 x 10 <sup>2</sup>                       |
| 07/24/14      | 100 block Columbia St., Brookline, MA 02446  | 42°20'47.04"N 71°08'01.51"W | 34  |
| 07/24/14      | 100 block Stedman St., Brookline, MA 02446   | 42°20'51.27"N 71°07'21.02"W | 1.5 x 10 <sup>2</sup>                       |
| 07/24/14      | 100 block Brainerd Rd., Boston, MA 02134     | 42°20'46.32"N 71°08'05.76"W | 3.1 x 10 <sup>3</sup>                       |
| 07/25/14      | 200 block Harrison Ave., Boston, MA 02111    | 42°20'51.37"N 71°03'45.72"W | 2.6 x 10 <sup>2</sup>                       |
| 07/25/14      | 0 block Harrison Ave., Boston, MA 02111      | 42°21'08.34"N 71°03'39.67"W | 9.1 x 10 <sup>2</sup>                       |
| 07/29/14      | 0 block Eliot St., Brookline, MA 02467       | 42°19'37.31"N 71°08'40.36"W | 5.0   |
| 07/29/14      | 0 block Eliot St., Brookline, MA 02467       | 42°19'37.68"N 71°08'40.47"W | 7.1 x 10 <sup>2</sup>                       |
| 07/29/14      | 0 block Eliot St., Brookline, MA 02467       | 42°19'37.42"N 71°08'39.13"W | 8.8 x 10 <sup>2</sup>                       |
| 07/29/14      | 0 block Gray Cliff Rd., Newton, MA 02459     | 42°19'57.52"N 71°11'14.25"W | 3.6 x 10 <sup>3</sup>                       |
| 07/30/14      | 0 block Castleton St., Boston, MA 02130      | 42°19'24.08"N 71°06'52.94"W | 75  |
| 07/30/14      | 200 block Jamaicaaway, Boston, MA 02130      | 42°19'25.92"N 71°06'52.94"W | 1.1 x 10 <sup>2</sup>                       |
| 07/30/14      | 0 block Lochstead Ave., Boston, MA 02130     | 42°19'04.36"N 71°06'54.26"W | 4.3 x 10 <sup>2</sup>                       |
| 07/30/14      | 600 block Centre St., Boston, MA 02130       | 42°18'52.29"N 71°06'50.00"W | 2.2 x 10 <sup>3</sup>                       |
| 07/31/14      | 1900 block Dorchester Ave., Boston, MA 02124 | 42°17'01.09"N 71°03'53.83"W | 90  |

| <b>Sampling Date</b> | <b>Block Address</b>                         | <b>Lat Long</b>             | <b>CH<sub>4</sub> Flux (g•day<sup>-1</sup>)</b> |
|----------------------|--|-----------------------------|---|
| 07/31/14             | 100 block Stoughton St., Boston, MA 02125    | 42°18'53.88"N 71°03'37.89"W | 2.1 x 10 <sup>2</sup>                           |
| 07/31/14             | 1900 block Dorchester Ave., Boston, MA 02124 | 42°17'00.00"N 71°03'53.54"W | 3.2 x 10 <sup>2</sup>                           |
| 08/19/14             | 200 block Beacon St., Boston, MA 02116       | 42°21'12.65"N 71°04'46.66"W | 6.2 x 10 <sup>2</sup>                           |
| 08/19/14             | 200 block Beacon St., Boston, MA 02116       | 42°21'13.18"N 71°04'48.70"W | 1.0 x 10 <sup>3</sup>                           |
| 08/19/14             | 200 block Hammond St., Newton, MA 02467      | 42°19'51.61"N 71°10'12.15"W | 1.1 x 10 <sup>3</sup>                           |
| 08/19/14             | 100 block Tappan St., Brookline, MA 02445    | 42°20'01.30"N 71°08'03.17"W | 1.6 x 10 <sup>3</sup>                           |
| 08/20/14             | 0 block Stanton Rd., Brookline, MA 02445     | 42°20'02.73"N 71°07'29.91"W | 97  |
| 08/20/14             | 300 block Walnut St., Brookline, MA 02445    | 42°19'38.11"N 71°07'50.04"W | 3.3 x 10 <sup>2</sup>                           |
| 08/20/14             | 0 block Welland Rd., Brookline, MA 02445     | 42°20'03.00"N 71°07'46.21"W | 3.7 x 10 <sup>2</sup>                           |
| 09/11/14             | 0 block Lanark Rd., Boston, MA 02135         | 42°20'24.19"N 71°08'45.28"W | 35  |
| 09/11/14             | 0 block Oakland Rd., Brookline, MA 02445     | 42°19'42.70"N 71°07'25.02"W | 36  |
| 09/11/14             | 0 block Channing Rd., Brookline, MA 02445    | 42°19'39.19"N 71°08'32.29"W | 45  |
| 09/11/14             | 0 Kingsboro Park, Boston, MA 02130           | 42°19'06.62"N 71°06'41.82"W | 48  |
| 09/11/14             | 100 block Dudley St., Brookline, MA 02445    | 42°19'16.56"N 71°08'14.43"W | 1.2 x 10 <sup>2</sup>                           |
| 09/12/14             | 0 block Kilsyth Rd., Boston, MA 02135        | 42°20'26.27"N 71°08'43.79"W | 1.0 x 10 <sup>2</sup>                           |
| 09/12/14             | 100 block Kilsyth Rd., Boston, MA 02135      | 42°20'19.67"N 71°08'47.42"W | 3.1 x 10 <sup>2</sup>                           |
| 09/12/14             | 0 block Windsor Rd., Brookline, MA 02445     | 42°20'22.27"N 71°08'37.39"W | 7.5 x 10 <sup>2</sup>                           |



### *Leak Characterization*

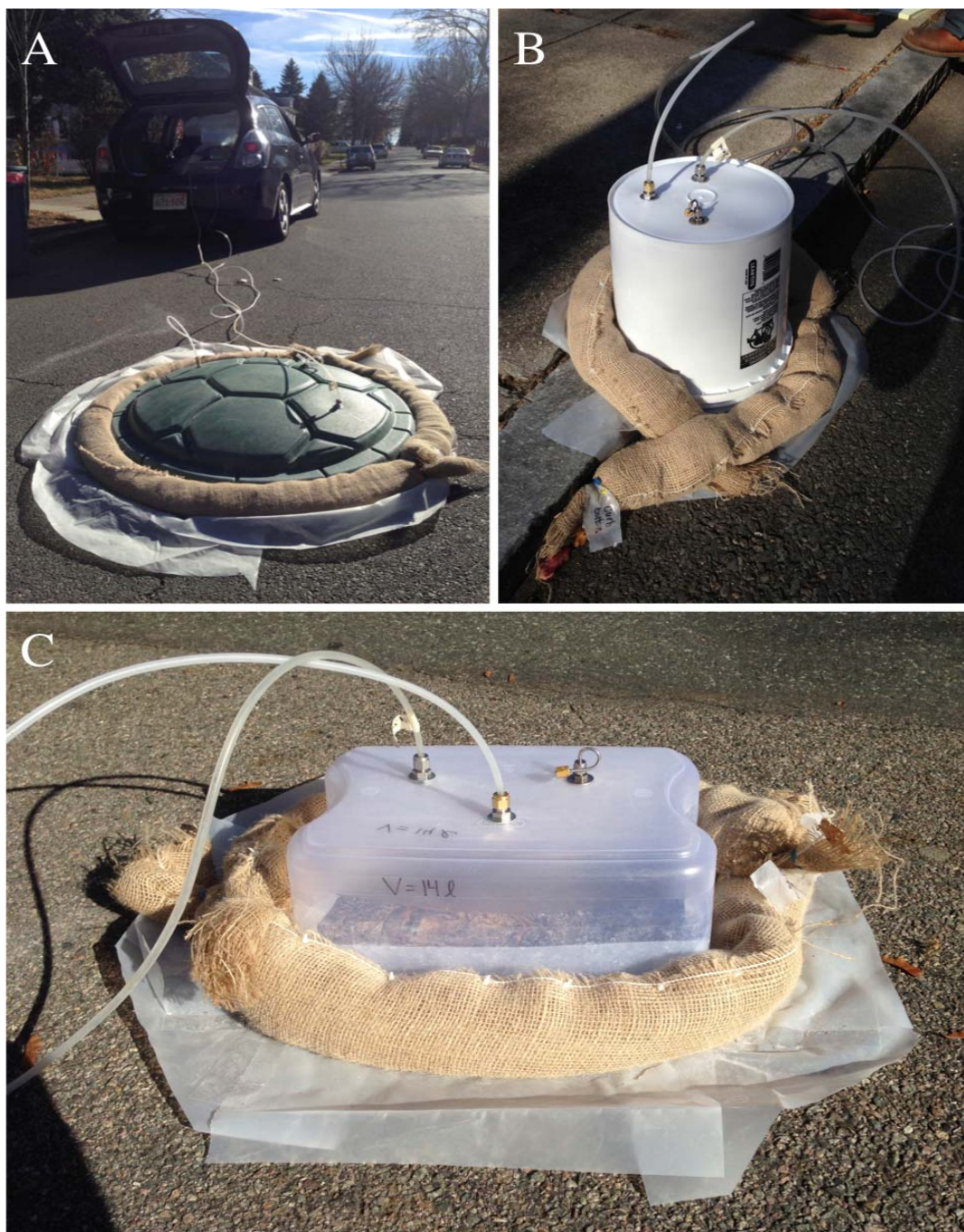
There are currently no universal criteria for determining what constitutes an individual natural gas leak. For our survey, we defined a leak as 1) at least 3.7 m (12 ft) in distance from adjacent leaks emanating from the same distribution main; 2) spatially distinct from leaks in parallel distribution mains; 3) spatially distinct from leaks in associated service lines; and 4) attributable to natural gas due to a recognizable odor of mercaptan. Leaks in cast iron distribution infrastructure arise primarily from corrosion or cracking at the joints, which attach 3.7 m segments of pipe (PHMSA). Leaks in the pipe itself are less common. Applying a horizontal 3.7 m buffer reduces the risk of double counting leaks on the same distribution main. We avoided double counting leaks from parallel distribution mains running under the same street by excluding leaks that we could not confidently assign to one pipe or the other. Natural gas leaks also arise from service lines, which are commonly composed of plastic, steel, or copper. As service lines attach directly to the distribution main, we similarly excluded leaks that we could not confidently assign to either the distribution main or the service line.

At each sampling site, we determined the extent of the leak, identified all gas escape points, diagrammed the sampling site, took CH<sub>4</sub> chamber measurements at each gas escape point, measured [CH<sub>4</sub>] in soil and utility access points, and assessed vegetation damage. Natural gas is lighter than air and migrates upward and away from the leak origin. As distribution pipes are often buried under impervious surfaces such as roads and sidewalks, leaked natural gas migrates underground along paths of least resistance for escape. Urban escape points include manholes, utility access points,

roadway or sidewalk cracks, curbs, tree wells, urban lawns, and roadway drill holes. We used a flame ionization unit (FIU; Dafarol A500 Flame Ionization Unit, Dafarol Inc., Hopedale, MA) to determine the spatial extent of each leak and the location of individual gas escape points within a sampling site. We checked the calibration on the FIU daily using 50 ppm CH<sub>4</sub> test gas (Balance: air; Spec Air Specialty Gases, Auburn, ME; reported precision  $\pm 5\%$ ). We diagrammed each sampling site to include dig safe markings, permanent landmarks such as fire hydrants and utility poles, road features including asphalt patches, manholes, utility access points, drill holes, storm water drains, and sidewalks, gas escape points, urban trees, vegetation, and bare soil.

After taking CH<sub>4</sub> chamber measurements at all natural gas escape points within a sampling site, we measured [CH<sub>4</sub>] in soil and utility access points and assessed vegetation damage caused by prolonged natural gas exposure. We took soil gas readings at every location where we had made a chamber measurement, from both bare soil and soil overlaid by impervious surface. We used a 'bang bar' to create a ~ 0.6 cm wide hole to a depth no greater than 15 cm (6 in) to accommodate a combustible gas indicator (CGI; Gas Sentry®, model CGI-201, Bascom-Turner Instruments, Inc., Norwood, MA ) probe. The CGI was calibrated every 30 days with 2.5% CH<sub>4</sub> test gas (MC-105 Methane & CO Calibration Gas; Bascom-Turner Instruments, Inc., Norwood, MA; reported precision  $\pm 2\%$ ). After inserting the CGI probe into the bang-bar hole, we allowed the reading to stabilize before recording. Because the bang bar disturbs the soil profile and disrupts the soil-atmosphere flux gradient, we only assessed soil gas concentrations following chamber measurements. We also measured [CH<sub>4</sub>] in voids under manholes, gas and water

valve boxes, electrical access points, and storm water drains. Following CGI readings, we noted all dieback, canopy damage, *Ganoderma sp.* colonization, and stunted growth patterns present in vegetation established at the sampling site. Discolored and dead vegetation, fungal growth, and heavy insect activity are bio-indicators employed by utility providers to identify proximate natural gas leakage (PHMSA, 2002).



**Figure A2.** Chambers quantify  $\text{CH}_4$  flux at leak sites in heterogeneous urban environments; A) the Turtle Chamber (55.6 L) captures emissions escaping from manholes and large cracks and seams in asphalt, B) the Curb\_1 chamber (16.1 L) and Curb\_2 chamber (17.2 L) capture emissions escaping from the seams in paver stones along road curbs, and C) the Tupp chamber (14.0 L) captures emissions escaping from utility access boxes and drill holes

## Chamber Measurements

We used a chamber-based method to measure CH<sub>4</sub> efflux from gas leaks. We designed chambers of varying shapes and volumes to accommodate manholes, utility access structures, curbs, soil, and cracks in asphalt and cement. We used four chambers during our field campaign, all crafted from everyday objects (Figure A2, Table A2). We equipped our chambers with plastic skirts, which were weighted down with gravel-filled burlap tubes to create a seal with the sampling surface. We placed battery-operated fans inside each chamber to ensure that the chamber air was well-mixed during sampling. The three smaller chambers (14.0, 16.1, 17.2 L) were each equipped with two Hand-Held Avon Sun Mini Sport Fans (UPC 0610373878368). We utilized one O2 Cool Flexi Clip Fan (UPC 0755247111131) in the largest chamber (55.6 L). We drilled three, one cm-wide vent holes at the top of each chamber. Two of these vent holes were fitted with Swageloks to facilitate gas sampling from the chamber headspace via ¼ in plastic tubing. We fit the third vent hole with a ‘pigtail’ extension to reduce pressure anomalies resulting from wind turbulence (Bain et al., 2005). We designed our chambers to accommodate two sampling techniques; a closed dynamic chamber method and a modified closed dynamic chamber method. Despite differences in chamber methodology, the size distribution of flux measurements is skewed regardless of sampling technique (Pearson’s coefficient of skewness for flux data collected using a closed dynamic chamber method = 9.1; Pearson’s coefficient of skewness for flux data collected using a modified closed dynamic chamber method = 12.5).

**Table A2.** We designed our CH<sub>4</sub> flux chambers from everyday objects in order to accommodate the heterogeneous urban landscape. The volume, product name, manufacturer, and Universal Product Code (UPC) are listed for each chamber. We removed the Latch Box lid to create the Tupp chamber, keeping the original structure intact. We modified two five-gallon buckets to create the Curb\_1 and Curb\_2 chambers, which fit over high and low profile street curbs, respectively. We used the lid of a Turtle Sandbox to create our Turtle Shell chamber.

| Chamber      | Volume (L) | Product Name   | Manufacturer  | UPC           |
|--------------|------------|----------------|---------------|---------------|
| Tupp         | 14.0       | Latch Box      | Sterilite®    | 0073149188489 |
| Curb_1       | 16.1       | Plastic Pail   | Ace®          | 0082901088363 |
| Curb_2       | 17.2       | Plastic Pail   | Ace®          | 0082901088363 |
| Turtle Shell | 55.6       | Turtle Sandbox | Little Tikes® | 0050743483097 |

#### *Closed Dynamic Chamber Method*

We utilized a closed dynamic chamber method (Bain et al., 2005), or flow-through non-steady-state (FT-NSS) chamber approach, for quantifying CH<sub>4</sub> emissions from relatively low flux gas escape points (where flux was  $\leq 96$  g CH<sub>4</sub>·day<sup>-1</sup>, with the exception of five chamber measurements). Of 535 individual chamber measurements made over the course of this study, 26% employed a closed dynamic chamber methodology (capturing 11% of all CH<sub>4</sub> emissions sampled). For these measurements, we used a Picarro G2301 Cavity Ring-Down Spectrometer (Picarro, Inc, Santa Clara, CA) to collect CH<sub>4</sub> flux data. As this analyzer resolves [CH<sub>4</sub>] the nearest parts per billion and has an upper [CH<sub>4</sub>] limit of ~40 ppm, it is particularly well suited for quantifying CH<sub>4</sub> emissions from relatively low flux gas escape points. We checked the calibration on the mobile Picarro G2301 Cavity Ring-Down Spectrometer (Picarro, Inc., Santa Clara, CA)

with 0 and 5 ppm CH<sub>4</sub> test gas (Balance: air; Spec Air Specialty Gases, Auburn, ME; reported precision ±10%) periodically throughout our sampling campaign.

Our closed dynamic chamber methodology requires three vent holes: one vent attached to the gas analyzer intake line, a second vent attached to the analyzer exhaust line, and a third vent equipped with a “pigtail” extension, which is aimed at reducing pressure anomalies resulting from wind turbulence (Bain et al., 2005). We equipped the three vent holes at the top of each chamber with Swagelok tube fittings. The intake line removes sample gas from the chamber (via ¼ in diameter plastic tubing) runs it through the analyzer, and then returns the intact sample gas back to the chamber through the exhaust valve (via ¼ in plastic tubing). In this way, [CH<sub>4</sub>] increases in the chamber headspace over time. We took three-minute chamber measurements as the Picarro G2301 Cavity Ring-Down Spectrometer recorded [CH<sub>4</sub>] (ppm) in the chamber headspace at one sec intervals. We took one chamber measurement per gas escape point. We purged each chamber by fully ventilating before every chamber measurement into clean upwind air to remove any gas residue from previous measurements. Similarly, before each and every chamber measurement we verified that the Picarro G2301 Cavity Ring-Down Spectrometer was sampling at or near ambient [CH<sub>4</sub>].

We fit a simple linear regression to plotted chamber data and used the slope of this line (ppm CH<sub>4</sub>•sec<sup>-1</sup>) to approximate the natural gas leakage rate, or CH<sub>4</sub> flux, at a particular gas escape point. Of these closed dynamic chamber measurements, the average R<sup>2</sup> for the goodness of fit for our simple linear regression was 0.9, and 96% of

measurements had an  $R^2 > 0.7$ . We calculated  $\text{CH}_4$  flux in  $\text{ft}^3 \text{CH}_4 \cdot \text{day}^{-1}$  ( $F_p$ ) using the following equation (equation A.1).

$$F_p = S_p \cdot (0.0001 \% \cdot \text{ppm}^{-1}) \cdot (60 \text{ sec} \cdot \text{min}^{-1}) \cdot (60 \text{ min} \cdot \text{hr}^{-1}) \cdot (24 \text{ hr} \cdot \text{day}^{-1}) \cdot (0.01 \%^{-1}) \cdot V \cdot (0.035 \text{ ft}^3 \cdot \text{L}^{-1})$$

(A.1)

Where  $S_p$  is the slope of the line fit to chamber data ( $\text{ppm CH}_4 \cdot \text{sec}^{-1}$ ) and  $V$  is the chamber volume (L). We summed flux from each chamber measurement taken within a sampling site to determine the total  $\text{CH}_4$  flux at that sampling site. We then converted volumes of  $\text{CH}_4$  to masses of  $\text{CH}_4$ , giving  $1 \text{ ft}^3 \text{CH}_4 = 19.26 \text{ g CH}_4$  ([www3.epa.gov/cmop/resources/converter.html](http://www3.epa.gov/cmop/resources/converter.html)).

#### *Modified Closed Dynamic Chamber Method*

We utilized a modified closed dynamic chamber method for quantifying  $\text{CH}_4$  emissions from relatively high flux gas escape points (where flux was  $\leq 1.6 \times 10^4 \text{ g CH}_4 \cdot \text{day}^{-1}$ ). Of 535 individual chamber measurements made over the course of this study, 74% employed a modified closed dynamic chamber methodology (capturing 89% of all  $\text{CH}_4$  emissions sampled). For these measurements, we used a CGI to collect  $\text{CH}_4$  flux data. This analyzer is less precise than the Picarro G2301 Cavity Ring-Down Spectrometer, but it is capable of measuring up to 100%  $\text{CH}_4$  gas. The CGI collects [ $\text{CH}_4$ ] data at 0.01% gas intervals (100 ppm), making it particularly well suited for quantifying  $\text{CH}_4$  emissions from relatively high flux gas escape points.

We refer to this sampling technique as ‘modified’ because it most closely approximates a closed dynamic chamber approach despite the fact that sample gas is not re-circulated through the chamber and analyzer. Our modified closed dynamic chamber methodology requires that one vent is attached to the gas analyzer intake probe, a second vent is sealed closed, and a third vent is equipped with a “pigtail” extension. The intake probe removes sample gas from the chamber (plastic probe is  $\frac{1}{4}$  in diameter) and runs it through the analyzer. The CGI does not preserve sample gas upon analysis, and therefore it is not subsequently returned to the chamber. While the CGI pump removes sample gas from the chamber at a rate of  $0.5\text{-}0.6\text{ L}\cdot\text{min}^{-1}$ , the pigtail extension normalizes any pressure changes within the chamber that could induce mass flow of sample air. We took three-minute chamber measurements and recorded CGI measurements of  $[\text{CH}_4]$  (%) in the chamber headspace at 30-sec intervals. We took one chamber measurement per gas escape point. We purged each chamber by fully ventilating before every chamber measurement into clean upwind air to remove any gas residue from previous measurements. Similarly, before each and every chamber measurement we verified that the CGI was sampling at or near ambient  $[\text{CH}_4]$ .

We fit a simple linear regression to plotted chamber data and used the slope of this line ( $\% \text{CH}_4\cdot\text{sec}^{-1}$ ) to approximate  $\text{CH}_4$  flux at gas escape points. We set the y-intercept at zero when curve fitting for this set of analyses. Unlike the Picarro chamber data, which generate a relatively smooth line at one sec intervals, the CGI data is coarser at 30 sec intervals and an anchored y-intercept improves curve fitting. Of the modified closed dynamic chamber measurements, the average  $R^2$  for the goodness of fit for our

simple linear regression was 0.9, and 89% of measurements had an  $R^2 > 0.7$ . We developed the following equation to correct for sample gas removed by the analyzer pump, which is applied after curve fitting (equation A.2).

$$S_{CGI \text{ Corrected}} = (S_{CGI} \cdot ((R \cdot T) / V)) + S_{CGI} \quad (\text{A.2})$$

Where  $S_{CGI}$  is the slope of the line fit to chamber data ( $\% \text{ CH}_4 \cdot \text{sec}^{-1}$ ),  $R$  is the CGI sample gas removal rate ( $0.0092 \text{ L} \cdot \text{sec}^{-1}$ ),  $T$  is the total sampling time (sec), and  $V$  is the chamber volume (L). This correction factor allowed us to mimic the closed dynamic chamber approach by accounting for all sample gas that would have accumulated in the chamber headspace during the three minute sampling event. We calculated  $\text{CH}_4$  flux in  $\text{ft}^3 \text{ CH}_4 \cdot \text{day}^{-1}$  ( $F_{CGI}$ ) using the following equation (equation A.3).

$$F_{CGI} = S_{CGI \text{ Corrected}} \cdot (60 \text{ sec} \cdot \text{min}^{-1}) \cdot (60 \text{ min} \cdot \text{hr}^{-1}) \cdot (24 \text{ hr} \cdot \text{day}^{-1}) \cdot (0.01 \text{ \%}^{-1}) \cdot V \cdot (0.035 \text{ ft}^3 \cdot \text{L}^{-1}) \quad (\text{A.3})$$

We summed flux from each chamber measurement taken within a sampling site to determine the total  $\text{CH}_4$  flux at that sampling site. We then converted volumes of  $\text{CH}_4$  to masses of  $\text{CH}_4$ , giving  $1 \text{ ft}^3 \text{ CH}_4 = 19.26 \text{ g CH}_4$  ([www3.epa.gov/cmop/resources/converter.html](http://www3.epa.gov/cmop/resources/converter.html)).

### *Chamber Quality Control Testing*

We measured the emission capture rate for each chamber by performing controlled releases of natural gas in a fume hood. We used a variable area flow meter

(flow range of 0.2 – 2.5 SCFH of air, 1.3 conversion factor applied for natural gas; Key Instruments, now Brooks Instrument) to measure the flow rate of natural gas during the controlled release. Natural gas was released from ¼ in tubing affixed to the work surface of the fume hood. Flux chambers were placed over the tubing and measurement proceeded in the same manner as in the field. We measured the capture rate for each chamber over a minimum of three trials using our modified closed dynamic chamber methodology (Table A3). We derived a correction scalar based on the mean capture rate for each chamber and applied them to all of our field flux measurements.

**Table A3.** Results of chamber quality control tests using our modified closed dynamic chamber methodology to capture controlled releases of natural gas within a fume hood (SD = standard deviation; AF = adjusted flux; MF = measured flux following adjustments as in equation A.3). Chamber specific correction scalars were applied to all field flux measurements.

| Chamber      | Chamber Volume (L) | Mean Emissions Captured (%) | Tests | SD  | Correction Scalar    |
|--------------|--------------------|-----------------------------|-------|-----|----------------------|
| Tupp         | 14.0               | 93.7                        | 3     | 8.2 | AF = (100 x MF)/93.7 |
| Curb_1       | 16.1               | 92.6                        | 3     | 6.7 | AF = (100 x MF)/92.6 |
| Curb_2       | 17.2               | 86.9                        | 3     | 4.0 | AF = (100 x MF)/86.9 |
| Turtle Shell | 55.6               | 105                         | 5     | 10  | AF = (100 x MF)/105  |

Fume hood measurements differ from field measurements on several fronts. The sampling surface within the fume hood is smooth and lacks the rugosity and/or substrate heterogeneity of sampling surfaces in the field. While the edges of the chamber may make more contact with the sampling surface in the fume hood as compared to a sampling surface in the field, we designed our flux chambers with large and flexible

plastic skirts in order to create a tight seal with any sampling surface. We performed the same sampling procedure in the fume hood as in the field, including weighting down the plastic skirts of each chamber with gravel-filled burlap tubes to seal the chamber during sampling events. We designed our chambers to be adaptable to any sampling surface, smooth or rough and variable, and in this way we minimize the error introduced by breaks in the seal with the sampling surface.

Fume hood measurements also differ from field measurements in terms of wind. The fume hood is ventilated, causing movement in the air surrounding the chambers, but the directionality and speed of the wind experienced in the field is not replicated. There are days in the field where wind is absent, however, so some variability is expected. Again, we designed our flux chambers to function properly in a variety of environments and in a variety of conditions. The chamber skirts and weights, as well as the Swagelok-fitted vent holes located at the top of each chamber, minimize the effects of wind.

### **Leak Size Distribution**

In order to determine the best-fit distribution to describe leak size ( $\text{g CH}_4 \cdot \text{day}^{-1}$ ), we excluded all resampled summer leaks ( $n = 13$ ) and one Grade 1 leak with a flux of zero  $\text{g CH}_4 \cdot \text{day}^{-1}$ . A Kolmogorov-Smirnov test revealed that the best-fit distributions to model the remaining 99 leaks are the Weibull (3) distribution ( $p = 0.87$ ), the Weibull (2) distribution ( $p = 0.82$ ), and the log-normal distribution ( $p = 0.56$ ). We employ a log-normal distribution to describe leak data for the purposes of this study. Leak size data remain skewed even when superemitter leaks are excluded (Fig. 1). Further, leak size

data remain skewed even when leaks sampled over mains operating at pressures greater than 0.5 PSIG are excluded ( $\mu = 5.4$ ,  $\sigma = 1.8$ , log-normal mean =  $1.0 \times 10^3$  g CH<sub>4</sub>•day<sup>-1</sup>, n = 92, Pearson's coefficient of skewness for flux data = 8.0).

### **Leak Grading**

All of the leaks surveyed that qualified as Grade 1 (PHMSA, 2002) were reported immediately to National Grid of Massachusetts at 1-800-233-5325. Remaining leaks were not reported.

The Pipeline and Hazardous Materials Safety Administration (PHMSA) classifies natural gas leaks into three grades, Grade 1 through 3 with Grade 1 being the most dangerous (Table A4). We adopted the same classification guidelines during our leak survey. Specifically, Grade 1 leaks are defined as posing an existing or probable hazard to persons or property and require immediate repair or continuous action until the conditions are no longer hazardous (PHMSA, 2002). Examples of Grade 1 leaks include, but are not limited to, any reading of gas at 80% LEL or greater in a confined space or a non-gas related substructure, any detection of gas at the outside wall of a building, and any leak that can be seen, heard, or felt, and which is in a location that may endanger the general public or property (PHMSA, 2002; Table A4). Grade 2 leaks are defined as non-hazardous at the time of detection, yet warrant scheduled repair based on probable future hazard and require reevaluation at least once every six months until fixed (PHMSA, 2002). Examples of Grade 2 leaks include, but are not limited to, any reading of gas between 20% and 80% LEL in a confined space and any reading of gas at 40% LEL or

greater under a sidewalk in a wall-to-wall paved area that does not qualify as a Grade 1 leak (PHMSA, 2002; Table A4). Finally, Grade 3 leaks are defined as non-hazardous at the time of detection and can be reasonably expected to remain non-hazardous, only requiring reevaluation at least once every 15 months until fixed (PHMSA, 2002).

Examples of Grade 3 leaks include, but are not limited to, any reading of gas under a street in areas without wall-to-wall paving where it is unlikely the gas could migrate to the outside wall of a building and any reading of gas at less than 20% LEL in a confined space (PHMSA, 2002; Table A4).

**Table A4.** Leak classification, action criteria, and examples of Grade 1, 2, and 3 leaks as defined by the Pipeline and Hazardous Materials Safety Administration. This table is adapted with text reproduced from Table 3A, 3B, and 3C found in Chapter 4 of the Guidance Manual for Operators of Small Natural Gas Systems (PHMSA, 2002).

| <b>Leak</b> | <b>Definition</b>  | <b>Action Criteria</b>  | <b>Examples</b>  |
|-------------|--|---|--|
| Grade 1     | A leak that represents an existing or probable hazard to persons or property, and requires immediate repair or continuous action until the conditions are no longer hazardous. | Requires prompt action* to protect life and property, and continuous action until the conditions are no longer hazardous<br><br>*The prompt action in some in-stances may require one or more of the following:<br>a. Implementation of company emergency plan (§192.615).<br>b. Evacuating premises.<br>c. Blocking off an area.<br>d. Rerouting traffic.<br>e. Eliminating sources of ignition.<br>f. Venting the area.<br>g. Stopping the flow of gas by closing valves or other means.<br>h. Notifying police and fire departments. | 1. Any leak which, in the judgment of operating personnel at the scene, is regarded as an immediate hazard.<br>2. Escaping gas that has ignited.<br>3. Any indication of gas which has migrated into or under a building, or into a tunnel.<br>4. Any reading at the outside wall of a building, or where gas would likely migrate to an outside wall of a building.<br>5. Any reading of 80% LEL, or greater, in a confined space.<br>6. Any reading of 80% LEL, or greater in small substructures (other than gas associated substructures) from which gas would likely migrate to the outside wall of a building.<br>7. Any leak that can be seen, heard, or felt, and which is in a location that may endanger the general public or property. |
| Grade 2     | A leak that is recognized as being non-hazardous at the time of detection, but justifies scheduled repair based on probable future hazard.                                     | Leaks should be repaired or cleared within one calendar year, but no later than 15 months from the date the leak was reported.<br><br>Grade 2 leaks should be reevaluated at least once every six months until cleared. The frequency of reevaluation should be determined by the location and magnitude of the leakage condition.  | <i>A. Leaks Requiring Action Ahead of Ground Freezing or Other Adverse Changes in Venting Conditions.</i><br>Any leak which, under frozen or other adverse soil conditions, would likely migrate to the outside wall of a building.<br><i>B. Leaks Requiring Action Within Six Months</i><br>1. Any reading of 40% LEL, or greater, under a sidewalk in a wall-to-wall paved area that does not qualify as a Grade 1 leak.<br>2. Any reading of 100% LEL, or greater, under a street in a wall-to-wall paved area that has significant gas migration and does not qualify as a Grade 1 leak.<br>3. Any reading less than 80% LEL in small substructures (other than gas  |

|         |   |   |  |
|---------|---|---|--|
|         |   |   | <p>associated substructures) from which gas would likely migrate creating a probable future hazard.</p> <ol style="list-style-type: none"> <li>4. Any reading between 20% LEL and 80% LEL in a confined space.</li> <li>5. Any reading on a pipeline operating at 30 percent SMYS, or greater, in a class 3 or 4 location, which does not qualify as a Grade 1 leak.</li> <li>6. Any reading of 80% LEL, or greater, in gas associated sub-structures.</li> <li>7. Any leak which, in the judgment of operating personnel at the scene, is of sufficient magnitude to justify scheduled repair.</li> </ol> |
| Grade 3 | A leak that is non-hazardous at the time of detection and can be reasonably expected to remain non-hazardous. | These leaks should be reevaluated during the next scheduled survey, or within 15 months of the date reported, whichever occurs first, until the leak is regraded or no longer results in a reading. | <p>Leaks Requiring Reevaluation at Periodic Intervals</p> <ol style="list-style-type: none"> <li>1. Any reading of less than 80% LEL in small gas associated substructures.</li> <li>2. Any reading under a street in areas without wall-to-wall paving where it is unlikely the gas could migrate to the outside wall of a building.</li> <li>3. Any reading of less than 20% LEL in a confined space.</li> </ol>   |

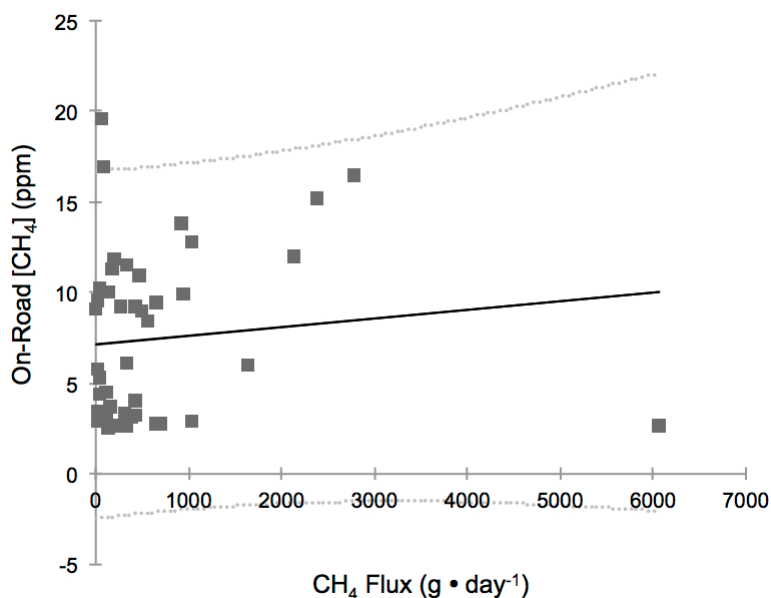
### **Pipeline Operating Pressure**

We sampled leaks over cast iron distribution mains operating at 0.5 (n = 93), 2 (n = 3), 22 (n = 3), and 60 (n = 1) pounds per square inch gage (PSIG) in order to capture a representative proportion of pipeline operating pressures across the total distribution network. The operating pressure in natural gas distribution pipes varies according to the proximity of the natural gas to a customer, pipeline diameter, and utility company operating procedures.

When natural gas is delivered from a transmission line to a local natural gas utility it passes through a 'gate station' where the pipeline operating pressure is reduced from 200 – 1,500 PSIG to 0.25 – 200 PSIG. Natural gas then moves from the gate station into the distribution mains that deliver natural gas to consumers. Natural gas distribution mains range in size from two to greater than 24 inches in diameter. Regulators control the operating pressure across the distribution network in order to ensure that customers receive natural gas at sufficient flow rates and pressure. Generally speaking, the closer the natural gas is to a customer and the narrower the distribution pipeline, the lower the operating pressure. There is also a legacy effect of consolidation of town gas companies, each of which operate according to their own operating pressures with household meters that are matched to those pressures. Therefore, old cities like Boston, MA now comprise a patchwork of different operating pressures that are not easily changed due to this legacy effect, because to equalize the operating pressures across the service area would necessitate changing a great many home meters and pressure regulators.

### On-Road Driving Surveys vs. Flux Measurements

To determine if there is a correlation between on-road  $[\text{CH}_4]$  measured during driving surveys and  $\text{CH}_4$  flux measured at co-located natural gas leaks, we ran a linear regression to compare the atmospheric  $[\text{CH}_4]$  (ppm) measured at 45 gas leaks sampled in a driving survey in 2011 (Phillips et al., 2013) with  $\text{CH}_4$  flux ( $\text{g CH}_4 \cdot \text{day}^{-1}$ ) measurements taken at the same locations in 2012, 2013, or 2014 (seven, four, and 34 leaks respectively; Figure A3). We found that  $\text{CH}_4$  flux from gas leaks does not explain variability in on-road atmospheric  $[\text{CH}_4]$  sampled at the same locations ( $R^2 = 0.01$ ,  $p = 0.48$ ).



**Figure A3.** Methane flux from gas leaks does not explain variability in on-road atmospheric  $[\text{CH}_4]$  sampled at the same locations. The black line ( $R^2 = 0.01$ ,  $p = 0.48$ ) represents the regression across 45 gas leaks that were sampled in a driving survey in 2011 (Phillips et al., 2013), and also with flux chambers in 2012, 2013, or 2014 (seven, four, and 34 leaks respectively). Grey squares represent plotted residuals and the dashed grey lines are 95% confidence intervals

## APPENDIX B

### Unleakable Carbon Quantitative Analysis

#### KNOWN:

Total recoverable gas reserves (McGlade & Ekins, 2015) = 359 Gt CO<sub>2</sub>

50% of recoverable gas reserves\* = 179.5 GtCO<sub>2</sub>

Low gas leakage rate for North America (Brandt et al., 2014) = 1.8%

High gas leakage rate for North America (Brandt et al., 2014) = 5.4%

Global warming potential of CH<sub>4</sub> evaluated over a 100 year time horizon (IPCC AR5, 2013) = 34

Global warming potential of CH<sub>4</sub> evaluated over a 20 year time horizon (IPCC AR5, 2013) = 86

\* The utilizable portion of recoverable gas reserves (2010 to 2050) that will allow us to meet a warming target of 2 °C (McGlade & Ekins, 2015)

#### CALCULATIONS: Table B1

*low leakage scenario (1.8%)*

$$(179.5 \text{ Gt CO}_2) \times 0.018 = 3.231 \text{ Gt CO}_2$$

→ mass of utilizable gas reserves lost in a low leakage scenario

$$(179.5 \text{ Gt CO}_2) - (3.231 \text{ Gt CO}_2) = 176.269 \text{ Gt CO}_2$$

→ mass of utilizable gas reserves minus mass of utilizable gas reserves lost in a low leakage scenario

$$3.231 \text{ Gt CO}_2 \times 34 = 109.854 \text{ Gt CO}_2$$

→ mass of utilizable gas reserves lost in a low leakage scenario evaluated using a GWP of 34 over a 100 year time horizon

$$3.231 \text{ Gt CO}_2 \times 86 = 277.866 \text{ Gt CO}_2$$

→ mass of utilizable gas reserves lost in a low leakage scenario evaluated using a GWP of 86 over a 20 year time horizon

$$(176.269 \text{ Gt CO}_2) + (109.854 \text{ Gt CO}_2) = 286.123 \text{ Gt CO}_2 \rightarrow \text{see Table B1}$$

$$(176.269 \text{ Gt CO}_2) + (277.866 \text{ Gt CO}_2) = 454.135 \text{ Gt CO}_2 \rightarrow \text{see Table B1}$$

*high leakage scenario (5.4%)*

$$(179.5 \text{ Gt CO}_2) \times 0.054 = 9.693 \text{ Gt CO}_2$$

→ mass of utilizable gas reserves lost in a high leakage scenario

$$(179.5 \text{ Gt CO}_2) - (9.693 \text{ Gt CO}_2) = 169.807 \text{ Gt CO}_2$$

→ mass of utilizable gas reserves minus mass of utilizable gas reserves lost in a high leakage scenario

$$9.693 \text{ Gt CO}_2 \times 34 = 329.562 \text{ Gt CO}_2$$

→ mass of utilizable gas reserves lost in a high leakage scenario evaluated using a GWP of 34 over a 100 year time horizon

$$9.693 \text{ Gt CO}_2 \times 86 = 833.598 \text{ Gt CO}_2$$

→ mass of utilizable gas reserves lost in a high leakage scenario evaluated using a GWP of 86 over a 20 year time horizon

$$(169.807 \text{ Gt CO}_2) + (329.562 \text{ Gt CO}_2) = 499.369 \text{ Gt CO}_2 \rightarrow \text{see Table B1}$$

$$(169.807 \text{ Gt CO}_2) + (833.598 \text{ Gt CO}_2) = 1003.405 \text{ Gt CO}_2 \rightarrow \text{see Table B1}$$

**Table B1.** When the mass of utilizable gas reserves is adjusted to reflect current estimates of CH<sub>4</sub> leakage, the mass of CO<sub>2e</sub> emissions for adjusted utilizable gas reserves far exceeds the allowable 179.5 Gt CO<sub>2</sub> from 2010 to 2050 to keep warming below 2 °C. Adjusted utilizable gas reserves are; the mass of utilizable gas reserves (50% of total recoverable gas reserves (McGlade & Ekins, 2015), or 179.5 Gt CO<sub>2</sub>), minus the mass of utilizable gas reserves lost in low and high leakage scenarios (Brandt et al., 2014), plus the mass of utilizable gas reserves lost in low and high leakage scenarios evaluated using two global warming potential values for CH<sub>4</sub> over two time horizons (IPCC AR%, 2013).

| GWP | Time horizon (years) | 1.8% Leakage rate        |                           | 5.4% Leakage rate |      |
|-----|----------------------|--------------------------|---------------------------|-------------------|------|
|     |                      | Low                      | High                      | Low               | High |
| 34  | 100                  | 286.1 Gt CO <sub>2</sub> | 499.4 Gt CO <sub>2</sub>  |                   |      |
| 86  | 200                  | 454.1 Gt CO <sub>2</sub> | 1003.4 Gt CO <sub>2</sub> |                   |      |

CALCULATIONS: Table 4.1

The percentage of natural gas reserves, including unleakable and unburnable CH<sub>4</sub> (using values of adjusted utilizable gas reserves; see Table B1), that must remain underground if we are to meet a warming target of 2 °C from 2010-2050. These percentages contrast with a recent analysis (McGlade & Ekins, 2015) that claims we may utilize up to 50% of our remaining reserves and still meet our mitigation goal.

*low leakage scenario (1.8%), evaluated over a 100 year time horizon (GWP is 34)*

$$(286.1 \text{ Gt CO}_2) / (359 \text{ Gt CO}_2) = 80\%$$

*low leakage scenario (1.8%), evaluated over a 20 year time horizon (GWP is 86)*

$$(454.1 \text{ Gt CO}_2) / (359 \text{ Gt CO}_2) = 127\%$$

*high leakage scenario (5.4%), evaluated over a 100 year time horizon (GWP is 34)*

$$(499.4 \text{ Gt CO}_2) / (359 \text{ Gt CO}_2) = 139\%$$

*high leakage scenario (5.4%), evaluated over a 20 year time horizon (GWP is 86)*

$$(1003.4 \text{ Gt CO}_2) / (359 \text{ Gt CO}_2) = 280\%$$

### **Unburnable Carbon Qualitative Analysis**

SEARCH ON GOOGLE SCHOLAR: Figure 4.1, Table B2

Term = 'unburnable carbon' (no citations, no patents, articles only)

Criteria\* = 'unburnable' carbon, reserves, coal/ oil/ natural gas, fossil fuels, fuels, within text

\*If the criteria are only met within the reference, citation, or bibliography sections, the source is not counted.

As of December 26, 2015 Google Scholar search with above criteria yields:

pages: 38

results: 381

legitimate sources: 165

**Table B2.** The number of publications per year that contain the term(s) ‘unburnable’ carbon, ‘unburnable’ reserves, or ‘unburnable’ coal/ oil/ natural gas recovered during a Google Scholar search for the term “unburnable carbon” (total = all publications per year; gray = reports, dissertations or theses, conference abstracts or papers, non-peer reviewed journals; peer review = publications in peer reviewed journals; other = blogs, non-peer reviewed advocacy journals, select online or print newspaper articles, divestment materials; books = published books). As of December 2015, Google Scholar yields 165 publications that utilize the concept of unburnable carbon within the body of their text since the term was first coined by the Carbon Tracker Initiative in 2011.

| <b>Year</b> | <b>Total</b> | <b>Gray</b> | <b>Peer Review</b> | <b>Other</b> | <b>Book</b> |
|-------------|--------------|-------------|--------------------|--------------|-------------|
| 2011        | 1            | 1           | 0                  | 0            | 0           |
| 2012        | 2            | 1           | 0                  | 1            | 0           |
| 2013        | 33           | 15          | 8                  | 7            | 3           |
| 2014        | 53           | 26          | 12                 | 9            | 6           |
| 2015        | 74           | 33          | 15                 | 14           | 12          |
| 2016        | 2            | 0           | 2                  | 0            | 0           |

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## MARGARET F. HENDRICK

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**SUMMARY:** Current Ph.D. Candidate investigating the environmental and public policy ramifications of investment in and consumption of natural gas fuels. Five years experience communicating results to diverse stakeholders to inform greenhouse gas mitigation, energy efficiency, and infrastructure management policies. Skilled researcher and cross-sector collaborator.

**EDUCATION:** **Boston University**, Ph.D. in Geography, expected September 2016  
**University of Montana**, M.S. in Organismal Biology and Ecology, 2011  
**Reed College**, B.A. in Biology, 2008

### ENVIRONMENTAL, SUSTAINABILITY, & POLICY EXPERIENCE

**Environmental Protection Agency**, Boston, MA

September 2014 – August 2016

*Science to Achieve Results (STAR) Graduate Fellow*

- Lead researcher on a two-year, \$84,000 grant to investigate fugitive methane emissions from natural gas systems.
- Collaborate with diverse stakeholders on greenhouse gas mitigation, energy efficiency, and aging infrastructure.
- Present on current research and policy of climate change, urban ecology, and natural gas to diverse audiences.
- Research, analyze data, and write on natural gas and climate for peer-reviewed journal articles and policy papers.

**Barr Foundation and Conservation Law Foundation**, Boston, MA

September 2013 – May 2014

*Graduate Research Assistant*

- Managed a team of researchers in the design, execution, and delivery of an investigation of urban natural gas leaks.
- Measured fugitive methane emissions and surveyed leak safety across leak-prone natural gas distribution pipes.
- Communicated results to media and academic, nonprofit, private, and public sector audiences.
- Produced policy-relevant research that informs greenhouse gas mitigation, energy efficiency, and public safety.

**Frederick S. Pardee Center for the Study of the Longer-Range Future**, Boston, MA

June 2013 – September 2013

*Graduate Summer Fellow*

- Interviewed stakeholders to characterize natural gas infrastructure management in Boston, MA.
- Analyzed best practices in coordinated infrastructure management in Boston and Brookline, MA.
- Produced policy-relevant research that informs strategies for long-term infrastructure efficiency.

**Curley K-8 School**, Boston, MA

September 2012 – June 2013

*National Science Foundation Graduate STEM Fellow in K-12 Climate Education*

- Developed and piloted middle school climate change curriculum on adaptation and mitigation strategies, energy systems, and environmental justice.
- Taught 7<sup>th</sup> and 8<sup>th</sup> grade science in a Boston Public School classroom for two academic semesters.
- Collaborated on an international climate change curriculum-building project in Belize with professors, graduate students, and public school teachers from Boston, MA and Belize.

**Conservation Law Foundation**, Boston, MA

September 2011 – May 2012

*Science and Research Intern, Natural Gas*

- Researched, wrote, and consulted on a white paper aimed at reducing fugitive methane emissions in MA.

**POLICY CONSULTING & OUTREACH****City of Boston**

February 2015 – September 2015

*Greenovate Boston 2014 Climate Action Plan*

- Consulted on greenhouse gas emissions attributed to leakage across aged natural gas distribution infrastructure.
- Presented an invited policy brief regarding the impact of natural gas leaks on urban vegetation.

**Home Energy Efficiency Team (HEET)**, Cambridge, MA

March 2014 – August 2015

*Mapping Natural Gas Leaks in Cities*

- Consulted on natural gas leak mapping methodology, quantification of carbon-based emissions, and public policy.

**League of Women Voters and Westwood Environmental Action Committee**, Westwood, MA

June 2015

*Expert Panelist at the Westwood Gas Pipeline Forum*

- Communicated safety, climate, and economic ramifications of a proposed natural gas transmission pipeline (Algonquin West Roxbury Lateral via Spectra Energy) to local and state-level stakeholders.

**State of Massachusetts**

June 2014

*Bill H.4164, An Act Relative to Natural Gas Leaks*

- Consulted with the office of MA State Senator Cynthia Stone Creem on content of Bill H.4164 (signed into law by Governor Patrick on 6-26-2014).

**Clean Water Action, Boston, MA**

November 2013 – March 2014

*Public Awareness Campaign on Aged Natural Gas Distribution Infrastructure*

- Contributed content for a website produced by Conservation Law Foundation and Clean Water Action on the impacts of urban natural gas leaks.
- Lead a ‘Boston Gas Leaks Safari’ with Clean Water Action, Boston Climate Action Network, elected officials, and the public to educate stakeholders on the safety, climate, and financial challenges posed by aged natural gas distribution infrastructure.

**Union of Concerned Scientists, Cambridge, MA**

February 2014

*Invited Presentation and Discussion on Natural Gas Systems*

- Communicated current research and policy on the climate change impacts, safety risks, and infrastructure management challenges of aged natural gas systems to the Union of Concerned Scientists.

**PEER-REVIEWED PUBLICATIONS**

**Hendrick MF**, Phillips NG. Aging natural gas infrastructure in the United States: Developing a coordinated and efficient infrastructure ecosystem. *Global Environmental Change*. in preparation.

**Hendrick MF**, Ackley R, Sanaie-Movahed B, Tang X, Phillips NG. 2016. Fugitive methane emissions from leak-prone natural gas distribution infrastructure in urban environments. *Environmental Pollution*. 213:710-716. doi: 10.1016/j.envpol.2016.01.094

**Hendrick MF**, Cleveland S, Phillips NG. 2016. Unleakable Carbon. *Climate Policy*. <http://dx.doi.org/10.1080/14693062.2016.1202808>

**Hendrick MF**, Finseth FR, Mathiasson ME, Palmer KA, Broder EM, Breigenzer P, Fishman L. 2016. The genetics of extreme microgeographic adaptation: an integrated approach identifies a major gene underlying leaf trichome divergence in Yellowstone *Mimulus guttatus*. *Molecular Ecology*. accepted.

Keller TL, Zocco D, Sundrud MS, **Hendrick MF**, Edenius M, Yum J, Kim Y-J, Lee H-K, Cortese JF, Wirth DF, Dignam JD, Rao A, Yeo C-Y, Mazitschek R, Whitman M. 2012. Halofuginone and other febrifugine derivatives inhibit prolyl-tRNA synthetase. *Nature Chemical Biology*. 8:311-317. doi: 10.1038/NCHEMBIO.790

Lekberg Y, Roskilly B, **Hendrick MF**, Zabinski CA, Barr CM, Fishman L. 2012. Phenotypic and genetic differentiation among yellow monkeyflower populations from thermal and non-thermal soils in Yellowstone National Park. *Oecologia*. 170(1):111-122. doi: 10.1007/s00442-012-2297-9

## ACADEMIC PRESENTATIONS

- Hendrick MF**, Ackley R, Sanaie-Movahed B, Tang X, Phillips NG. October 2015. Fugitive methane emissions from leak-prone natural gas distribution infrastructure in urban environments. Contributed Talk. Earth and Environment Graduate Student Seminar Series. Boston University, Boston, MA.
- Hendrick MF**, Ackley R, Sanaie-Movahed B, Tang X, Phillips NG. February 2015. Characterizing the impacts of fugitive methane emissions from natural gas distribution infrastructure in urban ecosystems. Contributed Talk. Earth and Environment Graduate Student Seminar Series. Boston University, Boston, MA.
- Hendrick MF**, Ackley R, Sanaie-Movahed B, Tang X, Phillips NG. August 2014. Characterizing the impacts of fugitive methane emissions from natural gas distribution infrastructure in urban ecosystems. Contributed Talk. 99<sup>th</sup> Annual Meeting of the Ecological Society of America. Sacramento, CA.
- Brossman CA, Gopal S, Stewart N, Keser R, **Hendrick MF**, Sanders-DeMott R. April 2014. An international collaboration: US and Belize partners on science curriculum. Contributed Talk and Poster. National Conference on Science Education. Boston, MA.
- Hendrick MF**. February 2014. Natural gas and our urban ecosystem. Invited Brown Bag Lunch Lecture, Union of Concerned Scientists. Cambridge, MA.
- Hendrick MF**. April 2013. Natural gas and our urban ecosystem: Parsing the biological impacts of elevated methane on ecosystem services and identifying new avenues for sustainable management. Contributed Talk. Geography Graduate Student Seminar Series. Boston University, Boston, MA.
- Hendrick MF**, Sanders-DeMott R. February 2013. Boston University GLACIER GK-12 Project: Integrating urban ecology into the ecology curriculum of urban schools. Contributed Poster. International Teacher-Scientist Partnership Conference. Boston, MA.
- Hendrick MF**, Ackley R, Phillips NG. August 2012. Novel soil ecosystems created by natural gas leaks. Contributed Talk. 97<sup>th</sup> Annual Meeting of the Ecological Society of America. Portland, OR.
- Hendrick MF**, Ackley R, Phillips NG. May 2012. Novel soil ecosystems created by natural gas leaks. Contributed Talk. First Conference on Atmospheric Biogeosciences. Boston, MA.
- Hendrick MF**. March 2011. The ecology and genetics of divergence in Yellow Monkeyflowers (*Mimulus guttatus*). Contributed Talk. Organismal Biology and Ecology Seminar Series. University of Montana, Missoula.
- Hendrick MF**. October 2009. Abiotic and edaphic adaptation. Invited Guest Lecture, Plant Evolution (biol 484) class. University of Montana, Missoula.
- Hendrick MF**. June 2008. Characterizing serpentine tolerance in *Mimulus guttatus* (Phrymaceae). Contributed Talk. Sixth International Conference on Serpentine Ecology. Bar Harbor, ME.

## **FELLOWSHIPS, AWARDS, AND GRANTS**

- 2014-2016: EPA STAR Fellowship, EPA Grant F13F31263 (\$84,000)
- 2014: Finalist for the Switzer Environmental Fellowship
- 2013-2014: Research Assistantship, Conservation Law Foundation/ Barr Foundation (full tuition and stipend)
- 2013: Pardee Graduate Summer Fellowship (\$5,000)
- 2012-2013: National Science Foundation GK12 Fellowship (full tuition and stipend)
- 2012: Biogeosciences Travel Award (\$500)
- 2011-2012: Boston University College of Arts and Sciences Dean's Award (full tuition and stipend)
- 2008: Best Undergraduate Student Oral Presentation, Sixth International Conference on Serpentine Ecology (\$150)
- 2008: Mellon Foundation Opportunity Grant (\$750)
- 2008: Miller Family Foundation Undergraduate Research Project Grant (\$1,375)

## **PROFESSIONAL SOCIETIES, CERTIFICATES, AND GRADUATE ORGANIZATIONS**

- 2014-2015: Graduate Student Representative to the Faculty, Department of Earth and Environment, Boston University
- 2012: Advanced Graduate Certificate in Terrestrial Biogeosciences, Boston University Biogeosciences Program
- 2011-present: Boston University Biogeosciences Program
- 2011-present: Graduate Women in Science and Engineering (GWISE), Boston University

## **FIELD EXPERIENCE**

- 2011-2015: Boston, MA – urban ecology, fugitive methane emissions accounting (bottom-up), tree physiology, soil microbial ecology
- 2013: Rio Bravo Conservation and Management Area, Belize – forest ecology, carbon accounting, biometrics
- 2013: Turneffe Atoll, Belize – marine ecology, carbon accounting, habitat quality assessment
- 2009-2011: Yellowstone National Park, MT and WY – soil ecology, population and evolutionary genetics, plant physiology
- 2006: Upland prairies of the Pacific Northwest, OR through British Columbia – prairie ecology, habitat restoration

## **SKILLS**

Microsoft Office, PowerPoint, Excel; XLSTAT; JMP; social media; scientific and grant writing; environmental consulting; policy analysis; public speaking; research; climate change; energy systems; science communication; problem solving; organization.