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Mitigation of methane emissions in cities: How new measurements and partnerships can contribute to emissions reduction strategies

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Key Points:

- Unintended (fugitive) methane emissions are ubiquitous in urban systems, and come from biogenic as well as natural gas sources
- Methane emission sources and their magnitudes vary greatly among cities
- Urban methane mitigation will require new observations with a suite of techniques, and new institutional partnerships

Supporting Information:

- Appendix S1
- Movie S1

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Abstract Cities generate 70% of anthropogenic greenhouse gas emissions, a fraction that is growing with global urbanization. While cities play an important role in climate change mitigation, there has been little focus on reducing urban methane (CH_4) emissions. Here, we develop a conceptual framework for CH_4 mitigation in cities by describing emission processes, the role of measurements, and a need for new institutional partnerships. Urban CH_4 emissions are likely to grow with expanding use of natural gas and organic waste disposal systems in growing population centers; however, we currently lack the ability to quantify this increase. We also lack systematic knowledge of the relative contribution of these distinct source sectors on emissions. We present new observations from four North American cities to demonstrate that CH_4 emissions vary in magnitude and sector from city to city and hence require different mitigation strategies. Detections of fugitive emissions from these systems suggest that current mitigation approaches are absent or ineffective. These findings illustrate that tackling urban CH_4 emissions will require research efforts to identify mitigation targets, develop and implement new mitigation strategies, and monitor atmospheric CH_4 levels to ensure the success of mitigation efforts. This research will require a variety of techniques to achieve these objectives and should be deployed in cities globally. We suggest that metropolitan scale partnerships may effectively coordinate systematic measurements and actions focused on emission reduction goals.

1. Introduction

Cities are a major source of greenhouse gas emissions globally and are critical players in the response to climate change. Urban areas constitute emission hotspots—important targets for greenhouse gas emissions mitigation [*Duren and Miller*, 2012]. City governments are uniquely poised to address climate change by controlling their own emissions through management and jurisdictional control over municipal and other local emissions sources [*Gurney et al.*, 2015]. Cities face fewer political difficulties with climate change mitigation than do nation-states [*Rosenzweig et al.*, 2010] and are already taking organized action at the global scale through associations such as the C40 Cities, which comprises 63 cities and >8% of the world's population [*Arup*, 2014], and Local Governments for Sustainability [*ICLEI USA*, n.d.], which counts 1000 participating cities. Urban emissions will grow in importance along with the world's urban population, which is forecast to double over the next 40 years to encompass the vast majority of the world's population [*United Nations Department of Economic and Social Affairs/Population Division*, 2012].

The growing scale of urban areas globally with respect to population and land area, and the willingness of metropolitan regions to sign on to organized climate action efforts suggest a great urgency for city-scale mitigation measures. One strategy that has been proposed recently for near-term climate mitigation is control of noncarbon dioxide (CO_2), short-lived climate pollutants with large radiative forcing such as methane (CH_4) [*Montzka et al.*, 2011]. CH_4 differs from CO_2 in that mitigation is technologically and economically feasible [*Shindell et al.*, 2012]. Unlike CO_2, a large fraction of CH_4 is lost as fugitive emissions from engineered systems, such as leaks from natural gas pipelines. These unintended fugitive emissions also represent a unique challenge for CH_4 that is different from activity-driven CO_2 emissions but also pose an opportunity to reduce loss of an economic commodity. In addition, mitigation techniques for CH_4 process emissions are well known and in wide use, such as flaring emissions from fossil fuel extraction or gas extraction from landfills. CH_4 mitigation in cities has substantial cobenefits for public health and safety by improving air quality in cities through global reductions in ozone pollution [*West et al.*, 2006; *Fiore et al.*, 2008]. CH_4 is also a safety hazard, already monitored by cities because it poses an explosion risk [e.g., *Building and Safety Division, Dept. of Public Works, County of Los Angeles*, 2002]. Fatal pipeline explosions in New York and San Bruno have drawn recent attention to the issue [*West*, 2014]. An unprecedented natural gas leak from an underground storage facility near Porter Ranch, California temporarily displaced thousands of residents and doubled CH_4 emissions from the Los Angeles Basin [*Conley et al.*, 2016; *Sahagun*, 2016]. Under orders from California's governor, the responsible parties are required to mitigate an equivalent amount of CH_4 elsewhere to offset the leak [*Barboza,* 2016].

Despite the existence of strategies to reduce CH_4 emissions that are particularly appropriate for cities [*Global Methane Initiative*, .; *Executive Office of the President of the U.S.*, 2014], there are limited mitigation approaches currently in practice [*Tang et al.*, 2010]. Indeed, some strategies to reduce CO_2 emissions, such as substituting natural gas for other fossil fuels such as coal and diesel, may have the unintended consequence of increasing radiative forcing by increasing fugitive CH_4 emissions [*Alvarez et al.*, 2012]. There are substantial barriers to be overcome before urban CH_4 mitigation can be implemented successfully, starting with large uncertainties in urban CH_4 budgets [e.g., *Hsu et al.*, 2009; *Wunch et al.*, 2009]. CH_4 inventories tend to underestimate emissions compared to emissions inferred from atmospheric measurements due to the difficulty of correctly accounting for fugitive CH_4 [*Brandt et al.*, 2014]. In addition, we lack a basic understanding of the locations and temporal patterns of urban CH_4 sources at relevant scales as well as information about the cost of repairs [*Forman*, 2014], and cooperation needed between diverse stakeholders to carry out mitigation activities.

We suggest that these barriers can be overcome by the cooperation of key stakeholders in individual cities to develop a scientific basis for CH_4 mitigation and a process by which CH_4 reductions can be evaluated and accounted. Here, we synthesize results from several recent studies and present new observations to create a new conceptual framework for effective city-wide CH_4 mitigation policy. We begin by reviewing the state of knowledge and emerging trends in important urban CH_4 emission sectors. We then present new data from four western U.S. cities to illustrate how CH_4 emissions vary among different cities. We describe the measurement goals and multiple approaches needed to inform mitigation. Finally, we suggest a role for new city-wide partnerships and adaptive management strategies tailored specifically for each unique metropolitan area to efficiently carry out mitigation policies.

2. Anthropogenic Urban Methane Sources

According to global inventories of anthropogenic CH_4 sources, the most important sectors for urban CH_4 emissions are energy, waste, agriculture, and transportation [Table 1; *Marcotullio et al.,* 2013]. Energy and transportation primarily emit fossil CH_4 derived from natural gas, whereas waste treatment and agriculture produce biogenic CH_4 from the process of anaerobic decomposition (Figure 1). Fossil sources produce CH_4 as a result of combustion or as fugitive emissions of natural gas from natural gas distribution networks or combustion units. Biogenic CH_4 is primarily produced from anaerobic decomposition but can also be unintentionally released as fugitive emissions from engineered systems designed to handle biogenic CH_4. Biogenic CH_4 is also produced (and consumed) by soils and from agricultural sources but will not be discussed further in this study. Observations suggest that the magnitude of CH_4 flux from urban soils is reduced relative to soils under native vegetation and is likely to be several orders of magnitude smaller than citywide areal fluxes [i.e., $<0.9\ \mathrm{nmol\ m^{-2}\ s^{-1}}$; *Kaye et al.,* 2004; *Groffman and Pouyat,* 2009]. Given these low rates, biogenic soil fluxes will not be further discussed.

A large fraction of natural gas consumption and waste treatment, along with their respective CH_4 emissions, are concentrated in cities. CH_4 emissions from both sectors are likely to increase—natural gas is currently promoted as a clean burning fuel for electricity generation and vehicles, and waste CH_4 emissions are growing along with the urban population. In addition, biogenic CH_4 is increasingly considered a source of renewable energy, resulting in increased production and utilization of biogas [*Global Methane*

Table 1. Inventory Estimates of Global and Urban Methane (CH_4) Emissions by Sector for Year 2000, From *Marcotullio et al.* [2013]

Sector	Global Emissions[a]	Urban Emissions[a]	Urban CH_4 as Percent of Sectoral CH_4	Urban CH_4 as Percent of Total CH_4
Agriculture	168	9	5	3
Energy	74	31	42	10
Waste	69	27	40	9
Transportation	1	<1	43	<1
Total	312	67		21

[a] Emissions are given as Tg CH_4-y^{-1}.

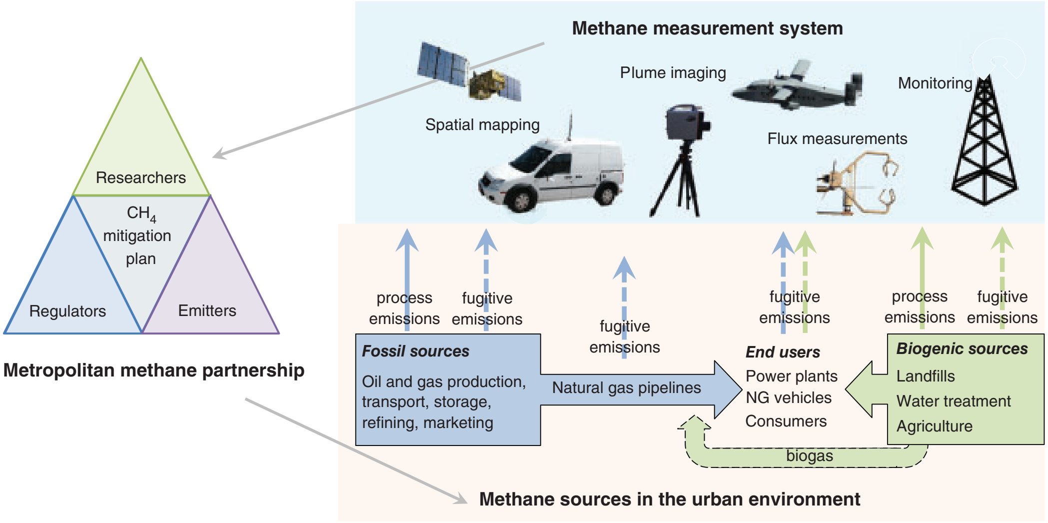

Figure 1. Conceptual framework for urban methane (CH_4) mitigation. CH_4 emissions in the urban environment originate directly from either fossil or biogenic sources or escape unintentionally from engineered systems and end users as fugitive emissions. A variety of measurement approaches, spanning scales of meters to hundreds of kilometers, gather data that can be used to understand complex patterns of urban CH_4 emissions. These observations can inform a shared CH_4 mitigation plan developed by a metropolitan CH_4 partnership, consisting of emitters, researchers and regulators, with the shared goal of adaptive management of urban CH_4 for safety and climate mitigation.

Initiative, 2011]. These diverse CH_4 sources pose an attribution challenge for atmospheric scientists; however, their urban confluence provides an opportunity for CH_4 mitigation and the development of new renewable energy sources.

Here, we present a detailed review of major CH_4-producing sectors in the urban environment, including the state of knowledge, emerging trends, challenges, and opportunities for mitigation. Across sectors, there is a need for improved quantification of emissions, cooperation between stakeholders for measurements and mitigation, development and deployment of new mitigation technologies, and verification of emissions reduction efforts.

2.1. New Approaches Are Needed for Reducing Natural Gas Leaks in Cities

Natural gas systems are the second largest anthropogenic source of CH_4 globally [*U.S. Environmental Protection Agency*, 2012]. CH_4, the primary component of natural gas, escapes to the atmosphere in nearly every step of the natural gas supply chain, namely production, gathering and processing, transmission, storage, distribution, and use. Fugitive emissions from the natural gas fuel cycle are primarily a function of use but also depend on the extraction and processing techniques, the distance gas travels to the end user, and the leakage rate of the pipeline [*U.S. Environmental Protection Agency*, 2013]. Natural gas consumption is growing rapidly because economic factors—recent advances in gas drilling, such as hydraulic fracturing with horizontal drilling—have lowered the price of the commodity. Natural gas use is also being promoted by governments as a means to improve air quality and reduce greenhouse gas emissions as it is a more efficient and clean burning energy source relative to other fossil fuels (i.e., combustion produces less CO_2, SO_2, NO_2, and particulate matter per unit of energy). However, recent studies have called attention to the potential for fugitive emissions in the natural gas fuel cycle to undermine greenhouse gas reduction goals of fuel switching [*Alvarez et al.*, 2012]. Recent estimates of natural gas leakage indicate that CH_4 emission rates are currently underestimated in greenhouse gas inventories [*Brandt et al.*, 2014], and thus, it is unclear if switching to CH_4-based fuels provides a net benefit for climate mitigation.

Atmospheric and facility-level measurements suggest that leaks in the natural gas network are also significant in cities, where storage, distribution, and use are concentrated [*Wunch et al.*, 2009; *Gioli et al.*, 2012; *Lamb et al.*, 2015; *McKain et al.*, 2015; *Subramanian et al.*, 2015]. CH_4 leaks from urban gas distribution systems have long been recognized from atmospheric observations in Europe [*Shorter et al.,* 1996]. More recently, road surveys of CH_4 in Washington, DC and Boston have uncovered many pipeline leaks, including several with CH_4 levels high enough to pose an explosive hazard [*Phillips et al.*, 2013; *Jackson et al.*, 2014]. Several recent explosions caused by pipeline gas leaks have resulted in mortality and extensive damage in incidents in San Bruno, California, in September 2010, and in New York, in March 2014 [*Lagos et al.*, 2010; *Santora*, 2014], drawing attention to the aging natural gas infrastructure of most North American cities [*Forman*, 2014; *McGeehan et al.*, 2014; *West*, 2014]. More leaks have been found in areas served by aged, cast-iron mains [*Phillips et al.*, 2013; *Jackson et al.*, 2014]; however, problems also have been identified with steel and plastic pipes [*Van Derbeken*, 2011]. A large leak at a natural gas storage facility near Porter Ranch, California in 2015–2016 recently drew attention to the vulnerability of underground gas storage to large CH_4 leaks. While this event is likely the largest gas release from a storage operation, dozens of leaks in similar facilities have been documented globally [*Evans*, 2008].

A lack of systematic understanding of pipeline leaks makes it difficult to prioritize repairs. Replacement of all pipelines in the next decade is impractical, with main pipeline replacement costing up to \$8 million dollars per mile [*Forman*, 2014]. Hence, utilities require information with which to identify those pipelines with the highest risk. Systematic evaluation of leaks is needed to understand the extent to which fugitive emissions originate from fittings, couplings with buildings, and other aboveground infrastructure downstream of consumer meters, including individual combustion units that may be less costly to repair. Utility companies use leak detection equipment designed for detecting explosive CH_4 concentrations, with a threshold for detection that is about ~10,000 times higher than the criteria for pipeline leak detection in recent urban studies by academic researchers [e.g., *Phillips et al.*, 2013; *Jackson et al.*, 2014]. To identify climate-relevant leaks and quantify gas losses, partnerships between utilities that understand and manage infrastructure, researchers with state-of-the-art equipment, and regulators with the ability to incentivize leak repair are critical [*Executive Office of the President of the United States*, 2014].

2.2. Minimize Leaks From Natural Gas Fueled Vehicles and Fueling Infrastructure

Currently, CH_4 emissions from transportation comprise a small portion (roughly 0.3%) of inventoried CH_4 emissions, globally and within the United States [*Marcotullio et al.,* 2013; *U.S. Environmental Protection Agency*, 2014]. Inventory estimates, however, represent a lower bound for transportation CH_4, as fugitive emission sources are often excluded [*Hopkins et al.,* 2016]. At present, transportation CH_4 emissions in the United States primarily come from conventional gasoline-fueled vehicles, which emit small amounts of CH_4 from the tailpipe as a result of incomplete combustion [*Kirchstetter et al.*, 1996; *Lipman and Delucchi*, 2002]. These emissions have declined over the past several decades due to improvements in emissions control technologies [*Lipman and Delucchi*, 2002]. However, the future of transportation CH_4 emissions will be transformed by increasing use of natural gas as a transportation fuel. Natural gas-powered vehicles are currently promoted as a means to reduce air pollution in cities [e.g., Delhi; *Goyal and Sidhartha*, 2003; *Chelani and Devotta*, 2007] as they produce fewer criteria pollutants than diesel and gasoline-powered vehicles [*Wang*, 1996]. Natural gas is a particularly popular choice for municipal fleets [*Yang et al.*, 1997; *Johnson*, 2010]. However, a switch to natural gas as a vehicle fuel is not likely to reduce radiative forcing in the near term because fugitive CH_4 emissions outweigh reduced CO_2 production from tailpipes [*Venkatesh et al.*, 2011; *Alvarez et al.*, 2012; *Burnham et al.*, 2012].

Fugitive CH_4 arises from vehicles that directly combust natural gas, in the form of compressed natural gas (CNG) or liquefied natural gas (LNG), and from vehicles that use natural gas as an energy feedstock, such as a fuel cell or hydrogen-powered cars. In addition to fugitive emissions from gas production and

Figure 2. Methane measurements at a compressed natural gas vehicle fueling station in Irvine, California. Fueling station outlined in blue.

transport, directly fueled CNG and LNG vehicles emit CH_4 during operation. CH_4 emissions from combustion are about 20 times higher from CNG vehicles than gasoline-powered vehicles [*Lipman and Delucchi*, 2002]. However, CH_4 from combustion only constitutes 4–10% of total CH_4 emitted from CNG vehicles, with the remainder from fugitive emissions [*Alvarez et al.*, 2012]. Emissions may also result from the process of converting pipeline gas to vehicle fuel and during the fueling process itself. For CNG vehicles, pipeline gas must be compressed before delivery to the fuel tank. For LNG vehicles, natural gas is liquefied and kept at low temperatures and high pressures to maintain a liquid state. CNG and LNG both require storage, compressors, fueling lines, valves, pump systems, and nozzles downstream of the natural gas pipeline [*Marathon Technical Services*, 2004]; however, there is little information about leak rates of these components [but see *Transportation Research Board*, 1998].

Recent surveys provide evidence for fugitive emissions in fueling stations—elevated CH_4 levels (>200 ppb above background) were observed at 12 of 13 different CNG filling stations surveyed by a mobile laboratory in Orange County, California (Figure 2; Appendix SI, Supporting Information). Particularly, high levels were found near storage tanks and connecting pipes; however, CH_4 enhancement was highly variable across stations, suggesting that fugitive leaks are responsible. The largest CH_4 enhancement observed in a mobile laboratory campaign in the Los Angeles Basin was attributed to a natural gas fueling station for heavy-duty vehicles in the Port of Long Beach [*Hopkins et al.,* 2016]. These observations suggest that CH_4 emissions are likely underestimated for CNG vehicles, particularly as commonly used lifecycle assessment models that calculate well-to-wheels emissions from natural gas-powered vehicles such as GREET (Greenhouse Gases, Regulated Emissions, and Energy Use in Transportation model [*Wang*, 1996]) neglect fugitive CH_4 emissions (A. Burnham, personal communication 2014).

Natural gas vehicle use has grown rapidly over the past decade and will continue to grow globally, particularly in developing countries in South Asia and Latin America [*Nijboer*, 2010]. In the United States, use of natural gas as a transportation fuel is growing most rapidly for heavy-duty and mass transit vehicles [*Nijboer*, 2010]. Many cities are switching fleets to natural gas with the assistance of the U.S. Department of Energy Clean Cities program in an effort to reduce petroleum use [*Johnson*, 2013]. In Los Angeles, nearly half of the refuse trucks run on natural gas fuel, and a large number of buses, taxis, and drayage trucks in the port have been switched to natural gas [*Nijboer*, 2010; *Udy*, 2011; *Weikel*, 2011; *San Pedro Bay Ports*, 2014]. Municipalities may also have access to biogas sources to fuel these vehicles from local landfills or wastewater treatment.

New mitigation strategies are needed to prevent CH_4 emissions from increasing with natural gas usage in the transport sector. Better quantification is needed for CH_4 emissions from downstream portions of the natural gas fuel cycle, including fueling infrastructure and combustion emissions of CH_4, which can vary widely across vehicles [*Lipman and Delucchi*, 2002]. Policy decisions promoting natural gas vehicles should consider the impact of fugitive CH_4 leaks in lifecycle analyses, even in the case of vehicles powered indirectly by natural gas (e.g., fuel cells). Also, decisions should consider whether natural gas vehicles actually contribute to air quality goals given that volatile organic compounds, such as ethane, are also emitted from fugitive natural gas leaks [*Moore et al.*, 2014]. Natural gas is a promising transportation fuel because of potential renewable sources (e.g., landfill gas); however, fugitive CH_4 may undermine climate mitigation goals without careful monitoring and leak repair.

2.3. Current Landfill Methane Mitigation Efforts Are Insufficient

The majority of waste CH_4 emissions globally come from urban landfills (Table 1) and will increase globally with urbanization and population growth. Landfills are the predominant means of waste disposal in urban settings [*Themelis and Ulloa*, 2007] and among the most CH_4-intensive form of waste management. Cities require landfills as a means to avoid the sanitation and air pollution problems of open dumping and trash burning common in rural areas, but produce more CH_4 due to anaerobic conditions created by waste compaction and burial [*Bogner et al.*, 2008; *Vergara and Tchobanoglous*, 2012]. Landfill CH_4 emissions from developed countries have declined in recent decades owing to increased landfill CH_4 recovery and waste diversion practices [*Bogner et al.,* 2008]. However, emissions from developing countries are likely to increase with urbanization, population growth, and higher standards of living [*Bogner and Matthews*, 2003; *Vergara and Tchobanoglous*, 2012].

CH_4 emissions from landfills are determined by several factors, including the amount and type of waste disposed, the physical environment, and CH_4 capture systems in place. Waste management practices control landfill CH_4 emissions by two general strategies: (1) reducing CH_4 production and (2) capturing landfill CH_4. CH_4 production can be prevented by reducing the amount of waste that ends up in landfills — cities have implemented this approach with pay-as-you-throw pricing and diversion of organic waste to alternative treatments such as composting [*Bogner et al.*, 2008; *Vergara et al.*, 2011]. Emissions from landfilled waste can be further reduced by altering the decomposition process that converts organic waste to CH_4 and CO_2, which is largely a function of anaerobic conditions in the landfill [*Bogner et al.*, 2008]. Landfill management strategies such as the use of caps and liners alter temperature, moisture, oxygen availability in a landfill, and hence the amount and rate of CH_4 production [*Bogner and Matthews*, 2003; *Scheutz et al.*, 2009].

Engineered systems to physically remove CH_4 produced in landfills are currently thought to be the most effective landfill mitigation technique [*Bogner and Matthews*, 2003]. Landfill gas collection systems use extensive networks of wells and pipes to extract gases produced inside the landfill. Captured landfill gas is vented to the atmosphere, flared, or used as a renewable fuel for electricity generation or vehicle fueling [*Cosulich et al.,* 1992]. Another strategy is to use microbial oxidation of CH_4 in landfill cover materials to destroy CH_4 before it reaches the atmosphere. Biological CH_4 oxidation can be promoted by additions of soil, compost, and sludge over landfills [*Bogner and Matthews*, 2003; *Scheutz et al.*, 2009].

Landfill gas collection systems alone are insufficient. Landfill gas recovery systems were designed primarily to prevent explosive hazard and for odor control, not to reduce CH_4 emissions [*Cosulich et al.*, 1992]. Some landfill gas recovery systems may paradoxically increase emissions by venting recovered CH_4 directly to the atmosphere, thereby preventing any oxidization by methanotrophic soil microorganisms that would otherwise occur. For example, CH_4 emissions from a closed landfill in Orange County, California are vented directly to the atmosphere from a landfill gas collection system (Web Object 1; Appendix SI). Extensive plumbing systems used for landfill gas recovery create ample opportunities for fugitive emissions, as recently observed by airborne infrared imaging at a large Los Angeles landfill [*Tratt et al.*, 2014]. The airborne spectrometer detected large plumes emanating from CNG fueling and gas flaring infrastructure. At sites where landfill gas is recovered for use as biogas, landfills may be managed to optimize CH_4 collection rather than to reduce CH_4 emissions [*Spokas et al.*, 2006; *Sierra Club*, 2010]. This suggests that biogas production may undermine greenhouse gas reduction goals of a landfill gas recovery project if there are significant fugitive emissions in the biogas lifecycle.

To maximize the potential of CH_4 mitigation, CH_4 emissions reduction should become an explicit goal of landfill management, and attainment should be verified with regular surveys. More research is needed to understand the effectiveness of currently practiced and proposed landfill mitigation activities. In particular, a better understanding of fugitive emissions from these highly engineered systems, e.g., from leaks in gas collection pipes or gaps between liners [*Spokas et al.*, 2006], could be useful to both mitigation efforts and improved quantification of landfill emissions in inventories [*Bogner and Matthews*, 2003]. Use of CH_4 imaging technology could enable better surveys of landfill areas and rapid determination of the location of leaks [*ARCADIS U.S. Inc.*, 2012]. Improving landfill cover technology that enhances biological CH_4 oxidation (e.g., *Adams et al.*, 2011; *Scheutz et al.*, 2011; *Lamb et al.*, 2014) is a promising route for reducing CH_4 emissions from landfills and other waste systems. This strategy has been demonstrated in combination with existing landfill gas recovery systems [*Spokas et al.*, 2006], can be used for former landfills that continue to emit CH_4 decades after closure [*Hopkins et al.,* 2016], and is likely the most cost-effective mitigation solution [*Bogner et al.*, 2010]. Going forward, cities need to develop and implement alternatives to landfilling organic waste to prevent the production of waste CH_4 and account for lifecycle greenhouse gas emissions, such as with composting programs [*Jaffe*, 2013] and mechanical biological treatment [*Bogner et al.*, 2008].

2.4. More Systematic Approaches Are Needed for Water Treatment Systems

CH_4 from wastewater is the fastest growing emission source outside of fossil fuels, expected to increase by 19% over the next two decades as population grows, particularly in developing economies [*U.S. Environmental Protection Agency*, 2013]. Centralized wastewater treatment in cities tends to reduce CH_4 emissions relative to more primitive forms of treatments such as lagoons, latrines, and septic systems. For cities in developing countries that lack centralized wastewater systems, development of urban sewer infrastructure could reduce CH_4 emissions while also improving sanitation and public health [*Rosso and Stenstrom*, 2008; *U.S. Environmental Protection Agency*, 2013]. In developed countries, urban wastewater treatment systems minimize CH_4 emissions by the energy-intensive process of aerobic sludge digestion [*Global Methane Initiative*, 2013]. More affordable anaerobic digester systems are common in the developing world and are thought to reduce climate impacts of wastewater treatment through reduced electricity use [*Greenfield and Batstone*, 2005], but do not account for fugitive CH_4 emissions. Anaerobic digestion produces large amounts of CH_4 that is usually recovered and combusted to produce energy [*Cakir and Stenstrom*, 2005]. Other anaerobic systems such as wastewater lagoons can also be retrofitted with biogas capture systems [*Global Methane Initiative*, 2013]. Nevertheless, anaerobic digestion tends to produce higher CH_4 emissions than aerobic treatment, even with CH_4 capture technology [*Daelman et al.*, 2013]. A recent survey of anaerobic wastewater treatment plants in Pennsylvania uncovered CH_4 leaks in five of the six tested facilities [*Erndwein*, 2012]. The most consistent leaks came from condensation drip traps, suggesting that preventative maintenance on these components can improve safety and reduce CH_4 emissions. The high frequency of leaks illustrates the need for regular leak monitoring with anaerobic wastewater treatment.

Apart from the digestion phase, other parts of wastewater treatment require new measurements to quantify and minimize CH_4 leaks. Sewer mains may emit nearly as much CH_4 as wastewater treatment plants, yet, these emissions have been neglected by greenhouse gas emissions inventories [*Guisasola et al.*, 2008]. In situ mapping of sewer gas concentration using new sensor technology shows promise for improving estimates of CH_4 emissions, with the dual goal of informing sewer maintenance and repair in a cost-effective manner [*Lim et al.*, 2013]. Anaerobically treated effluent contains large quantities of dissolved CH_4 that can escape to the atmosphere without further treatment. Methods to capture dissolved CH_4 after it leaves the reactor, such as in a closed column with high turbulence or a subsequent aerobic treatment to allow biological oxidation should be developed and widely implemented [*Cakir and Stenstrom*, 2005; *Global Methane Initiative*, 2013].

2.5. Different Cities: Different Methane Sources, Different Mitigation Opportunities

Greenhouse gas emissions vary among cities, depending on population size and density, geographic factors such as climate and access to resources, and economic factors, including industries, affluence, and technology [*Kennedy et al.*, 2009]. Specifically, differences in latitude and climate alter the rates of biogenic CH_4 production from anthropogenic sources such as landfills, and from natural sources, such as local soils. Cultural and economic factors also play an important role in determining the presence and integrity of CH_4 emitting infrastructure, including fuel distribution networks and waste treatment facilities. Hence, cities require local information about emissions for greenhouse gas mitigation planning [*Fong et al.,* 2014]. To this end, many cities have initiated the development of their own greenhouse gas emission inventories; however, most efforts to date are limited to CO_2 emissions [*Hoornweg et al.,* 2011]. In the case of CH_4, local observations are required because of the importance of fugitive emissions.

Here, we present CH_4 data collected by on-road sampling for four urban regions in the western United States during the summer of 2013 (Figure 3). We used fast-response in situ measurements of CH_4 made from a laboratory vehicle while driving in Fairbanks, Alaska; Los Angeles and San Diego, California; and Salt Lake City, Utah [Appendix SI; see also *Bush et al.,* 2015; *Hopkins et al.,* 2016]. These regions represent a range of sizes and urban forms, from roughly 100,000 residents in Fairbanks to 12.8 million inhabitants in the Los Angeles metropolitan area [*U.S. Census Bureau*, 2011]. The highest CH_4 levels, reported as excess above local background levels, were observed in Los Angeles, followed by Salt Lake City, San Diego, and Fairbanks (Table 2). The number of CH_4 hotspots, defined as locations with CH_4 levels exceeding 200 ppb above background, was highly variable among cities (see Appendix SI). Numerous CH_4 hotspots were observed in the Los Angeles Basin, which serves as a gateway for trade and fossil fuel inputs to the region, and contains one of the largest active oil fields in the United States. More hotspots were detected in Salt Lake City than in San Diego, possibly reflecting greater industrial activity despite its smaller size or a more aged infrastructure, and no hotspots were detected in Fairbanks.

The frequency of hotspots observed in Los Angeles, Salt Lake, and San Diego were more than an order of magnitude lower than previously reported for Boston [*Phillips et al.*, 2013] and Washington, DC [*Jackson et al.*, 2014] (11–19 vs. 390–420 hotspots per 100 road miles; Table 2). Higher emissions in cities of the northeast United States are likely caused by leaks in older natural gas pipeline infrastructure, compared to more recently developed cities in the western United States. Indeed, Fairbanks does not have pipeline distribution of natural gas. Differences such as these are likely to be especially large between these developed urban regions and those of the developing world, which typically do not have extensive pipeline distribution networks. Research in these regions is needed as cities in the developing world are one of the fastest growing sources of emissions [*Duren and Miller*, 2012].

3. Methane mitigation strategy for cities

New research on urban CH_4 emissions can provide a scientific basis for mitigation activities. We suggest three hypotheses to drive future research: (H1) *Urban methane emissions are poised to grow because of ineffective current mitigation practices and increasing use of natural gas and biogas fuels*. More studies of the distribution, frequency and rate of fugitive CH_4 across different engineered urban systems are needed, as well as a better understanding of how different management practices influence emissions rates. (H2) *Mitigating urban methane emissions will require new measurements over a range of scales using multiple techniques*. Facility-level measurements, attribution studies, and new inventory approaches are needed to resolve discrepancies between purely top-down estimates inferred from atmospheric measurements and traditional activity-based inventories typically used by governments to calculate emissions. (H3) *Cities differ greatly in their methane emissions and require unique mitigation approaches.* Interdisciplinary research is needed to understand how differences in economy, population, climate, geography, policy, and development affect CH_4 emissions, and how differences in governance structures, culture, economy, and emitting sectors affect CH_4 mitigation activities and their effectiveness. This work will help determine mitigation priorities and best practices among regions.

3.1. Urban Methane Monitoring

If mitigation efforts are successful, emissions reductions over time may leave a trend in surface concentrations that is detectable with a citywide monitoring network [*National Research Council*, 2010]. Specifically,

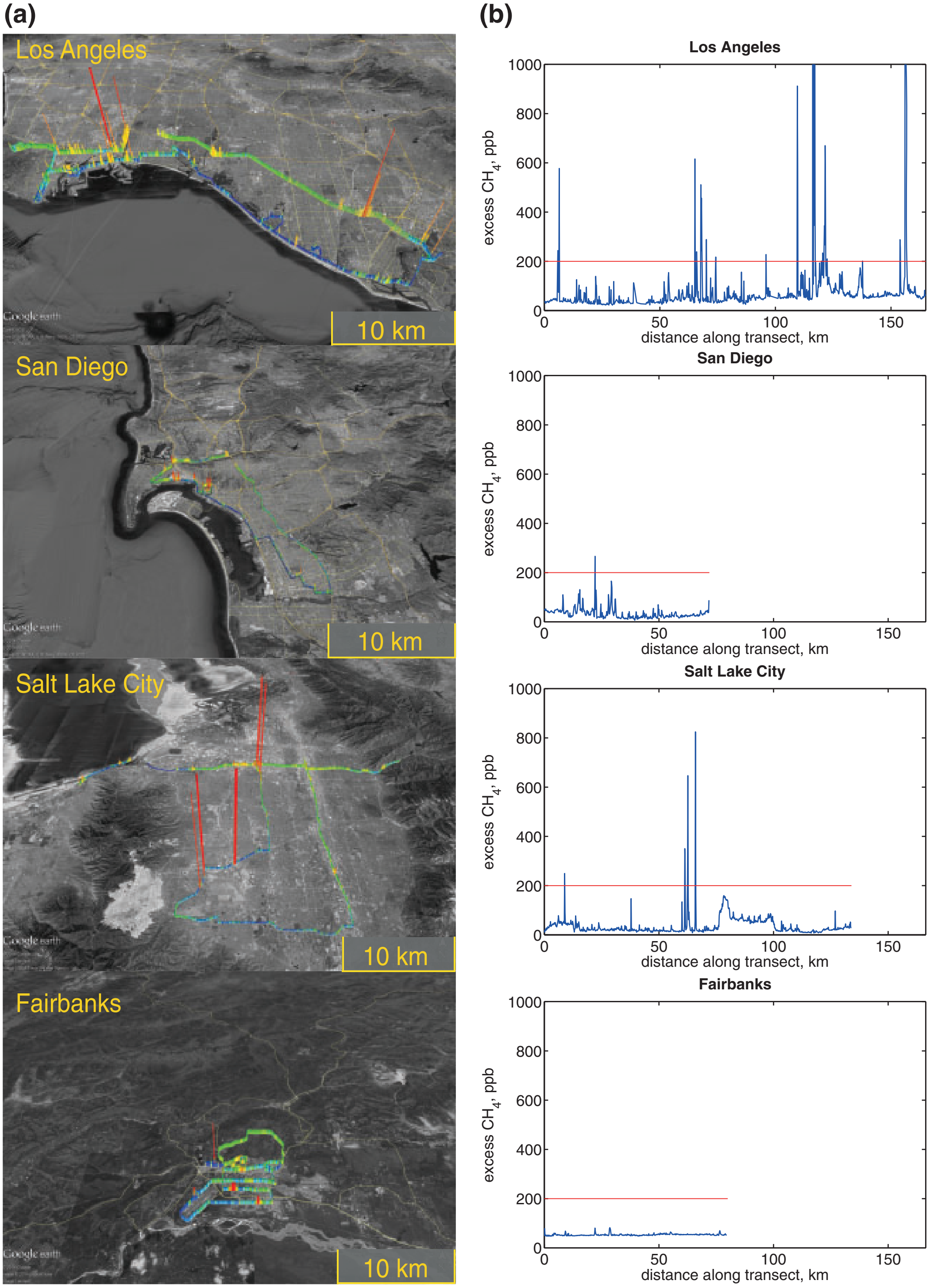

Figure 3. Atmospheric methane (CH_4) patterns from mobile laboratory studies in four western U.S. cities. Spatial patterns of CH_4 from transects covering major emission sources in each city conducted during summer 2013. Colored bars on map panels (a) show measured CH_4 mole fractions. Bar heights are proportional to absolute CH_4 excess over background levels, and bar colors were determined by the range of values observed for an individual city. Plot panels (b) show CH_4 excess values for the same transects plotted in blue by distance traveled. CH_4 excess values >200 ppb (red line) are considered to be CH_4 hotspots.

Table 2. Comparison of Four Metropolitan Regions in the Western United States Based on Mobile Methane (CH_4) Sampling During Summer 2013

	Population		Summer 2013 Transects							
Metropolitan Region	Metro area (Millions) [*United States Census Bureau*, 2011]	Density (pop./km^2) [*United States Census Bureau*, 2011]	Number of Transects	Distance Traveled (km)	Background CH_4 (ppm) ± 1σ	Mean Excess CH_4 (ppm)	95th Percentile Excess CH_4 (ppm)	Percent of Transect >3σ Above Background	Number of Hotspots	Hotspot Frequency (Hotspots/km)
Los Angeles	12.8	3100	11	1585	1.821 (±0.007)	0.185	0.353	95	190	0.12
San Diego	3.1	1400	5	354	1.847 (±0.002)	0.057	0.205	99	23	0.07
Salt Lake Valley	1.1	700	4	718	1.824 (±0.003)	0.082	0.157	82	62	0.09
Fairbanks	0.1	400	7	574	1.823 (±0.005)	0.047	0.077	90	0	0

surface concentrations are elevated over urban areas compared with more remote locations because of the intensity of local emissions and finite rates of removal by atmospheric transport. The magnitude of this gradient, sometimes described as an "urban dome" is proportional to emission levels over time, assuming that atmospheric mixing remains unchanged [*Pataki et al.,* 2010].

Recent advances in cavity- enhanced laser absorption spectroscopy and tunable lasers have enabled new instruments capable of making high-frequency, high-precision measurements of CH_4 and key tracer species [*Hendriks et al.*, 2007; *Crosson*, 2008; *Mønster et al.*, 2014; *Yacovitch et al.*, 2014]. This capability facilitates new data collection approaches, such as mobile street-level sampling of multiple trace gases [*Bush et al.*, 2015] and long-term stationary monitoring [*Andrews et al.*, 2014]. In this context, the science community is poised to make a valuable contribution to mitigation planning by developing locally appropriate, comprehensive sampling strategies that place fugitive emissions from natural gas in the context of other sources.

One major challenge to mitigation and monitoring that has been identified consistently across cities is that emission estimates derived from atmospheric measurements are larger than can be explained by CH_4 inventories (e.g., London [*Helfter et al.,* 2016] and Los Angeles [*Wong et al.,* 2015]). Resolving this discrepancy will require a new combination of investigative approaches. Citywide CH_4 emission studies using multiple measurement techniques and a consortia of cooperating researchers have been tried in several cities, including Indianapolis and Boston [*McKain et al.,* 2015; *Lamb et al.,* 2016], and are currently underway in many other North American and European cities. A metropolitan CH_4 monitoring system should (1) estimate regional CH_4 emissions and detect changes over time, (2) apportion CH_4 among different source sectors, and (3) systematically characterize important CH_4 point sources. Achieving these objectives requires a variety of measurement platforms and approaches can be deployed in urban settings (Table 3).

Top-down budgets of city-wide emissions can be determined with representative measurements of CH_4 and another trace gas with a known urban emission rate [*Blake et al.*, 1984; *Moriizumi et al.*, 1996]. This approach works with regional-scale measurements that observe well-mixed air with an integrated urban signal that varies in time or space, such as remote sensing, tall towers, and aircraft. For example, several recent studies have used CO and CO_2 inventories to quantify CH_4 emissions in Los Angeles, revealing emissions up to 50% larger than inventory estimates [*Hsu et al.*, 2009; *Wunch et al.*, 2009]. Top-down budgets can also be made with smaller scale, in situ observations like urban tower networks, but require inverse modeling to delineate the region of influence on the measurement and a prior emission map that reasonably represents the spatial distribution of emissions [*McKain et al.,* 2015; *Lamb et al.,* 2016].

To understand relative contributions of different CH_4 sources to urban emissions, apportionment can be performed at a variety of scales. Measurements of co-emitted gases such as ethane and propane or CH_4 isotopes can be used to distinguish fossil and biogenic sources from the regional down to the facility level [e.g., *Hopkins et al.*, 2016]. In Los Angeles, tracer measurements show that fossil sources constitute a majority of CH_4 emissions and are the likely source of discrepancy between measurement and inventory [*Townsend-Small et al.*, 2012; *Wennberg et al.*, 2012; *Peischl et al.*, 2013]. Spatial surveys can also help distinguish among CH_4 sources and explain differences between inventory and observed emissions. For example, airborne infrared imaging surveys can locate uninventoried fugitive CH_4 sources over large areas and multiple facilities [*Hulley et al.,* 2016]. Fugitive gas leaks observed by mobile sampling in Boston are consistent with findings of high contributions of fossil CH_4 to city budgets [*Phillips et al.*, 2013; *McKain et al.*, 2015].

Finally, systematic measurements of individual emission sources are needed to refine bottom-up estimates that rely on accurate facility counts and emission factors. Specifically, uninventoried fugitive emissions should be included, as well as super-emitters that disproportionately contribute to sectoral emissions [*Brandt et al.,* 2014]. Quantification of emissions at the facility level can improve inventories and help determine priorities for mitigation. New, fine-scale inventories of CH_4 emissions that include all potential sources of fugitive CH_4 could be useful for designing targeted, statistically robust sampling and for interpreting urban-scale CH_4 surveys.

3.2. Design and Attributes of a Methane Mitigation Partnership

Urban CH_4 mitigation will require the involvement of diverse stakeholders in addition to new observational data [*Kennedy et al.*, 2009; *Hoornweg et al.,* 2011]. Cooperation among partners is needed, for example, to

Table 3. Urban CH_4 Measurement Approaches

Application	Technique	Advantage	Disadvantage	References
Top-down regional budget	Remote sensing (e.g., satellite, scanning Fourier transform spectrometer)	• Regional to global coverage • Repeated surveys	• Measurement confined to specific overpass times during cloud-free, daylight hours • Coarse spatial resolution	*Wong et al.* [2014]
	Total column measurements of CH_4 (ground-based Fourier transform spectrometer)	• Avoids influence of planetary boundary layer height on measurement • Effective for trend detection	• Requires separation of city and free troposphere contributions to column • Limited to cloud-free periods	*Wunch et al.* [2009]
	Stationary tall tower site or tower network	• Continuous, long term in situ measurements can detect trends in time • Source attribution possible with additional tracer measurements	• Requires measurements of planetary boundary layer height, meteorology, and inverse models to calculate a flux • Height and location determines footprint; access to appropriate sites is challenging	*Hsu et al.* [2010]; *McKain et al.* [2015]; *Jeong et al.* [2013] Source attribution: *Wennberg et al.* [2012]; *Lowry et al.* [2001]
	Airborne in situ sampling (e.g., aircraft, unmanned aerial vehicles)	• Extensive spatial coverage: city to regional scale • Measurements of individual facilities/area sources • Source attribution possible with additional tracer measurements	• Use of airspace requires air traffic control permission/approval • Infrequency and expense of campaigns limits time resolution: just a "snapshot" • Spatial resolution limited by minimum allowable height	*Miller et al.* [2013]; *Berman et al.* [2012]; *Khan et al.* [2012] Source attribution: *Wennberg et al.* [2012]; *Peischl et al.* [2013]
	Inventoried trace gas with other urban sources (e.g., CO)	• Necessary to estimate a top-down budget using the scaling ratio method	• Relies on accuracy of inventory	*Wunch et al.* [2009]; *Hsu et al.* [2010]; *Blake et al.* [1984]; *Moriizumi et al.* [1996]
Source apportionment	Co-emitted species (e.g., alkanes such as ethane)	• Apportionment of biogenic and fossil sources • May be able to distinguish pipeline gas from unprocessed fuel emissions	• Other sources of these co-emitted species may not be well constrained	*Peischl et al.* [2013]; *Katzenstein et al.* [2003]
	Isotopes of CH_4	• Apportionment of biogenic and fossil sources	• Cannot clearly distinguish natural gas pipeline leaks from other fossil sources	*Townsend-Small et al.* [2012]

Table 3. Continued

Application	Technique	Advantage	Disadvantage	References
	On-road mobile sampling	• Fine-scale pattern of CH_4 in a city	• Difficult to integrate to obtain a regional emissions flux	*Phillips et al.* [2013]; *Jackson et al.* [2014]; *Bush et al.* [2015]; *Pétron et al.* [2012]; *Farrell et al.* [2013]; *Leifer et al.* [2013]
		• Point source measurements over city to continental scales • CH_4 hotspot location • Source attribution with additional tracer measurements	• Point source access limited by road network and facility access	Source attribution: *Hopkins et al.* [2016]
	Satellite CH_4 imaging	• Global coverage	• Difficult to resolve city-scale	*Frankenberg et al.* [2011]; *Kort et al.* [2014]
	Airborne CH_4 imaging	• Broad spatial surveys possible (~100 s of km^2)	• Air traffic control height restrictions in urban areas	*Tratt et al.* [2014]; *Harig et al.* [2003]; *Thorpe et al.* [2014]; *Hulley et al.* [2016]
		• Additional tracer gases can be retrieved (e.g., NH_3)	• Infrequency and expense	
Point source/facility-level characterization	Eddy covariance towers	• Flux measurements at neighborhood scale (2–3 km^2) [*Gioli et al.*, 2012] • Direct measurement of emissions rate	• Access to appropriate sites is challenging [see *Velasco and Roth,* 2010] • Multiple sites needed for city-scale budget estimation	*Gioli et al.* [2012]; *Helfter et al.* [2016].
	Ground infrared imaging	• Visualize plume, pinpoint emission sources	• Does not give quantitative results except with custom made sensor [see *Gålfalk et al.*, 2015]	*Gålfalk et al.* [2015]
		• Temporal evolution of emission source	• Spatial scaling for area sources	
	Chamber-based approaches	• Direct flux measurements	• Chamber shape limits applications	*Bogner et al.* [2011]; *Kaye et al.* [2004]
	Tracer release (e.g., acetylene)	• Quantify flux from a point or area source	• Need to know location of source	*Mønster et al.* [2014]
			• Does not work for collocated sources	

determine the cost of appropriate repairs. Cost estimates require knowing the location of CH_4 leaks, only possible with precise CH_4 detecting equipment that is often too costly for individual operators. Meanwhile, researchers who have this specialized equipment cannot make these measurements without site access. In order to overcome these barriers, we suggest the formation of regional CH_4 partnerships composed of researchers, regulators, and representatives of CH_4 emitting industries, including public utilities and for profit corporations, that share the goal of managing regional CH_4 emissions. The Environmental Defense Fund, a nongovernmental organization, recently coordinated a partnership to study CH_4 emissions from the U.S. natural gas supply chain that included research and industry partners [*Environmental Defense Fund*, 2016]. This partnership led to new bottom-up measurements of leaks in natural gas distribution, transmission, and storage [*Lamb et al.*, 2015; *Subramanian et al.*, 2015] and demonstrated the value of multiple measurement techniques [*Harriss et al.*, 2015]. As yet, however, no new natural gas regulations of these sectors have resulted.

Metropolitan regions could be an effective scale for these partnerships, particularly at the level of regulatory action (e.g., air pollution control district) and because of stakeholders' shared interest in local economic development, public health, and consumer perception. For industries where CH_4 is an economic commodity, technical and perhaps financial assistance to repair fugitive CH_4 leaks could be an incentive for participation. Even in cases where CH_4 capture is not economical, reduced liability from CH_4 safety hazard in populated areas may be sufficient motivation. Municipal contracts with landfill operators or natural gas utilities could also require participation. In addition to reaching climate and air quality goals, municipalities could benefit from collaborations with researchers to verify emission reductions for international mitigation initiatives [*Hsu et al.*, 2015]. Government and academic researchers from a variety of disciplines could use the partnership as a springboard for research on the urban CH_4 budget, to develop and test new mitigation technologies, and a host of other topics related to climate mitigation. One promising area of collaboration is in the design a city-wide CH_4 inventory, drawing on knowledge of infrastructure held by industry, experience, and tools needed to compile inventories from government partners, and new data collected by researchers. In addition to better accounting for emissions, the inventory can be used as a prior for inverse studies and for policy analysis.

The partnership should have a specific mitigation target and allotted time to achieve the goal, e.g., 10 years to reduce CH_4 emissions by 20%. To achieve this goal, the partnership needs to build a scientific basis for mitigating CH_4 emissions in the metropolitan region. Strategic, coordinated measurements can eliminate discrepancies between bottom-up inventories and top-down atmospheric measurements that impede communication between regulators and researchers. Of particular importance is resolving the contribution of super-emitters that are thought to contribute disproportionately to urban emissions, which may be effective mitigation targets. The partnership also needs to create a process by which leaks can be systematically detected and evaluated as mitigation targets and then repaired as appropriate in the context of a cost-efficient, city-wide mitigation goal.

There are major organizational challenges that must be overcome for these partnerships to be realized. One potential conflict is the requirement of privacy and liability issues for emitters, and possibly regulators, versus academic freedom needs of researchers. To motivate participation and free sharing of information among partners, deliberations by the team could be protected by confidentiality agreements, similar to the operation of the National Research Council committees overseen by the U.S. National Academies. Other products from such a partnership, including information on outcomes of mitigation efforts, would be freely accessible by the public. Another challenge is the variety of different industries involved; however, several multisectoral CH_4 projects already exist that can provide guidance to metro-scale efforts. Examples include the Global Methane Initiative, a voluntary partnership among governments, private sector members, development banks, universities, and nongovernmental organizations and the United Nations Environment Program's Climate and Clean Air Coalition to Reduce Short-Lived Climate Pollutants [*United Nations Environment Program*, .]. Organizations such as U.S. DOE's Clean Cities Program, U.S. EPA's Natural Gas Star Program, and C40 Cities may already have established some of the collaborations needed among potential participants. Finally, metropolitan scale coalitions might not be able to influence major emitters, for example, as natural gas utilities are often regulated at the state level. However, lobbying at the metropolitan scale may be able to influence future regulations, as demonstrated by state and national level responses to natural gas leak

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events in cities [*Simon*, 2011; *Wire*, 2016]. These organizations may also be able to extend their reach by sharing best practices with other cities globally.

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