4 Understanding Urban Carbon Fluxes

Lead Authors

Kevin Robert Gurney, Northern Arizona University; Paty Romero-Lankao, National Center for Atmospheric Research (currently at National Renewable Energy Laboratory); Stephanie Pincetl, University of California, Los Angeles

Contributing Authors

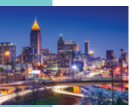
Michele Betsill, Colorado State University; Mikhail Chester, Arizona State University; Felix Creutzig, Mercator Research Institute on Global Commons and Climate Change; Kenneth Davis, The Pennsylvania State University; Riley Duren, NASA Jet Propulsion Laboratory; Guido Franco, California Climate Change Research Center; Sara Hughes, University of Toronto; Lucy R. Hutyra, Boston University; Chris Kennedy, University of Victoria; Rob Krueger, Worcester Polytechnic Institute; Peter J. Marcotullio, Hunter College, City University of New York; Diane Pataki, University of Utah; David Sailor, Arizona State University; Karina V. R. Schäfer, Rutgers University

Acknowledgments

Paty Romero-Lankao (Science Lead), National Center for Atmospheric Research (currently at National Renewable Energy Laboratory); Nathaniel A. Brunsell (Review Editor), University of Kansas; Elisabeth Larson (Federal Liaison), North American Carbon Program and NASA Goddard Space Flight Center, Science Systems and Applications Inc.; Karina V. R. Schäfer (former Federal Liaison), National Science Foundation

Recommended Citation for Chapter

Gurney, K. R., P. **Romero-Lankao**, S. **Pincetl**, M. Betsill, M. Chester, F. Creutzig, K. Davis, R. Duren, G. Franco, S. Hughes, L. R. Hutyra, C. Kennedy, R. Krueger, P. J. Marcotullio, D. Pataki, D. Sailor, and K. V. R. Schäfer, 2018: Chapter 4: Understanding urban carbon fluxes. In *Second State of the Carbon Cycle Report (SOCCR2): A Sustained Assessment Report* [Cavallaro, N., G. Shrestha, R. Birdsey, M. A. Mayes, R. G. Najjar, S. C. Reed, P. Romero-Lankao, and Z. Zhu (eds.)]. U.S. Global Change Research Program, Washington, DC, USA, pp. 189-228, https://doi.org/10.7930/SOCCR2.2018.Ch4.



KEY FINDINGS

1. Urban areas in North America are the primary source of anthropogenic carbon emissions, with cities responsible for a large proportion of direct emissions. These areas are also indirect sources of carbon through the emissions embedded in goods and services produced outside city boundaries for consumption by urban dwellers (*medium confidence, likely*).

2. Many societal factors drive urban carbon emissions, but the urban built environment and the regulations and policies shaping urban form (e.g., land use) and technology (e.g., modes of transportation) play crucial roles. Such societal drivers can lock in dependence on fossil fuels in the absence of major technological, institutional, and behavioral change. Some fossil fuel–related infrastructure can have lifetimes of up to 50 years (*high confidence*).

3. Key challenges for urban carbon flux studies are observational design, integration, uncertainty quantification, and reconciliation of the multiple carbon flux approaches to detect trends and inform emissions mitigation efforts (*medium confidence, likely*).

4. Improvements in air quality and human health and the reduction of the urban heat island are important co-benefits of urban carbon emissions mitigation (*high confidence, very likely*).

5. Urban methane (CH_4) emissions have been poorly characterized, but the combination of improved instrumentation, modeling tools, and heightened interest in the problem is defining the range of emissions rates and source composition as well as highlighting infrastructure characteristics that affect CH_4 emissions (*high confidence*).

6. Urban areas are important sites for policymaking and decision making that shape carbon fluxes and mitigation. However, cities also are constrained by other levels of government, variations in their sources of authority and autonomy, capacity, competing local priorities, and available fiscal resources (*high confidence*).

Note: Confidence levels are provided as appropriate for quantitative, but not qualitative, Key Findings and statements.

4.1 Introduction

Urban areas are concentrated domains of carbon fluxes because of the sheer magnitude of 1) urban populations; 2) economic activities; and 3) the fossil fuel–based energy, goods, and services on which these areas currently depend. Though sensitive to the urban boundary definition chosen and the accounting framework adopted (production versus consumption), carbon fluxes resulting from urban activities are estimated to be responsible for up to 80% of the total North American anthropogenic flux of carbon dioxide (CO_2) to the atmosphere (Jones and Kammen 2014; Seto et al., 2014). Per capita energy consumption in U.S. urban areas is estimated to be 13% to 16% less than the national average, and consumption varies more widely across cities than in rural areas (Parshall et al., 2010; see Figure 4.1, p. 191). This concentrated source of carbon emissions is dominated by the combustion of fossil fuels (see Ch. 3: Energy Systems, p. 110, for a detailed treatment of carbon emissions associated with energy systems). However, other direct fluxes include carbon exchanged by the urban biosphere, methane (CH_4) emissions from leaking infrastructure, anaerobic decomposition (e.g., landfills and wastewater treatment), and human respiration. Cities are also responsible for large indirect fluxes via the demand for goods and services that are produced elsewhere. Understanding urban carbon fluxes is essential to understanding the spatiotemporal distribution of global anthropogenic carbon flux, the forces driving fossil fuel–based consumption,

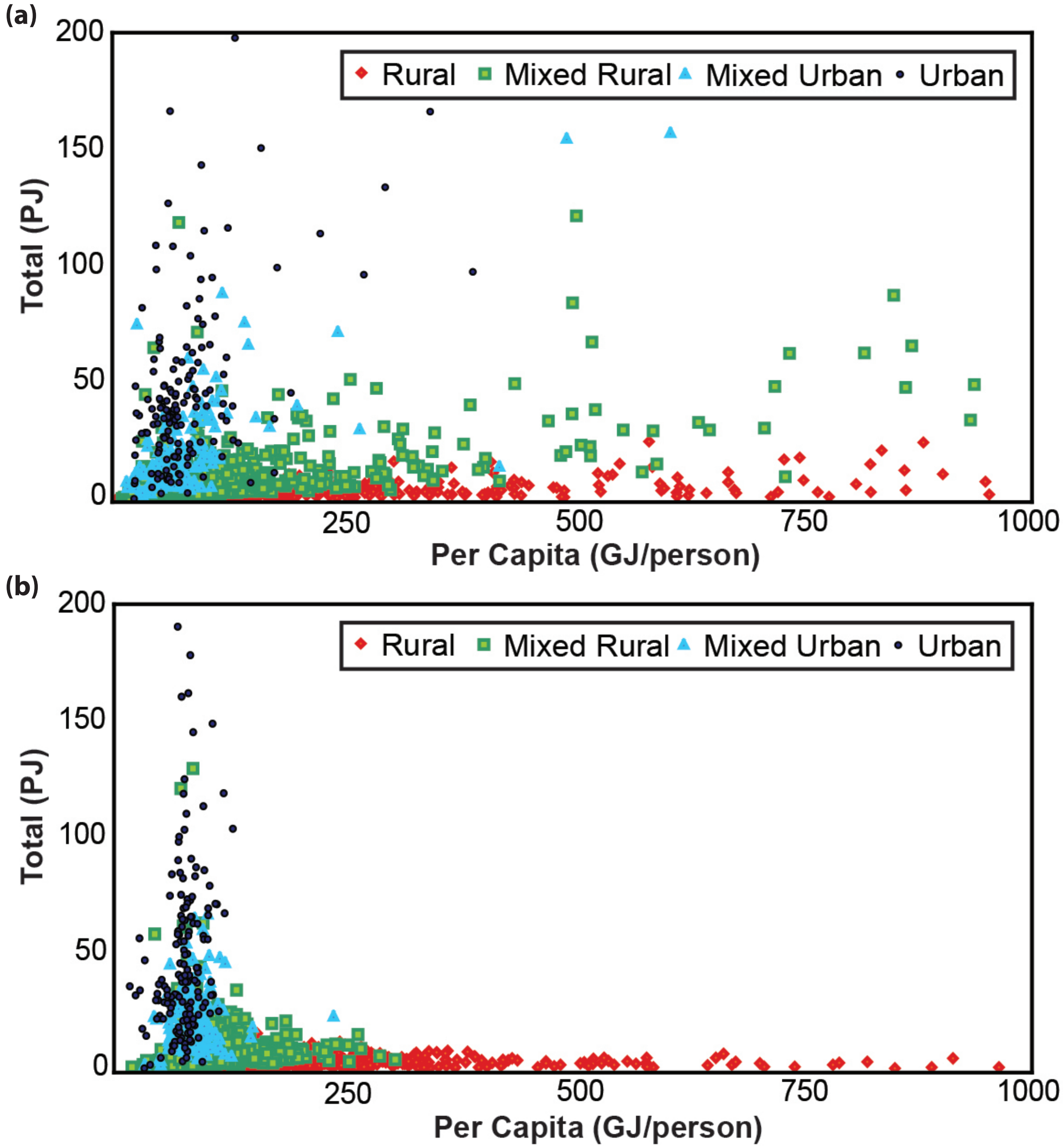


Figure 4.1. Per Capita Energy Consumption Versus Total Energy Consumption in Rural to Urban U.S. Counties. (a) Direct energy consumption measured in petajoules (PJ) and gigajoules (GJ) in building and industry and **(b)** direct energy consumption for transportation. [Figure source: Reprinted from Parshall et al., 2010, copyright Elsevier, used with permission.]

and the policy options available to cities in their role as innovators in emissions mitigation. This chapter aims to assess this understanding.

The current understanding of carbon fluxes from urban areas has improved considerably since the *First State of the Carbon Cycle Report* (SOCCR1;

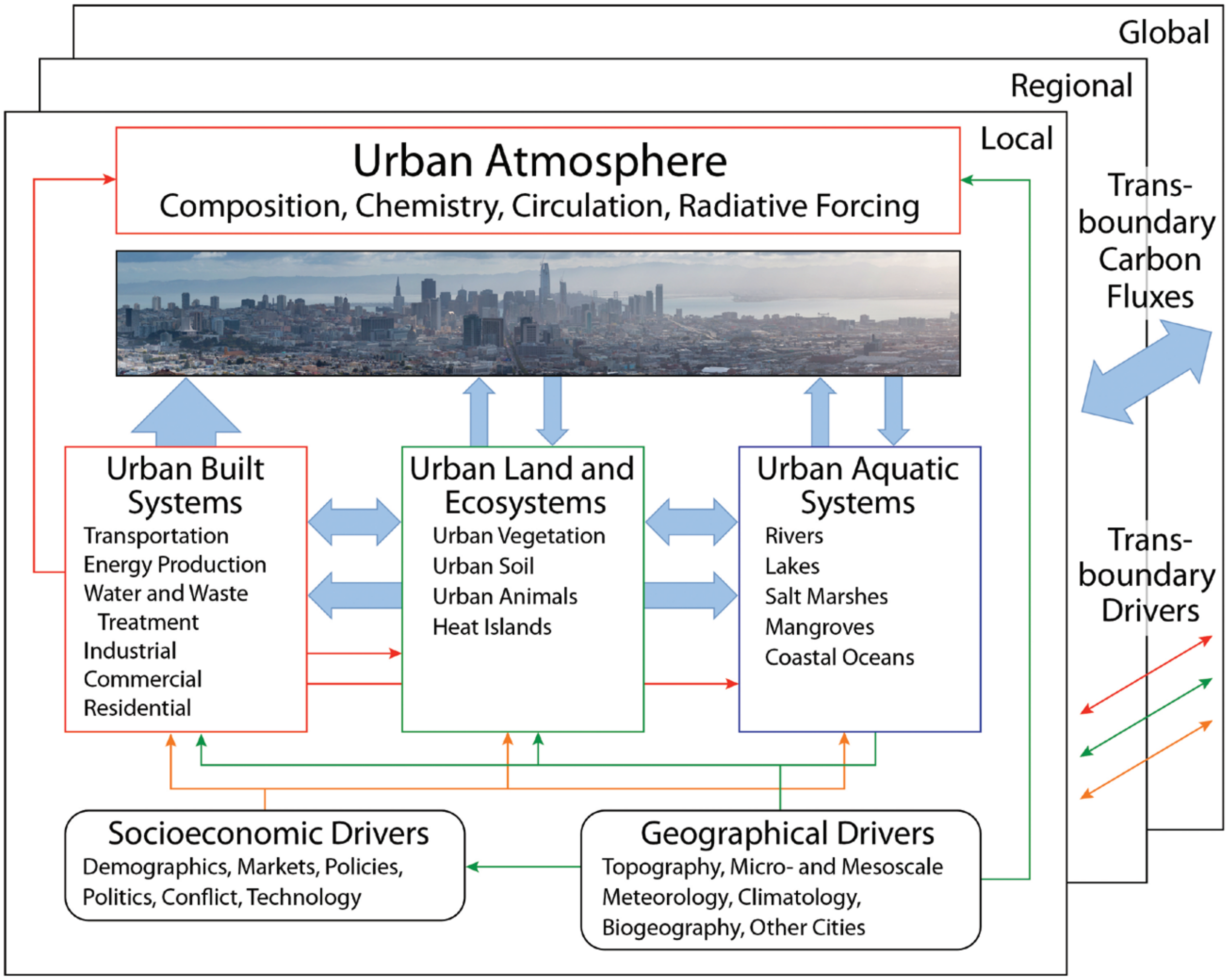
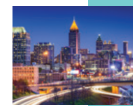


Figure 4.2. Key Components of Urban Carbon Cycling. Major reservoirs and processes (colored boxes) are depicted, along with carbon (C) emission and removal fluxes (blue block arrows), major drivers (oval boxes), and examples of process linkages (colored thin arrows). Outer boxes depict the relationships among local, regional, and global carbon through transboundary (lateral) carbon fluxes as well as interconnected drivers (e.g., socioeconomic, geographical, and built systems). [Figure source: Redrawn from Hutyra et al., 2014, used with permission under a Creative Commons license (CC-BY-NC-ND 3.0).]

CCSP 2007). Numerous urban carbon flux studies have been completed, and long-term research aimed at understanding aspects of urban carbon flows, drivers, and policy dimensions continues in some cities. Though often challenging to integrate, the growing number of studies within the North American urban domain are helping to improve understanding and establish new scientific knowledge and application to policymaking (Chester et al., 2014; Gurney et al., 2015; Hutyra et al., 2014; Marcotullio et al., 2014; Romero-Lankao et al., 2014).

Carbon flux differences within and across urban areas are more complex than the sum of populations, reflecting complex relationships among consumption, technology, infrastructure, economics, and behavior and lifestyle (see Figure 4.2, this page; Lenzen and Peters 2009; Lenzen et al., 2008; Seto et al., 2014). A key component of urban



carbon emissions, and a driver of future trends, is the interaction between human activity and the built environment, which includes large infrastructural systems such as buildings, roads, and factories. One need is to explore how urban infrastructure and morphology will influence current and future energy consumption and development (Creutzig et al., 2016; Müller et al., 2013; Salat and Bourdic 2012; Schiller 2007; Tanikawa and Hashimoto 2009).

The emerging role of subnational and transnational organizations and stakeholders within international policymaking, combined with the dominance of urban carbon emissions, has brought mitigation of carbon emissions from cities into consideration (Hsu et al., 2015; Rosenzweig et al., 2010, 2016; Wang 2012). Carbon mitigation approaches in North American cities vary widely due to a number of factors such as the urban economic profile, local policy initiatives, climate, and interactions with other governance levels (Homsy and Warner 2014; Krause 2012; Markolf et al., 2017; Sharp et al., 2010; Zahran et al., 2008). The impact of local policies on carbon emissions often is not monitored or assessed (Bulkeley 2010; Portney 2013), nor are the drivers for carbon mitigation policies systematically understood. Thus, causal links between policy and atmospheric effects are not always well known and may be unique to the city (Hughes 2017). Critically, urban emissions mitigation opportunities are often dependent upon or limited by interaction with governance at county, state, or provincial scales, emphasizing a need to better understand these relationships within the context of climate policy. For a better understanding of the societal drivers, further research is necessary on the interrelated environmental costs, benefits, constraints, and opportunities of different approaches within North American cities.

4.2 Current Understanding of Carbon Fluxes and Stocks

4.2.1 Accounting Framework and Methods

Many urban researchers, using a spectrum of methodological frameworks and measurement approaches, have quantified urban carbon flows and stocks in North American cities. The accounting framework determines the meaning and application of urban carbon flux information. Broadly speaking, two frameworks have been used: accounting for direct fluxes only or accounting that also includes indirect fluxes occurring outside the chosen urban area but driven by activities within it (Gurney 2014; Ibrahim et al., 2012; Wright et al., 2011). The former, also variously referred to as "production-based" or "in-boundary" accounting, quantifies all direct carbon flux between the Earth's surface and the atmosphere within the geographic boundaries of the urban area of study (Chavez and Ramaswami 2011; Ramaswami and Chavez 2013; Wright et al., 2011). In-boundary accounting also is aligned with "scope 1" flux, a term emanating from carbon footprinting of manufacturing supply chains (WRI/WBCSD 2004). This framework will include within-city combustion of fossil fuels, exchange of carbon with vegetation and soils, absorption by concrete, human respiration, anaerobic decomposition, and CH_4 leaks. An in-boundary accounting framework often is favored for integration with atmospheric measurements, which also can be used to estimate surface-to-atmosphere fluxes within the chosen geographical domain (Lauvaux et al., 2016).

Indirect fluxes include those associated with energy used to create or deliver electricity, products, or services consumed in a given urban area or the carbon flux associated with waste decay or removal of material to the waste stream (Minx et al., 2009; Mohareb and Kennedy 2012). These fluxes include consumption-based flow of products manufactured outside the consuming city (see Figure 4.3, p. 194). A study of eight cities found that the urban carbon footprint increased by an average of 47% when indirect fluxes were included (Hillman and Ramaswami 2010). Quantification of indirect fluxes typically employs a life cycle assessment framework and also can quantify the carbon stock residing in urban infrastructure or materials (Churkina et al., 2010; Fraser and Chester 2016; Hammond and Jones 2008; Lenzen 2014; Reyna and Chester 2015).

Figure 4.3. Relationships Between Carbon Inventory Approaches. Interactions are depicted between in-boundary or production-based urban carbon inventories and those that incorporate embedded or embodied carbon emissions. [Figure source: Adapted from Wright et al., 2011, used with permission.

In practice, urban carbon flux studies have used hybrids of the two frameworks, and the mixture reflects academic disciplinary interest, practical policy needs, and differing notions of responsibility or environmental justice (Blackhurst et al., 2011; Lin et al., 2015). There have been important attempts at standardizing urban carbon flux accounting frameworks via protocols or Intergovernmental Panel on Climate Change (IPCC)–approved methods (Carney and Shackley 2009; Ewing-Thiel and Manarolla 2011; Fong et al., 2014; WRI/WBCSD 2004). However, comparing urban carbon fluxes remains challenging without careful consideration of the accounting framework, city boundaries, and flux categories (Bader and Bleischwitz 2009; Hsu et al., 2016; Kennedy et al., 2009; Lamb et al., 2016; Parshall et al., 2010).

Distinct from the accounting framework used to conceptualize an urban carbon budget, the methods used to quantify urban carbon fluxes can be classified into two measurement approaches. "Top-down" approaches infer fluxes by using atmospheric measurements of CO_2 and CH_4 (and associated tracers)

and either measured or simulated atmospheric transport (Cambaliza et al., 2014; Lamb et al., 2016; Lauvaux et al., 2013, 2016; McKain et al., 2015; Miles et al., 2017; Turnbull et al., 2015; Wong et al., 2015). (See Ch. 8: Observations of Atmospheric Carbon Dioxide and Methane, p. 337, for more information on top-down approaches.) Multiple carbon sampling strategies have been used, including *in situ* stationary sampling from the ground (Djuricin et al., 2010; Miles et al., 2017; Turnbull et al., 2015), mobile ground-based sampling, aircraft measurements (Cambaliza et al., 2014, 2015), and remote sensing (Kort et al., 2012; Wong et al., 2015; Wunch et al., 2009). In addition, eddy covariance measurements have been employed on towers, buildings, and aircraft (Christen 2014; Crawford and Christen 2014; Grimmond et al., 2002; Menzer et al., 2015; Velasco and Roth 2010; Velasco et al., 2005). Recent aircraft and satellite remote-sensing studies have demonstrated the ability to map and estimate regional anthropogenic CO_2 (Hakkarainen et al., 2016) and facility-scale sources of CH_4 fluxes within cities and other complex areas (Frankenberg et al., 2016; Thompson et al., 2016).

"Bottom-up" approaches, by contrast, include a mixture of direct flux measurement, indirect estimation, and modeling. For example, a common estimation method uses a combination of economic activity data (e.g., population, number of vehicles, and building floor area) and associated emissions factors (e.g., amount of CO_2 emitted per activity), socioeconomic regression modeling, or scaling from aggregate fuel consumption (Gurney et al., 2012; Jones and Kammen 2014; Pincetl et al., 2014; Porse et al., 2016; Ramaswami and Chavez 2013). Direct end-of-pipe flux monitoring often is used for large facility-scale emitters such as power plants (Gurney et al., 2016). Indirect fluxes can be estimated through either direct atmospheric measurement (and apportioned to the domain of interest) or modeled through process-based (Clark and Chester 2017) or economic input-output (Ramaswami et al., 2008) models.

A key advance in quantifying urban carbon flux over the past decade has been the emergence of space and time bottom-up flux estimation to subcity scales (Brondfield et al., 2012; Gately et al., 2013; Gurney et al., 2009, 2012; Parshall et al., 2010; Patarasuk et al., 2016; Pincetl et al., 2014; Shu and Lam 2011; VandeWeghe and Kennedy 2007; Zhou and Gurney 2011). These approaches enable the interpretation of top-down approaches in addition to informing policy at the local scale for many cities globally (Duren and Miller 2012; Gurney et al., 2015). Despite recent attempts to integrate and reconcile various approaches to estimating urban carbon fluxes (Davis et al., 2017; Gurney et al., 2017; Lamb et al., 2016; Lauvaux et al., 2016; McKain et al., 2015), much research clearly remains to be done.

Table 4.1, p. 196, provides a sample of published research on urban carbon fluxes in North American cities, including key information about the studies, such as the accounting framework, flux measurement and estimation techniques, and references.

4.2.2 Human Activity and the Built Environment

The dominant source of carbon flux to the atmosphere from cities is associated with human activities and behaviors within the built landscape—energy use in buildings, fuel consumed in transportation (e.g., cars, airplanes, and rail), energy for manufacturing in factories, production of electricity, and energy used to build and rebuild urban infrastructure. (See Ch. 3: Energy Systems, p. 110, for more information on energy system carbon emissions and Ch. 6: Social Science Perspectives on Carbon, p. 264, for an analysis of the social and institutional practices and behaviors shaping carbon fluxes.) In addition to the combustion of fossil fuels (within and outside the urban domain), human activity within the built environment generates fluxes from 1) waste streams associated with the decomposition of materials containing carbon, 2) infrastructure leaking natural gas (composed primarily of CH_4), and 3) industrial processes that emit carbon without fuel combustion. Urban carbon fluxes associated with human activity and the built landscape often

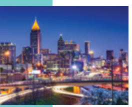


Table 4.1. Scientifically Based Urban Carbon Estimation Studies in North American Cities

Domain	Framework, Scope, Boundary[a]	Estimation Technique[b]	Sectors Estimated[c]	References	Notes[d]
Indianapolis, IN	In-boundary	Direct flux, activity-EF, and fuel statistics; airborne eddy flux measurement; isotopic atmospheric measurement; atmospheric inversion	All FF	Cambaliza et al. (2014); Gurney et al. (2012, 2017); Lauvaux et al. (2016); Turnbull et al. (2015)	Much of the work is space and time explicit; atmospheric monitoring includes $^{14}CO_2$, CO, and CH_4
Toronto, Canada	Life cycle (scopes 1, 2)	Activity-EF	Residential	Kennedy et al. (2009); VandeWeghe and Kennedy (2007)	Annual and census tract
Los Angeles, CA	In-boundary; embedded in buildings	Atmospheric measurement; activity-EF	All FF; on-road transportation; buildings	Feng et al. (2016); Kort et al. (2012); Newman et al. (2016); Pincetl et al. (2014); Porse et al. (2016); Reyna and Chester (2015); Wong et al. (2016); Wunch et al. (2009)	Some work is space and time explicit; atmospheric monitoring includes $^{14}CO_2$, CO, and CH_4
Salt Lake City, UT	In-boundary; consumption	Atmospheric measurement; direct flux, activity-EF, and fuel statistics; forest growth modeling and eddy flux measurement	All FF; biosphere	Kennedy et al. (2009); McKain et al. (2012); Pataki et al. (2006, 2009); Patarasuk et al. (2016)	Some work is space and time explicit
Baltimore, MD	In-boundary	Eddy flux measurement	All FF; biosphere	Crawford et al. (2011)	
Denver, Boulder, Fort Collins, and Arvada, CO; Portland, OR; Seattle, WA; Minneapolis, MN; Austin, TX	Hybrid life cycle (scopes 1, 2, 3)	Activity-EF	All FF	Hillman and Ramaswami (2010)	Addition of scope 3 emissions increased total footprint by 47%

Continued on next page

(Continued)

Table 4.1. Scientifically Based Urban Carbon Estimation Studies in North American Cities

Domain	Framework, Scope, Boundary[a]	Estimation Technique[b]	Sectors Estimated[c]	References	Notes[d]
New York City, NY; Denver; Los Angeles; Toronto; Chicago, IL	Scopes 1, 2, 3	Activity-EF, fuel statistics, and downscaling	Excludes some scope 3 emissions	Kennedy et al. (2009, 2010, 2014)	
Boston, MA; Seattle; New York City; Toronto	Scopes 1, 2 (some scope 3 included); scope 1 in lowland area	Activity-EF, fuel statistics and downscaling; flux chambers and remote sensing	Excludes some sectors; biosphere carbon stock change	Hutyra et al. (2011); Kennedy et al. (2012)	
Boston	In-boundary	Activity-EF; atmospheric monitoring; atmospheric monitoring and inversion	Onroad; pipeline leak; biosphere respiration	Brondfield et al. (2012); Decina et al. (2016); McKain et al. (2015); Phillips et al. (2013)	Some work is space and time explicit; includes some CH_4
Washington, D.C.; New York City; Toronto	Scope 1	Activity-EF and fuel statistics	All greenhouse gases	Dodman (2009)	Mixture of methods from multiple sources
Chicago				Grimmond et al. (2002)	
Mexico City, Mexico	In-boundary	Eddy flux measurement; activity-EF	All FF, biosphere; onroad	Chavez-Baeza and Sheinbaum-Pardo (2014); Velasco and Roth (2010); Velasco et al. (2005, 2009)	Footprint of single monitoring location; whole-city inventory
Halifax, Canada	Scopes 1, 2	Activity-EF	Buildings, transportation	Wilson et al. (2013)	Spatially explicit
Pittsburgh, PA	Scopes 1, 2	Activity-EF, fuel statistics, and downscaling	Residential, commercial, industrial, and transportation	Hoesly et al. (2012)	
Phoenix, AZ	In-boundary	Activity-EF and soil chamber	Onroad, electricity production, airport and aircraft	Koerner and Klopatek (2002)	
Vancouver, Canada	In-boundary	Eddy flux measurement	All FF, biosphere	Crawford and Christen (2014)	

Continued on next page

(Continued)

Table 4.1. Scientifically Based Urban Carbon Estimation Studies in North American Cities

Domain	Framework, Scope, Boundary[a]	Estimation Technique[b]	Sectors Estimated[c]	References	Notes[d]
Vancouver, Edmonton, Winnipeg, Toronto, Montreal, and Halifax, Canada	Scopes 1, 2	Activity-EF	Residential building stock	Mohareb and Mohareb (2014)	
20 U.S. cities	In-boundary; consumption; hybrid	Activity-EF	All energy related	Ramaswami and Chavez (2013)	

Notes

a) In-boundary refers to fluxes exchanged within a geographic boundary of a city (equivalent to scope 1); scope 2 refers to fluxes from power production facilities allocated to the electricity consumption within the boundary of a city; scope 3 refers to fluxes from the production of goods and services consumed within the boundary of a city.

b) Estimation Technique refers to the measurement or modeling approach taken to estimate or report emissions. "Activity-EF" refers to the combination of activity data (i.e., proxies of fuel consumption) and emissions factors to estimate fluxes. "Fuel statistics" refers to methods that use estimated fuel consumption and carbon content to estimate fluxes. "Downscaling" refers to the use of estimates at larger scales downscaled to the urban scale via spatial proxies or scaling factors. "Direct flux" refers to *in situ* flux measurement distinct from eddy flux approaches, such as measurement of stack flue gases.

c) Sectors Estimated refers to the categories of emissions included in the study. They can be broadly referred to as *residential*, *commercial*, *industrial*, *transportation* (includes onroad, nonroad, airport and aircraft, waterborne, and rail), *electricity production*, and *biosphere* (includes photosynthesis and respiration). "All FF" refers to all emissions related to fossil fuel combustion (all sectors).

d) $^{14}CO_2$, radioisotopic carbon dioxide; CO, carbon monoxide; CH_4, methane.

are categorized into economic sectors such as "residential," "commercial," "industrial," and "transportation," but the descriptions vary. Similarly, the distribution of fluxes among these sector divisions varies across urban areas, depending on the many intersecting drivers of carbon fluxes including history, geography, climate, technology, energy supply, urban form, and socioeconomics.

Among these economic sectors, activities within buildings and vehicle transportation are often the largest emitters and thus have garnered the greatest amount of study. For example, depending on the urban definition adopted, recent research found that up to 77% of onroad gasoline and diesel consumption occurs in urban areas within the United States and that urban areas accounted for 80% of the onroad emissions growth since 1980 (Gately et al., 2015; Parshall et al., 2010). In Mexico City, onroad vehicles account for 44% of metropolitan emissions of greenhouse gases (GHGs) such as CO_2, CH_4, and nitrous oxide (N_2O; Chavez-Baeza and Sheinbaum-Pardo 2014), while all of the country's transportation accounts for 31% of total emissions (INECC 2012).[1] Similarly, between 37% and 86% (varying with the definition of "urban") of direct fuel consumption in buildings and industry occurs in urban areas (Parshall et al., 2010).

While urban CO_2 emissions are dominated by fossil fuel combustion (see Figure 4.4, p. 199), a large portion of urban CH_4 emissions arise from leaking natural gas infrastructure serving cities (Alvarez et al., 2012; Cambaliza et al., 2015; Jackson et al., 2014; Lamb et al., 2016; McKain et al., 2015; Phillips et al., 2013; Wennberg et al.,

[1] Also see unfccc.int/national_reports/annex_i_ghg_inventories/national_inventories_submissions/items/9492.php.

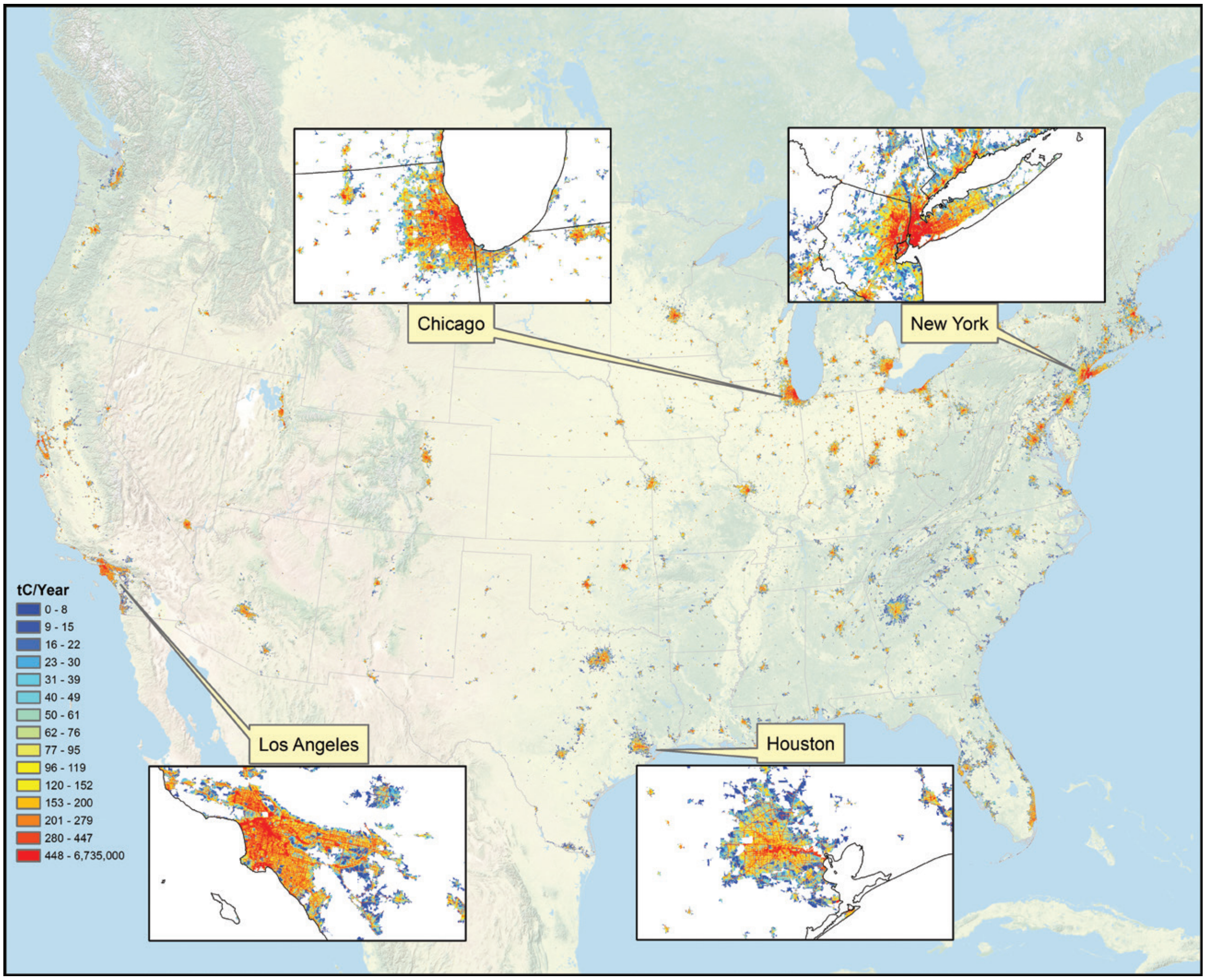
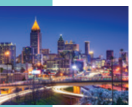


Figure 4.4. U.S. Fossil Fuel Carbon Emissions, Highlighting Four Urban Areas. [Data source: Gurney et al., 2009; units in log 10 tons of carbon (t C) per year.]

2012). (See Ch. 3: Energy Systems, p. 110, for details of leaked CH_4 emissions at the regional scale.) A study of CH_4 emissions from 13 urban distribution systems showed that emissions were roughly a factor of two smaller than U.S. Environmental Protection Agency (EPA) estimates, suggesting possible improvements in leak detection and maintenance work. However, the different methodologies between the two approaches would make assessing changes in leakage rates difficult (Lamb et al., 2015). At the same time, CH_4 emissions downstream from natural gas consumption meters on homes, buildings, and industrial facilities seem to be much higher than expected. A study in the San Francisco region suggests that emissions from the natural gas system can be equivalent to 0.3% to 0.5% of the region's natural gas consumption (Jeong et al., 2017). A similar study for the Los Angeles region estimates emissions at about 1.6% of consumption (Wunch et al., 2016). Los Angeles emissions may be higher because this region produces crude oil and natural gas. Aircraft mass balance and tower-based atmospheric inversions in Indianapolis differed by a factor of two and also exceeded the emissions estimated from a bottom-up inventory (Lamb et al., 2016).



This difference suggested that the aircraft estimate and the inventory did not account for widespread distribution of relatively small diffuse sources. These comparisons are complicated by the fact that they do not overlap in time and that emissions may be quite episodic and vary temporally. Long-term trend studies with sufficient precision to detect changes over time do not yet exist in the literature.

Methane also is produced by municipal waste facilities. In Toronto, these facilities account for as much as 10% of urban emissions (City of Toronto 2013); in Indianapolis, about 35% of emissions are attributed to one landfill (Cambaliza et al., 2015; Lamb et al., 2016).

4.2.3 Land and Ecosystems

Urban development directly and indirectly alters above- and belowground vegetation carbon pools and fluxes through land clearing, removal of vegetation, and disruption of soils (Raciti et al., 2012). Estimates of urban vegetation carbon densities vary substantially among cities or states and are based on extrapolation of limited, nonrandom sampling. Using extensive remote sensors and field observations, case studies in both Maryland and Massachusetts found that developed areas hold about 25% of the biomass per unit area of nearby forests (Huang et al., 2015; Raciti et al., 2014). Trees in urban areas in the United States and Canada store an estimated 643 teragrams of carbon (Tg C) and 34 Tg C, respectively (Nowak et al., 2013). In contrast, studies in xeric ecosystems show relative enhancement in urban biomass densities that result from landscaping preferences and addition of non-native vegetation (McHale et al., 2017).

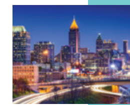
Growing conditions for vegetation in urban areas typically differ from nonurban ecosystems, potentially accelerating the cycling of carbon and nutrients (Briber et al., 2015; Reinmann and Hutyra 2017; Zhao et al., 2016). For example, urban areas experience elevated ambient air temperatures (i.e., the "urban heat island" [UHI] effect; Oke 1982). These elevated temperatures cause seasonally dependent changes in carbon fluxes from urban vegetation and soils (Decina et al., 2016; Pataki et al., 2006; Zhang et al., 2004; Zhao et al., 2016), altering the length of the urban growing season (Melaas et al., 2016; Zhang et al., 2006). Urban respiration and growth patterns also may differ due to human additions of water and fertilizers, removal or addition of labile carbon sources (e.g., leaf litter and mulch), and planting preferences (Templer et al., 2015). Urban vegetation also can influence local climate and energy use (Abdollahi et al., 2000; Gill et al., 2007; Lal and Augustin 2012; Nowak and Greenfield 2010; Wilby and Perry 2006). For example, urban trees may affect building energy consumption and associated carbon emissions directly through shading of building surfaces and altered use of cooling equipment (Raji et al., 2015) and indirectly through local reductions in air temperature (Nowak 1993; Sailor 1998). These effects require accounting for water and energy penalties associated with irrigation of managed urban vegetation (Litvak et al., 2017). In addition, fertilization of urban landscapes and management practices such as lawn mowing can carry a high energy cost that must be assessed when determining the net effect of urban vegetation on the carbon cycle (McPherson et al., 2005; Townsend-Small and Czimczik 2010).

4.3 Societal Drivers

Investigations across a variety of research disciplines (e.g., urban economics, urban planning, urban geography, and urban physics) have tried to discern the driving factors of per capita urban carbon fluxes. International comparisons have demonstrated that economic factors such as available income and energy price levels play crucial roles, but so do urban density profiles, building age and construction, climate, and technology (Creutzig et al., 2015a).

4.3.1 Consumption

Manufacturing of goods such as clothing emits carbon if energy consumption is satisfied by fossil fuels, but consumption of goods and services, production systems, and supply chains are the fundamental drivers of emissions. As mentioned in Section 4.2.1, p. 193, accounting frameworks that



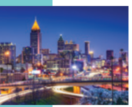
reflect a consumption perspective will allocate to the importing consumer the carbon fluxes associated with the production of goods and services. In particular, urban populations in wealthier nations that are nominally decarbonizing or stabilizing their carbon emissions often have total emissions that are increasing once traded carbon is considered in this way (Baiocchi and Minx 2010; Peters et al., 2011). Movement of goods among nations often is a result of trade policy, labor, and land costs that drive production location choices (Hertwich and Peters 2009). In U.K. cities, for example, a large carbon footprint is embedded in trade with large import partners such as China (Baiocchi and Minx 2010; Minx et al., 2013). Trade agreements, such as the North American Free Trade Agreement, have shifted automobile production and clothing manufacturing, along with their associated carbon emissions, from the United States to Canada and Mexico (Shui and Harriss 2005).

4.3.2 Economics—Wealth and Energy Prices

Economic development and urbanization reinforce each other through co-location of activities and investments (Fujita et al., 1999). In a global typology of cities, per capita gross domestic product (GDP) is identified as the most relevant sorting variable; transportation fuel prices also are relevant, distinguishing emissions among richer cities (Creutzig et al., 2015a). Urban development theories suggest that factors such as the clustering of investment and production, land development and transportation policies, and fuel prices shape urban form over the long run. For instance, incentives for dense urbanization exist when fuel prices are high and for sprawled suburbanization when prices are low, though legacy land uses—initiated during low fuel prices—continue to drive private automobile transportation use (Creutzig 2014; Fujita 1989). More recent urbanization patterns in mature cities have trended toward rehabilitation or gentrification of urban cores. However, more time is needed to know the long-term impact of these patterns and whether they represent a shift toward lower GHG emissions due to less reliance on automobiles (Florida 2010). Cities also create new public transportation systems to reduce automobile dependence, but carbon fluxes from infrastructure creation remain significant in the short term (Chester et al., 2013). In an international comparison, the United States belongs to a grouping of countries with high incomes but low fuel prices. A nationwide study estimating U.S. household flux at the zip code level found that the number of vehicles per household and annual household income were the most relevant variables explaining estimated household carbon emissions (Jones and Kammen 2014). This finding illustrates the difficulties of meeting multiple policy objectives in most North American cities; when priority is given to development and urbanization, there are implications for the carbon cycle (Romero-Lankao et al., 2015, 2017).

4.3.3 Behavior—Lifestyles and Norms

Urban mobility in North America is dominated by personal automobile use, shaping and reconfiguring daily urban life (Sheller and Urry 2000). Lifestyles and norms clearly play a powerful role in explaining everyday decisions about urban mobility and energy use, but their importance as drivers for carbon emissions generally has not been studied quantitatively (Axsen and Kurani 2012; Mattauch et al., 2016; Wilson and Dowlatabadi 2007). In the United Kingdom, lifestyle changes could contribute as much to climate mitigation in the transport sector as technological changes (Anable et al., 2012). A typology of residential carbon emissions reveals that infrastructure patterns are mirrored in lifestyle classes. For example, low-emitting households in the dense urban cores of London and some U.S. cities typically are either "young professionals" or "multicultural inner city" communities of young people seeking inner-city living with downsizing or elimination of personal automobiles. Households in peri-urban London having higher emissions mostly identify as "affluent urban commuters" living in relatively inefficient houses (Baiocchi et al., 2015). However, whether these patterns are indicative of a long-term shift or merely a short-term adjustment is unclear. Another example from the Los Angeles Energy Atlas finds that wealthy neighborhoods have



higher per capita energy consumption than low-income residents who have higher consumption per unit area (Porse et al., 2016). In Salt Lake City, Utah, increments of wealth among high-income residents were found to lead to greater residential CO_2 emissions than those of low-income residents (Patarasuk et al., 2016). A systematic investigation of lifestyles, especially in interaction with urban infrastructures, has been identified as a major priority for further research (Creutzig et al., 2016). Social norms and behavior patterns in terms of energy use and consumption also exhibit carbon "lock-in," whereby norms act in isolation and in concert with institutional and technological constraints to add inertia to existing patterns of consumption and carbon emissions (see further details in Section 4.3.5, this page).

4.3.4 Urban Form and Density

Research has identified urban form and the density of cities as key drivers of urban carbon emissions (Baiocchi et al., 2015; Creutzig et al., 2015a; Karathodorou et al., 2010; Mindali et al., 2004; Newman and Kenworthy 1989, 1999). In theory, dense settlement affords energy efficiencies by encouraging multidwelling living, reduced travel distances, public transit use, and walking and cycling (Boyko and Cooper 2011; Oleson et al., 2008). In the United States, analysis has shown declines in per capita carbon emissions with increasing population density at densities greater than 1,158 persons per km^2 (Jones and Kammen 2014). At lower densities, typical of suburban areas, carbon emissions rise with increases in density (Glaeser and Kahn 2010; Jones and Kammen 2014). These results are supported by recent research on transportation energy consumption (Liddle 2014), electricity consumption in buildings (Lariviere and Lafrance 1999), and overall urban carbon emissions (Marcotullio et al., 2013). A recent study found that the high correlation between per capita electricity use and urbanized area per person can be explained by the higher per capita building floor area in less-dense cities (Kennedy et al., 2015).

Urban form and density are determined by local plans, existing infrastructure, land costs, and public attitudes (Ewing and Rong 2008). These factors often are determined by local actions and constrained by national, state, or other regulations, such as the Federal Emergency Management Agency's 100-Year Flood Maps, insurance policies, and perceived costs of existing infrastructure and land. Change in land-use patterns, as well as services such as public transportation, require long-term commitment, public support, and funding. Once a pattern has been set, it tends toward obduracy, making change difficult (Unruh 2000). Zoning codes that segregate land uses contribute to urban sprawl and a car-dependent road infrastructure that, in turn, influences carbon emissions (Fischel 2015; Hamin and Gurran 2009). These rules vary across states, provinces, and cities because of different relationships of autonomy between cities and other governmental scales. Policy drivers may be generated at the different scales, including national (e.g., transportation infrastructure investments), state, provincial (e.g., requirements for cities to create general plans or set building codes), or city (e.g., specific zoning codes; Knaap et al., 2015). These rules, codes, and standards establish frameworks for cities, including facilitating sprawled urban form through road subsidies or land regulation or encouraging density and efficient building through strict building codes and tax policy that discourages automobile use and ownership (Grazi and van den Bergh 2008). Stricter land-use regulation can induce sprawl development in nearby suburban and peri-urban areas, an occurrence that may increase overall carbon emissions. That is, cities with stricter land-use regulations externalize development to adjacent communities with more lenient regulations, engendering higher rates of suburbanization in the region (Glaeser and Kahn 2010). Harmonization of land-use regulation or higher fuel taxes can reduce the likelihood of this outcome.

4.3.5 Technology

Technological attributes, such as power generation (see Ch. 3: Energy Systems, p. 110), urban design, and waste processing, partly determine city profiles for carbon emissions (Kennedy et al., 2009). Availability of low-carbon technologies reduces urban per

capita carbon emissions. For example, cities with carbon intensity of electricity below approximately 600 metric tons (t) CO_2 equivalent[2] (CO_2e) per gigawatt hour (GWh), such as Los Angeles, New York City, and Toronto, can reduce life cycle carbon emissions through electrification of transportation and heating systems (Kennedy 2015; Kennedy et al., 2014). However, because of the relative permanence of large technological and infrastructural systems in urban areas, the notion of infrastructure lock-in is critical and often makes shifts to low-carbon technologies and systems costly or not feasible (Unruh 2000). Lock-in results from the high cost of the infrastructure; the expended energy in the infrastructure; and the social systems of regulation, codes, and conventions that reinforce existing systems (Pincetl et al., 2016; Reyna and Chester 2015; Seto et al., 2016). However, technology is influenced by institutions, individual behavior, and policy actions (Chester et al., 2014), and technology has replacement or turnover cost implications with fossil fuel–burning infrastructure having lifetimes of up to 50 years (Erickson et al., 2015; see Figure 4.5, p. 204). The issue of carbon lock-in is another example of the interactions, constraints, and opportunities that involve multiple scales of governance beyond urban domains.

In 16 U.S. states and Washington, D.C., regulatory changes, such as Incentives for Renewables and Efficiency, are both facilitating and requiring decarbonization of energy (www.nrel.gov/tech_deployment/state_local_governments/basics_portfolio_standards.html). U.S. public utilities commissions (PUCs) regulate the large investor-owned utilities, and PUCs of states such as New York and California are creating new regulatory frameworks for increased renewable energy generation, purchase, and storage to decrease reliance on fossil fuel–generated energy. In 2015, California established a 50% renewable portfolio standard for the electricity system that is to be accomplished by 2030 (Senate Bill 350). The state also adopted a new legal mandate in September 2016 requiring statewide reductions of GHG emissions by 40% from 1990 levels by 2030 (Senate Bill 32).

4.3.6 Climate

Local climate is also a modifier of urban carbon emissions in conjunction with socioeconomic and urbanization characteristics (Baiocchi et al., 2015; Creutzig et al., 2015a; Glaeser and Kahn 2010; Kennedy et al., 2015). Global climate change typically modifies local energy use by reducing heating and increasing air conditioning demands (Huang and Gurney 2016). Local climate also can be partly influenced by human activity via the UHI effect (Boehme et al., 2015; Georgescu et al., 2014; Oke 1982), which, in turn, drives changes in energy consumption and carbon emissions (Lin et al., 2015; Wang et al., 2010).

4.4 Trends and Feedbacks

A quantitative understanding of contemporary urban carbon trends continues to face limitations related to data availability across the North American domain. Some understanding can be gleaned from statistics on urban growth in general, along with several case studies of urban carbon fluxes over particular time spans or locations. For example, Mexico's annual urban population grew at a rate of 1.9% between 1995 and 2015, while both Canada and the United States had urban growth rates of 1.2% (UN DESA 2015). Future projections at the global level and for North America suggest increases in urban land use. For example, there is a greater than 75% probability that global urban land will increase from 652,825 km^2 in 2000 to 1,863,300 km^2 in 2030 (Seto et al., 2012). Other studies have projected a near tripling in the percentage of land devoted to urban cover by midcentury (Nowak and Walton 2005).

The future trajectory of urban carbon fluxes is unambiguously tied to increases in aggregate urban energy demand and the proportion met by fossil fuels (Hoornweg et al., 2011; Jones and Kammen 2014; Marcotullio et al., 2013). Theoretically, these

[2] Carbon dioxide equivalent (CO_2e): Amount of CO_2 that would produce the same effect on the radiative balance of Earth's climate system as another greenhouse gas, such as methane (CH_4) or nitrous oxide (N_2O), on a 100-year timescale. For comparison to units of carbon, each kg CO_2e is equivalent to 0.273 kg C (0.273 = 1/3.67). See Preface for details.

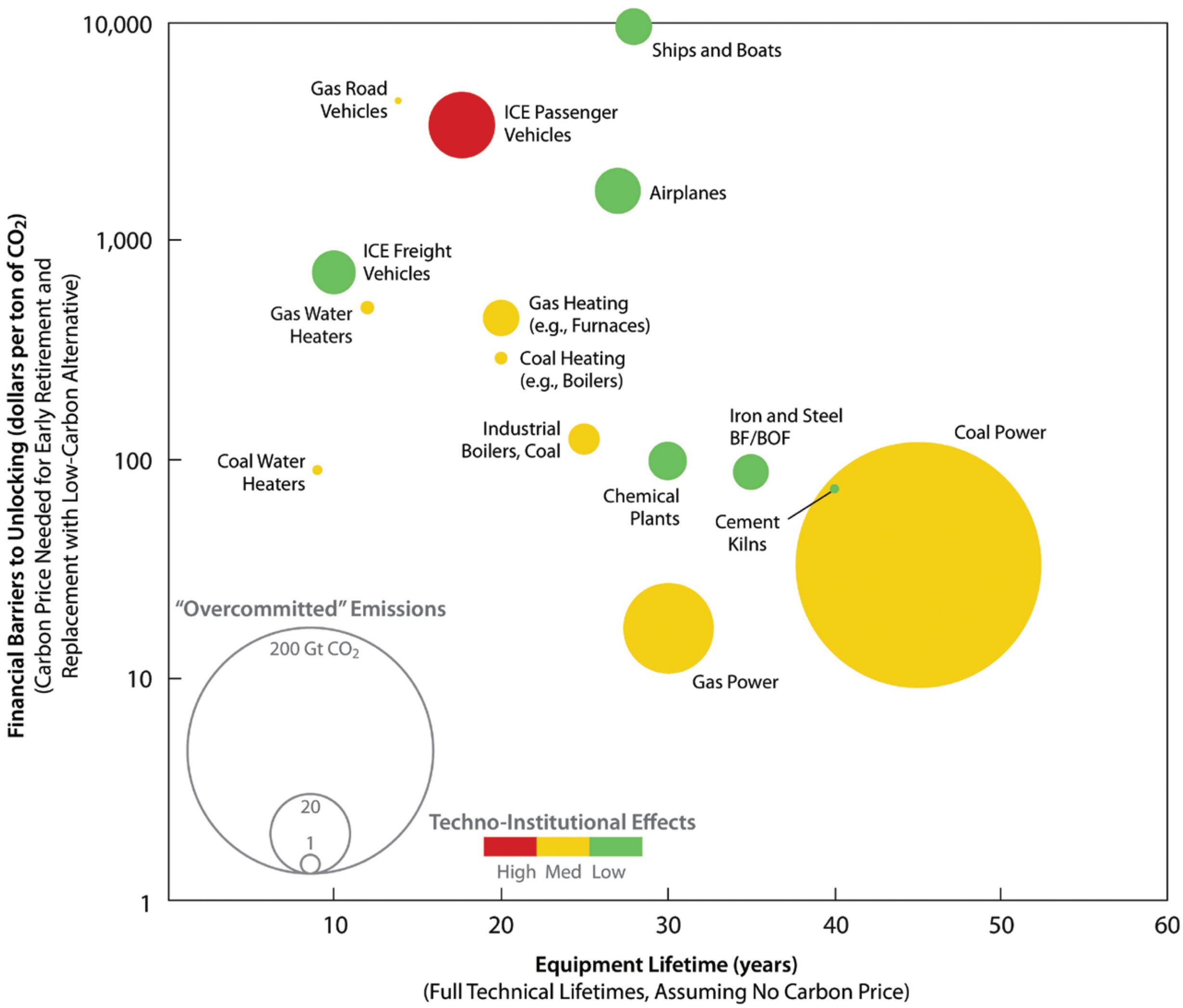


Figure 4.5. Assessments of Lock-In Related to Different Types of Infrastructure Emitting Carbon Dioxide (CO_2). Different fossil fuel–burning infrastructures are plotted according to their historical lifetime (x-axis) and the carbon price (in dollars per ton of CO_2) required to equalize the marginal cost of existing infrastructure (mainly fuel) with the total levelized cost (i.e., including capital and operating expenses) of a low-carbon replacement (y-axis). Circle sizes reflect the cumulative future emissions of each type of infrastructure that are in excess of what that infrastructure can emit under a 2°C climate scenario. Colors are qualitative indicators of the techno-institutional resistance of that type of infrastructure to unlocking (e.g., stocks of very specific intellectual capital, established subsidies, entrenched social norms, large supporting infrastructures, and political influence). Key: ICE, internal combustion engine; BF, blast furnace; BOF, basic oxygen furnace; Gt, gigaton. [Figure source: Redrawn from Seto et al., 2016 (originally adapted from Erickson et al., 2015), used with permission.]

increases are the cumulative result of concentrated population and economic activity, which today are predicated on the more energy intensive processes in agriculture, transportation, buildings, industry, and waste management (Liddle 2014). However, despite consensus about the positive correlation between population and energy demand or carbon emissions, there is debate about the magnitude of the effect and the implications of future urbanization. The effect of population size on carbon

emissions or energy demand may be contingent on other factors, including, for example, a city's starting population size (Bettencourt et al., 2007). Some evidence for this scaling relationship suggests that urban areas with larger population sizes have proportionally smaller energy infrastructures than smaller cities (Bettencourt et al., 2007; Fragkias et al., 2013). Other evidence suggests that carbon emissions may increase at a rate greater than population growth rates, so that larger cities exhibit proportionally higher energy demand as they grow than do smaller cities (Marcotullio et al., 2013). Theoretically, such an outcome is possibly due to diminishing returns, threshold effects, negative synergisms, and the disproportionate escalation of cost for maintaining environmental quality with population growth (Ehrlich and Holdren 1971). Finally, the difficulty occurs with predicting not only trends in policymaking, but also the impact of policy change on energy sources (Tuckett et al., 2015). For instance, in some U.S. states, policy is shifting some of the energy generation toward renewables (Lutsey and Sperling 2008). However, cost drivers for energy sources evolve over time and influence the choice of energy supply (Gan et al., 2007).

The generation of waste heat, coincident with carbon emissions from the combustion of fossil fuels, has the potential to initiate feedbacks with the urban carbon cycle through the UHI effect—a phenomenon whereby urban areas are warmer than their unbuilt surroundings (Boehme et al., 2015; Oke 1982). Averaged at the city scale, the magnitude of this waste heat can be up to 100 watts per m^2 (Sailor et al., 2015), potentially increasing urban warming by 2 to 3°C in winter and 0.5 to 2°C in summer (Fan and Sailor 2005). As urban areas warm due to both large-scale changes in climate and localized UHI, the energy consumed for space cooling in summer increases while the energy used for heating in winter decreases, "spilling over" into other seasons (Li et al., 2015; Wang et al., 2010). For example, recent research found that summer electricity demand may increase up to 50% in some U.S. states at the end of this century due to increased cooling needs under climate change alone (Huang and Gurney 2016). In fact, a recent modeling study by Georgescu et al. (2014) found that for U.S. cities, the effects of urban expansion on urban air temperatures by 2100 will be on the same order of magnitude as GHG-induced climate change. The UHI effect, in addition to changes in heatwave event frequency and magnitude, would further exacerbate this feedback (Li and Bou-Zeid 2013).

4.5 Global, North American, and Regional Context

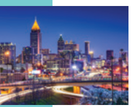
4.5.1 Global Urban Carbon

Of the nearly 1,000 urban agglomerations with more than 500,000 people across the world, three-quarters are in developing countries (UN DESA 2015). The share of energy-related urban CO_2 emissions worldwide is 71%, somewhat less than the share in North America (IEA 2008). Given the greater levels of current urbanization in North America and recent trends across the world, most future urban growth and associated urban carbon emissions likely will be dominated by low- and middle-income countries. In smaller urban areas within the United States and Europe, de-urbanization is occurring (Martinez-Fernandez et al., 2012), and its implications for carbon emissions are still poorly understood.

Within the global context, North America (particularly Canada and the United States) has smaller urban population densities but greater per capita built-up area (Seto et al., 2014). Due to extensive urbanization levels and fossil fuel consumption associated with transportation and urban infrastructure, North America has the largest percent of total carbon emissions emanating from urban areas (Marcotullio et al., 2013).

4.5.2 United States, Canada, and Mexico—Urban Carbon in Context

Cities in the United States and Canada generally have recorded amongst the highest per capita carbon emissions when compared to global cities (Dodman 2009; Hoornweg et al., 2011; Kennedy et al., 2009; Sovacool and Brown 2010). In cities for which there



are repeat carbon inventories (e.g., Boston, New York City, Toronto, and Seattle, from 2004 to 2009), per capita emissions are declining at the same rate as national inventories (Kennedy et al., 2012). But when indirect emissions are included in city inventories, urban per capita emissions are about the same as national per capita emissions (Ramaswami et al., 2008). This measurement further highlights the importance of understanding indirect carbon fluxes and the increase in the export of emissions outside the North American urban domain. Core aspects of per capita energy and material consumption have been found to be inversely correlated to urban population density (Kennedy et al., 2015).

4.6 Carbon Management Decisions

Since the mid-1990s, cities around the world have increasingly engaged in carbon management efforts, reflecting a growing recognition that cities are both locations where emissions-producing activities occur and political jurisdictions with authority over some of those activities (Castan Broto and Bulkeley 2013). The number of cities that have committed to some form of carbon reduction has increased exponentially, from fewer than 50 in the early 1990s, several hundred by the early 2000s (Bulkeley and Betsill 2003), and several thousand a decade later (Krause 2011; Pitt 2010). North American cities have played a particularly important leadership role, emerging as key sites for experimentation and innovation with different types of policies, technologies, and programs (Burch 2010; Castan Broto and Bulkeley 2013; Hoffmann 2011; Hughes and Romero-Lankao 2014, 2015).

4.6.1 Importance of Governance and Multilevel Networks

Key factors in the ability of city governments to manage carbon emissions are the mandates and competencies of municipal governments, financial resources, presence of political champions, multilevel networks, an open political opportunity structure, and the ability to capitalize on co-benefits valued by local residents (Betsill and Bulkeley 2007; Ryan 2015). Local authorities in North America also encounter a number of barriers, including the lack of coordination across different parts of city government, sunk investments in infrastructure, and resistance to change of the local political economy (Romero-Lankao et al., 2013, 2015; Sharp et al., 2010; Tang et al., 2010; Tozer 2013). A recent study found that U.S. city membership in the International Council for Local Environmental Initiatives (ICLEI) declined 22% between 2010 and 2012 and that large numbers of cities had abandoned their climate policy efforts altogether (Krause 2015).

Local carbon mitigation efforts also are limited by infrastructure lock-in and "path dependencies" created from previous policy decisions and investments, which can make changing direction politically difficult and expensive (Unruh 2000). Path dependency is a function of infrastructure cost and life cycle and is influenced by the way that decisions are made (Romero-Lankao et al., 2017). For instance, the low-density urban form of North American cities such as Los Angeles has been largely the result of freeway construction programs of the California Division of Highways (Wachs 1993). These decisions have created a path-dependent use of private vehicles, associated with more energy use and more carbon emissions (Kenworthy 2006).

There is one important difference in the policy contexts of cities in the United States, Canada, and Mexico. Cities occupy different jurisdictional space and face different economic, institutional, and political contexts. Decision making in the United States is generally more decentralized than that in Canada and Mexico, potentially giving city governments more autonomy (Bulkeley and Betsill 2013). Notwithstanding these across-country differences, the challenges and opportunities cities face, such as economic development, air pollution, and transit access, vary as much within countries as between them. For example, policy aimed at mitigation of local air pollution has resulted in climate policy co-benefits in most large North American cities, including Mexico City, but results typically are not as salient for smaller cities (Romero-Lankao 2007).

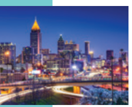
While municipal governments have some control over carbon emissions, urban carbon management ultimately takes place in a multilevel governance context, whereby climate policy efforts have the potential to be spread across different levels of political jurisdiction and pursued through diverse forms of governance instruments (see Ch. 3: Energy Systems, p. 110; Ch. 6: Social Science Perspectives on Carbon, p. 264; and Ch. 18: Carbon Cycle Science in Support of Decision Making, p. 728). For example, utilities can be governed by federal, regional, and state institutions and by public, private, and nonprofit partnerships that each make decisions on policy, infrastructure, and the mix of power generation in the electricity grid (Bulkeley 2010; Pincetl et al., 2016; Schreurs 2008). Municipal priorities and outcomes are shaped not only locally, but also by international agreements; national policies, legislation, and regulation; and state- and provincial-level efforts such as the adoption of renewable portfolio standards and the initiation of emissions trading markets (Bulkeley 2010; Bulkeley and Betsill 2013; Burch 2010; Romero-Lankao et al., 2017). National and state or provincial policies shape urban management efforts by creating a permissive or restrictive institutional setting for local action (Bulkeley and Betsill 2013; Burch 2010; Homsy and Warner 2014; Romero-Lankao et al., 2013, 2015, 2017). For example, federal and state agencies (e.g., public utility commissions) independently shape a number of energy-supply characteristics through rules, regulations, and standards. In California, state-level regulations are playing a significant role in spurring local action, such as calling for Zero Net Energy residential buildings by 2020, doubling energy efficiency for the existing building stock by 2030, and meeting renewable portfolio standards. In many North American cities, there is relatively little explicit interaction or coordination among these different levels of government (Betsill and Rabe 2009; Jacoby et al., 2014).

Thousands of North American cities and towns have joined municipal networks such as the C40 Cities Climate Leadership Group and the ICLEI (Kern and Bulkeley 2009; Robinson and Gore 2011), though participation is declining, as noted. Municipal climate change networks play a role in generating norms and standards for setting targets and monitoring and measuring progress (Betsill and Bulkeley 2004). These networks also provide opportunities for information sharing and capacity building. Cities join such networks to demonstrate leadership and secure recognition. However, the impact of network membership on local implementation or broader-scale policy change has yet to be demonstrated (Gore 2010; Krause 2012).

4.6.2 Sectoral Mitigation Approaches

Three urban sectors have been identified as key for mitigating urban carbon emissions: the built environment, transportation, and energy systems (see Section 4.2.2, p. 195). Carbon emissions from energy use in buildings can contribute as much as 80% of a city's total and primarily are controlled by private building owners (Rosenzweig et al., 2010). As a result, states and local authorities in many North American cities have begun to partner with private actors—the owners of these buildings—to integrate carbon mitigation and transition to low-carbon development within broader urban agendas (Bulkeley and Betsill 2013; Bulkeley and Castán Broto 2013; Hodson and Marvin 2010; While et al., 2010). Reducing energy consumption through energy-efficient building design and construction is an ongoing effort at the state and local levels in North America (Griego et al., 2012; Koski 2010; Larsson 1999). Mexico hosts the seventh largest green building market in the world,[3] and Canada is the largest green building market outside the United States. Cities also can incentivize or require energy conservation more directly. Energy-use benchmarking policies for the private sector are being promoted for North American cities, several of which have adopted these policies including New York City, Philadelphia, San Francisco, and Seattle (Cox et al., 2013). New York City's Greener, Greater Buildings program benchmarks energy use in private buildings and mandates energy efficiency

[3] www.gbes.com/blog/mexico-is-a-leed-leader/



and conservation measures (Block and Semel 2010). Similarly, California's Senate Bill 802 may make benchmarking mandatory for commercial buildings.[4] These examples have informed the National Resources Defense Council's City Energy Project, which is helping cities introduce benchmarking and conservation efforts of their own. The actual performance of buildings also depends on correct equipment installation, occupant behavior, and attitudes toward energy conservation (Mills and Schleich 2012; Virote and Neves-Silva 2012). Additionally, local authorities in Toronto are piloting a carbon credit trading program, and many cities have placed energy use and efficiency at the center of their climate change mitigation efforts (IEA 2015; Sun et al., 2015). California's Title 24 building codes, first established in 1978, have required increasingly stringent energy conservation for buildings, including insulation, window glazing, and more. These codes are credited for much of the state's energy savings (CEC 2015), but there also is evidence for a rebound effect as buildings, though more efficient, are bigger overall (Porse et al., 2016). Finally, the energy embodied in building construction can be incorporated into green building policy (Biswas 2014; Hammond and Jones 2008; Reyna and Chester 2015). Accounting and labeling systems, for example, measure and inform consumers about the environmental impacts of a structure (Dixit et al., 2010; Monahan and Powell 2011).

Transportation mitigation options include facilitating the transition to lower-emission vehicles and expanding the availability and use of public transit (Creutzig et al., 2015b). Cities are building electric vehicle charging stations, requiring low-emission vehicles in their own fleets, and encouraging biking and walking. Transit-oriented developments are designed to reduce the carbon emissions correlated with low-density suburban sprawl (Glaeser and Kahn 2010), though high capital costs and fragmented decision making continue to pose challenges. Additional challenges include long-term tradeoffs regarding the carbon impacts of different transit and fuel-mix options that continue to be evaluated (Chester et al., 2013).

Because cities consume about 75% of power generation worldwide (Dodman 2009), a common mitigation focus for cities is energy production itself. Many cities do not have formal authority to dictate the fuel sources for their energy supply and thus must rely on action from other levels of government and the private sector (Kern and Alber 2009). Reliance and cooperation require indirect action on the part of city governments, such as facilitating or incentivizing the expansion of renewable energy sources and lobbying relevant decision-making bodies. Examples include Toronto and Halifax's use of deep lake water to cool buildings, though there are barriers to scaling up such technologies (Newman and Herbert 2009). At the same time, there is increasing understanding of the need to couple solar generation with storage. Currently, "excess solar" generated in the middle of the day is not stored, requiring other electricity generation sources for peak load times and in the evening. Often this energy is provided by natural gas "peaker" power plants that constantly are powered, emitting CO_2 (St. John 2014).

Cities often have more direct control in areas such as waste-to-energy schemes and local distributed solar generation. For example, CH_4 capture at two of Toronto's largest landfills is responsible for just over 10 million tons of GHG reductions since 2004 (City of Toronto 2007, 2015). In California, local governments have begun to create Community Choice Aggregation alternative utilities that offer customers greater proportions of renewable energy (Roberts 2015). Key to ensuring the success of these programs is maintaining the subsidies and incentives to overcome behavioral and technological challenges (Kammen and Sunter 2016).

Two additional urban carbon cycle components deserve mention when considering sectoral mitigation approaches: CH_4 leakage (referred to as "fugitive" emissions) and urban vegetation. As mentioned in Section 4.2.2, p. 195, several studies have identified CH_4 emissions from leaking

[4] www.energy.ca.gov/sb350/

natural gas infrastructure serving cities (Jackson et al., 2014; Lamb et al., 2016; McKain et al., 2015; Phillips et al., 2013). Methane emissions also can occur downstream of building meters, for example, from leaky gas pipes in buildings, stoves, hot water heaters, and other appliances (Jeong et al., 2017; Lavoie et al., 2017; Wunch et al., 2016). The quantity of CH_4 emissions from the natural gas system is not well constrained (Brandt et al., 2014; Hendrick et al., 2016; Lamb et al., 2016; McKain et al., 2015), but there are specific thresholds for CH_4 loss from natural gas, which, if exceeded, would negate the climate benefit of switching to natural gas. According to Alvarez et al. (2012),[5] realizing an immediate net climate benefit from the use of natural gas would require CH_4 emissions from the natural gas system to be lower than 0.8%, 1.4%, and 2.7% of production to justify a transition from heavy-duty diesel vehicles, gasoline cars, and coal-burning power plants, respectively.

At the municipal scale, reports indicate that biological carbon uptake within urban boundaries constitutes 0.2% to 3% of total emissions, depending on the locality (Escobedo et al., 2010; Liu and Li 2012; Tang et al., 2016; Velasco et al., 2016). However, biological carbon respiration rates are sensitive to management practices (e.g., Decina et al., 2016), and urban vegetation possibly can constitute a net source of carbon to the atmosphere. The role of urban vegetation dynamics may be much more significant in affecting emissions through indirect impacts on the urban carbon cycle, such as shading of buildings that reduces energy consumption, evaporative cooling of urban vegetation, and wind sheltering (Akbari et al., 2001; Shashua-Bar et al., 2009; Susca et al., 2011). These indirect carbon reductions—a result of urban vegetation on energy consumption rather than direct carbon emissions–reducing technologies, for example—must be weighed against the energy and water penalty of increasing vegetation cover in locales with little or no historic vegetation canopy, such as the southwestern United States (Middel et al., 2014, 2015).

4.6.3 Co-Benefits and Tradeoffs—Links to Air Quality, Health, and UHI

Studies have identified co-benefits between carbon mitigation in urban areas and improvements in human health and other urban environmental issues (Harlan and Ruddell 2011; Milner et al., 2012; Viguié and Hallegatte 2012; see Ch. 6: Social Science Perspectives on Carbon, p. 264). For example, reducing fossil fuel consumption or CH_4 emissions also decreases emissions of traditional air pollutants such as carbon monoxide (CO), sulfur oxides (SO_x), volatile organic compounds (VOC), particulates, and oxides of nitrogen (NO_x). Three of these—NO_x, VOCs, and CO—are associated with the production of ground-level ozone, which is linked to respiratory diseases such as emphysema, bronchitis, and asthma (Kim et al., 2011). Various studies have linked fine particulate exposure to significant health problems including aggravated asthma, chronic respiratory disease in children, and premature death in people with heart or lung disease (Valavanidis et al., 2013). However, carbon mitigation practices also have tradeoffs. For instance, renewable energy systems that lower carbon emissions and reduce health impacts of traditional air pollutants are not completely free from environmental and health impacts (Miller et al., 2013).

Carbon emissions often are associated with waste heat production, which plays a role in the UHI effect. Strategies that reduce fossil fuel carbon emissions may contribute to reduced waste heat and, subsequently, a decrease in both summer and winter urban air temperatures. The magnitude of urban cooling may be modest and dependent on the location and timing of reduced energy consumption (Huang et al., 2013; Ostro et al., 2011; Sarofim et al., 2016) and the fuel mix used for electricity production and building heating systems (Jacobson and Ten Hoeve 2012).

[5] These numbers were modified from the Alvarez et al. (2012) study by the Environmental Defense Fund to account for new data (see www.energy.ca.gov/2014_energypolicy/documents/2014-06-23_workshop/presentations/13_O_Connor_EDF_IEPR-Presentation.pdf).

4.7 Synthesis, Knowledge Gaps, and Outlook

Dozens of completed or underway studies on urban carbon flux are now reported in the peer-reviewed literature (see Table 4.1, p. 196). Among these are intensive efforts testing different methods and approaches to understanding flux magnitudes, trends, driving activity, emissions mitigation guidance, and reduction performance tracking. Despite these efforts, consistent and comparable data on carbon fluxes in cities are still lacking, particularly at spatial resolutions below the whole-city level (Kennedy et al., 2015). Greater integration of these studies and greater exploration of whether and how this information can be used by stakeholders are needed. This will require continued efforts in interdisciplinary integration of existing subcommunities engaged in urban carbon research. For example, the use of sometimes singular reliance on atmospheric concentration observations common in inversion studies could move toward an assimilation framework in which all available observational constraints are incorporated with their accompanying uncertainties to arrive at optimized carbon fluxes, further integrating bottom-up and top-down approaches. Equally important are 1) the integration of information on CO_2, CH_4, and relevant local air pollution and 2) the continued trend toward data with higher space and time resolutions, particularly relevant to urban stakeholders. Finally, integration across ongoing urban studies will provide more insight into which research methods and approaches are successful under differing urban morphologies and social and physical constraints (e.g., urban density, data transparency, and topography). These advances could be achieved in part by integrating existing approaches with remote sensing of urban CO_2 and other attributes relevant to the urban carbon cycle.

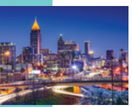
Urban carbon trends remain difficult to assess because of a lack of compatible and comparable data and limited historical information. Results from a number of intensive studies underway should begin to inform trend information in North America. Improvement to trend detection is critical to the assessment and prognostic capabilities important to urban stakeholders. Integration of urban trend detection with trend activity at larger scales could advance the ability of observing systems to systematically assess urban trends.

Urban carbon fluxes are dominated, directly and indirectly, by the human activities within the built environment that includes large infrastructural systems such as buildings, roads, and factories, along with their co-evolution with fossil fuel energy sources. The carbon fluxes associated with this co-evolved technological system are modulated by underlying climate and socioeconomic dynamics such as consumption, wealth, lifestyles, social norms, governance, and energy prices. A quantitative understanding of these drivers and flux outcomes remains difficult to generalize. This challenge is due to both the emergent properties of urban carbon fluxes and the idiosyncratic nature of cities and the studies performed thus far, which tend to focus on single urban domains. Particularly in Mexico, for example, little work has been accomplished outside the Mexico City metropolitan area. More research is needed that systematically explores multiple urban domains to better understand the relationships between emissions and the physical, social, and technological dynamics in cities.

The urban domain is a source of significant carbon mitigation potential evidenced by the rapid rise in individual urban-scale climate policy efforts. This mitigation, combined with the dominant role that cities play in total anthropogenic carbon emissions, implies that proposed emissions mitigation measures must be tested against documented success in urban areas. The ability of cities to manage carbon fluxes is determined by what control cities can exert over flux sources or their drivers. Cities and their carbon management efforts exist within a larger multilevel governance matrix that can both enable and hinder carbon mitigation efforts. For example, without control over energy supply systems, some cities have limited capability to mitigate emissions.

More targeted research evaluating how specific reductions in emissions are linked to specific policies would enhance the ability to design and implement effective policies in the future. There is limited evidence on the effects of urban climate policy on reducing community-wide emissions, advancing other urban policy goals, or contributing to a transition to low-carbon development. Attributing changes in urban carbon emissions to the actions of city governments also can be challenging, partly because of the complex networks of authority at play. Moreover, there has been little effort to study other effects of urban climate policy, such as cost-effectiveness, co-alignment with other goals and processes, and distributional effects on marginalized populations. Without common frameworks and comparable case studies, the extent to which local or distant political and economic factors shape these outcomes is unclear.

Given the increasing role that urban areas play in the total carbon fluxes within the three North American countries, there is a critical need to improve urban carbon flux projection capabilities in North American cities. Better information on fluxes and their drivers, combined with improved understanding of successful mitigation, would offer researchers and urban decision makers the means to bend urban flux trajectories toward low-carbon pathways. Continued work on the co-benefits and tradeoffs associated with carbon mitigation practices will further enrich carbon emissions planning to account for the important related issues of the UHI, urban air quality, and human health.



SUPPORTING EVIDENCE

KEY FINDING 1

Urban areas in North America are the primary source of anthropogenic carbon emissions, with cities responsible for a large proportion of direct emissions. These areas are also indirect sources of carbon through the emissions embedded in goods and services produced outside city boundaries for consumption by urban dwellers (*medium confidence, likely*).

Description of evidence base

Key Finding 1 is supported by empirical evidence and modeling studies aimed at quantifying and understanding urban extent, energy, carbon, and material flows (Jones and Kammen 2014; Hoornweg et al. 2011; Seto et al., 2014). Research has highlighted the importance of direct versus indirect carbon fluxes in addition to the relative importance of urban carbon flows within the national landscape (Lin et al., 2015).

Major uncertainties

Very few studies have attempted a comprehensive assessment of the urban portion of North American carbon emissions. Only two have attempted estimates for the North American domain (Marcotullio et al., 2013; Grubler et al., 2012). Both contain unquantified uncertainties acknowledged to include not only the underlying data, but also the definition of "urban" and objective methods to spatially enclose urban areas (Parshall et al., 2010). Uncertainty also exists in the exact quantification of urban versus nonurban carbon emissions because of limited data and methodological inconsistencies in defining direct and indirect carbon fluxes.

Assessment of confidence based on evidence and agreement, including short description of nature of evidence and level of agreement

Key Finding 1 is supported by a growing number of urban carbon footprint studies in North America. Much of this work is in the United States, with some work in Canada and very few studies in Mexico. There is general agreement that urban areas constitute the majority of anthropogenic carbon emissions in North America. However, a more precise assessment remains uncertain because of a lack of comprehensive data. Recent formalization of methods now defines direct versus indirect anthropogenic carbon emissions, but these methods are applied inconsistently in studies of urban carbon emissions, challenging attempts to compare emissions among cities.

Summary sentence or paragraph that integrates the above information

For Key Finding 1, anthropogenic carbon fluxes associated with North American cities represent the majority of total anthropogenic carbon emissions from North America, though uncertainty remains on the precise share. These emissions consist of both direct and indirect emissions, the latter of which are recognized as important, but often poorly characterized, components of total urban anthropogenic carbon flux.

KEY FINDING 2

Many societal factors drive urban carbon emissions, but the urban built environment and the regulations and policies shaping urban form (e.g., land use) and technology (e.g., modes of transportation) play crucial roles. Such societal drivers can lock in dependence on fossil fuels in the absence of major technological, institutional, and behavioral change. Some fossil fuel–related infrastructure can have lifetimes of up to 50 years (*high confidence*).

Description of evidence base

Key Finding 2 involves societal factors that drive urban carbon emissions, including consumption and supply chains (Baiocchi and Minx 2010; Peters et al., 2011), wealth (Creutzig et al., 2015a), fuel prices (Creutzig 2014), lifestyle and norms (Patarasuk et al., 2016; Porse et al., 2016), urban form and density (Baiocchi et al., 2015; Creutzig et al., 2015a; Karathodorou et al., 2010; Mindali et al., 2004; Newman and Kenworthy 1989, 1999), technology (Kennedy et al., 2009, 2014, 2015), and climate (Baiocchi et al., 2015; Creutzig et al., 2015a; Glaeser and Kahn 2010; Kennedy et al., 2015). Research continues to establish the relative permanence of large technological and infrastructural systems in urban areas. For example, fossil fuel–burning infrastructures have lifetimes up to 50 years, leading to systemic dependence (i.e., "lock-in") on fossil fuel–based technology (Unruh 2000; Seto et al., 2016; Erickson et al., 2015).

Major uncertainties

Increasing numbers of studies examine relationships between urban density and 1) atmospheric emissions and 2) building energy use. Uncertainty exists relative to the ability of cities to change their infrastructure because of cost considerations and municipal regulations, as well as state and national regulations that affect city form and infrastructure. Relationships among the core elements of carbon lock-in (i.e., technological, institutional, and behavioral) are poorly understood and involve interactions among scales of governance larger than urban areas. All these aspects vary widely across cities and North American countries.

Assessment of confidence based on evidence and agreement, including short description of nature of evidence and level of agreement

Studies are emerging that investigate these relationships, but more research is needed to understand the processes.

Summary sentence or paragraph that integrates the above information

For Key Finding 2, cities are complex systems with a mix of societal factors driving carbon emissions. Uncertainties remain regarding a complete typology of driving factors and the extent to which these factors lead to path dependencies and the ability of urban areas to alter infrastructure and technological trajectories.

KEY FINDING 3

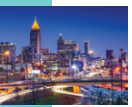
Key challenges for urban carbon flux studies are observational design, integration, uncertainty quantification, and reconciliation of the multiple carbon flux approaches to detect trends and inform emissions mitigation efforts (*medium confidence, likely*).

Description of evidence base

Key Finding 3 is supported by recent research that begins to integrate and reconcile carbon flux information from intensive urban study sites in North America. Key supporting references include Gurney et al. (2017), Lamb et al. (2016), Lauvaux et al. (2016), and McKain et al. (2012, 2015).

Major uncertainties

The major uncertainties related to integrating and reconciling urban carbon budget studies are those intrinsic to the different methodologies used. For trend detection and mitigation guidance, major uncertainties arise from the differences in scientific goals versus policy application.



Assessment of confidence based on evidence and agreement, including short description of nature of evidence and level of agreement

There is broad agreement that integration and reconciliation remain challenging. However, the various disciplines that pursue different methodological approaches to urban carbon flux assessment have different 1) definitions of uncertainty, 2) needs for attribution, and 3) criteria for successful mitigation guidance. Hence, some disagreement exists over specific policy application and utility.

Estimated likelihood of impact or consequence, including short description of basis of estimate

Continued integration and reconciliation of urban carbon fluxes are likely to achieve methodologically consistent and agreed-on approaches, results of which will be useful for trend detection and mitigation guidance. Assessment of enacted policy has received limited study, and thus the ability to independently assess atmospheric trends and use that information to inform mitigation progress and potential is highly important and relevant to urban carbon mitigation and climate policy.

Summary sentence or paragraph that integrates the above information

For Key Finding 3, the research community recently has begun to integrate and reconcile multiple approaches to urban carbon flux assessments for intensive study sites of urban carbon in North America. These efforts are ongoing but remain challenging due to methodological differences, methodological uncertainties, and differing disciplinary perspectives and criteria. The relevance and importance of these efforts are high because there remains limited independent assessment of urban carbon mitigation efforts or progress.

KEY FINDING 4

Improvements in air quality and human health and the reduction of the urban heat island are important co-benefits of urban carbon emissions mitigation (*high confidence, very likely*).

Description of evidence base

Numerous studies contribute to Key Finding 4, including research on the impacts of carbon emissions reductions on local air pollution, related human health benefits, and reduction of waste heat discharge (Harlan and Ruddell 2011; Huang et al., 2013; Jacobson and Ten Hoeve 2012; Milner et al., 2012; Ostro et al., 2011; Sarofim et al., 2016; Viguié and Hallegatte 2012).

Major uncertainties

Uncertainties include the precise magnitude of health and environmental benefits associated with reductions of carbon emissions. Benefits will vary with a number of factors such as urban population sociodemographics, urban meteorology, composition of emissions sources, and energy fuel mix. Tradeoffs require further research and remain uncertain.

Assessment of confidence based on evidence and agreement, including short description of nature of evidence and level of agreement

There is broad agreement about the benefits of reducing carbon emissions. Major uncertainties are related to assessing quantitatively the impacts and precise relationships between carbon emissions reductions and urban health and environmental benefits.

Estimated likelihood of impact or consequence, including short description of basis of estimate

Key Finding 4 is of high impact. The quantitative relationship between carbon emissions reductions and urban health and environmental impacts has direct and important implications for stakeholder decision making associated with urban air quality, urban climate policy, and general urban planning.

Summary sentence or paragraph that integrates the above information

For Key Finding 4, fossil fuel energy systems emit carbon dioxide (CO_2) and methane (CH_4). These systems also result in emissions of local air pollution and heat discharge in urban environments. Hence, reducing fossil fuel dependence can provide co-benefits to human health and environmental impacts associated with urban heat. The net benefit of these related outcomes remains uncertain because of potential tradeoffs and unforeseen outcomes.

KEY FINDING 5

Urban methane (CH_4) emissions have been poorly characterized, but the combination of improved instrumentation, modeling tools, and heightened interest in the problem is defining the range of emissions rates and source composition as well as highlighting infrastructure characteristics that affect CH_4 emissions (*high confidence*).

Description of evidence base

For Key Finding 5, consistent and persistent evidence of under-reported CH_4 emissions was found in Los Angeles, Boston, and Indianapolis (Lamb et al., 2016; McKain et al., 2015; Wong et al., 2016). Other studies report inverted distributions of CH_4 emissions in Los Angeles (75% thermogenic, 20% biogenic; Hopkins et al., 2016) compared with San Francisco (17% thermogenic, 82% biogenic; Jeong et al., 2017). Intensive field surveys of urban natural gas systems in seven cities indicate large variations in CH_4 leakage rates from urban gas distribution infrastructure attributed to differences in pipeline material and age (Hopkins et al., 2016; Jackson et al., 2014; Phillips et al., 2013; von Fischer et al., 2017).

Major uncertainties

The uncertainties in urban-scale CH_4 emissions estimates are not well established because the number of cities where these emissions have been studied is small and the temporal duration of the studies is very limited. While Key Finding 5 is of high confidence for the limited times and numbers of cities represented in the literature, this finding cannot yet be generalized across other North American cities.

Assessment of confidence based on evidence and agreement, including short description of nature of evidence and level of agreement

The assessment of confidence is based on a small number of cities where emissions have been studied over a short period of time. The confidence level is based on the results of these studies, which are robust and agreed upon, but this confidence does not necessarily apply across the continent due to the limited number of studies conducted to date.

Summary sentence or paragraph that integrates the above information

For Key Finding 5, urban CH_4 emissions estimates exist for several North American cities. Yet there are discrepancies between these estimates and governmental inventories. As such, further

research is needed to gain a complete understanding of uncertainties and assess the representativeness of these studies.

KEY FINDING 6

Urban areas are important sites for policymaking and decision making that shape carbon fluxes and mitigation. However, cities also are constrained by other levels of government, variations in their sources of authority and autonomy, capacity, competing local priorities, and available fiscal resources (*high confidence*).

Description of evidence base

Thousands of North American cities have joined municipal networks to pursue co-benefits from climate mitigation measures, including benchmarking initiatives. However, many cities do not have authority to dictate fuel sources for their energy supply or for vehicles, nor they do control carbon inputs into products that come into cities. Evidence for Key Finding 6 indicates that municipal carbon emissions mitigation initiatives in the United States vary significantly among states. This variation suggests that state-level policies and characteristics may influence the propensity of cities in their borders (Krause 2011). Jurisdictional barriers that restrict decision making by municipalities may impede change because of a lack of authority over decision making (Tozer 2013).

Major uncertainties

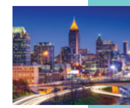
Cities vary in extent and type of innovation, though the precise motivation lacks sufficient evidence to provide a clear understanding of the factors involved. In addition, each country has different governmental arrangements that affect city autonomy; even within states in the same country, these arrangements may vary.

Assessment of confidence based on evidence and agreement, including short description of nature of evidence and level of agreement

Evidence of the importance of cities is supported by the large proportion of North American anthropogenic carbon emissions (see Key Finding 1). The evidence for the moderated influence over carbon emissions is supported by the mixture of political, economic, and social authority of cities over direct and indirect emissions sources.

Summary sentence or paragraph that integrates the above information

For Key Finding 6, cities are making policies to reduce their carbon emissions, but they also are constrained by many factors that can limit their authority. Moreover, cities vary widely among themselves. An understanding of the limitations in the ability of cities to mitigate their carbon emissions and why certain cities are more proactive than others is still to be developed.



REFERENCES

Abdollahi, K. K., Z. H. Ning, and A. Appeaning, 2000: *Global Climate Change and the Urban Forest.* [Gulf Coast Regional Climate Change Council (eds.)]. Franklin Press.

Akbari, H., M. Pomerantz, and H. Taha, 2001: Cool surfaces and shade trees to reduce energy use and improve air quality in urban areas. *Solar Energy*, **70**(3), 295-310, doi: 10.1016/S0038-092x(00)00089-X.

Alvarez, R. A., S. W. Pacala, J. J. Winebrake, W. L. Chameides, and S. P. Hamburg, 2012: Greater focus needed on methane leakage from natural gas infrastructure. *Proceedings of the National Academy of Sciences USA*, **109**(17), 6435-6440, doi: 10.1073/pnas.1202407109.

Anable, J., C. Brand, M. Tran, and N. Eyre, 2012: Modelling transport energy demand: A socio-technical approach. *Energy Policy*, **41**, 125-138, doi: 10.1016/j.enpol.2010.08.020.

Axsen, J., and K. S. Kurani, 2012: Social influence, consumer behavior, and low-carbon energy transitions. *Annual Review of Environment and Resources*, **37**, 311-340, doi: 10.1146/annurev-environ-062111-145049.

Bader, N., and R. Bleischwitz, 2009: Measuring urban greenhouse gas emissions: The challenge of comparability. *SAPIENS*, **2**(3), 1-15.

Baiocchi, G., and J. C. Minx, 2010: Understanding changes in the UK's CO_2 emissions: A global perspective. *Environmental Science and Technology*, **44**(4), 1177-1184, doi: 10.1021/es902662h.

Baiocchi, G., F. Creutzig, J. Minx, and P. P. Pichler, 2015: A spatial typology of human settlements and their CO_2 emissions in England. *Global Environmental Change: Human and Policy Dimensions*, **34**, 13-21, doi: 10.1016/j.gloenvcha.2015.06.001.

Betsill, M., and H. Bulkeley, 2007: Looking back and thinking ahead: A decade of cities and climate change research. *Local Environment*, **12**(5), 447-456, doi: 10.1080/13549830701659683.

Betsill, M. M., and H. Bulkeley, 2004: Transnational networks and global environmental governance: The cities for climate protection program. *International Studies Quarterly*, **48**(2), 471-493, doi: 10.1111/j.0020-8833.2004.00310.x.

Betsill, M. M., and B. G. Rabe, 2009: Climate change and multilevel governance: The Evolving state and local roles. In: *Toward Sustainable Communities: Transition and Transformations in Environmental Policy*. [D. A. Mazmanian and M. E. Kraft (eds.)]. MIT Press, pp. 201-225.

Bettencourt, L. M. A., J. Lobo, D. Helbing, C. Kuhnert, and G. B. West, 2007: Growth, innovation, scaling, and the pace of life in cities. *Proceedings of the National Academy of Sciences USA*, **104**(17), 7301-7306.

Biswas, W. K., 2014: Carbon footprint and embodied energy consumption assessment of building construction works in Western Australia. *International Journal of Sustainable Built Environment*, **3**(2), 179-186, doi: 10.1016/j.ijsbe.2014.11.004.

Blackhurst, M., H. Scott Matthews, A. L. Sharrard, C. T. Hendrickson, and I. L. Azevedo, 2011: Preparing U.S. community greenhouse gas inventories for climate action plans. *Environmental Research Letters*, **6**(3), 034003, doi: 10.1088/1748-9326/6/3/034003.

Block, K. M., and H. Semel, 2010: New York city's greener, greater buildings plan becomes law. *New York Law Journal*, **243**(5).

Boehme, P., M. Berger, and T. Massier, 2015: Estimating the building based energy consumption as an anthropogenic contribution to urban heat islands. *Sustainable Cities and Society*, **19**, 373-384, doi: 10.1016/j.scs.2015.05.006.

Boyko, C. T., and R. Cooper, 2011: Clarifying and re-conceptualising density. *Progress in Planning*, **76**(1), 1-61, doi: 10.1016/j.progress.2011.07.001.

Brandt, A. R., G. A. Heath, E. A. Kort, F. O'Sullivan, G. Petron, S. M. Jordaan, P. Tans, J. Wilcox, A. M. Gopstein, D. Arent, S. Wofsy, N. J. Brown, R. Bradley, G. D. Stucky, D. Eardley, and R. Harriss, 2014: Methane leaks from North American natural gas systems. *Science*, **343**(6172), 733-735, doi: 10.1126/science.1247045.

Briber, B. M., L. R. Hutyra, A. B. Reinmann, S. M. Raciti, V. K. Dearborn, C. E. Holden, and A. L. Dunn, 2015: Tree productivity enhanced with conversion from forest to urban land covers. *PLOS One*, **10**(8), e0136237, doi: 10.1371/journal.pone.0136237.

Brondfield, M. N., L. R. Hutyra, C. K. Gately, S. M. Raciti, and S. A. Peterson, 2012: Modeling and validation of on-road CO_2 emissions inventories at the urban regional scale. *Environmental Pollution*, **170**, 113-123, doi: 10.1016/j.envpol.2012.06.003.

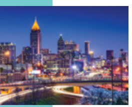
Bulkeley, H., 2010: Cities and the governing of climate change. *Annual Review of Environment and Resources*, **35**(1), 229-253, doi: 10.1146/annurev-environ-072809-101747.

Bulkeley, H., and M. M. Betsill, 2003: *Cities and Climate Change: Urban Sustainability and Global Environmental Governance.* Routledge, 237 pp.

Bulkeley, H., and M. M. Betsill, 2013: Revisiting the urban politics of climate change. *Environmental Politics*, **22**(1), 136-154, doi: 10.1080/09644016.2013.755797.

Bulkeley, H., and V. Castán Broto, 2013: Government by experiment? Global cities and the governing of climate change. *Transactions of the Institute of British Geographers*, **38**(3), 361-375, doi: 10.1111/j.1475-5661.2012.00535.x.

Burch, S., 2010: Transforming barriers into enablers of action on climate change: Insights from three municipal case studies in British Columbia, Canada. *Global Environmental Change*, **20**(2), 287-297, doi: 10.1016/j.gloenvcha.2009.11.009.



Cambaliza, M. O. L., P. B. Shepson, D. R. Caulton, B. Stirm, D. Samarov, K. R. Gurney, J. Turnbull, K. J. Davis, A. Possolo, A. Karion, C. Sweeney, B. Moser, A. Hendricks, T. Lauvaux, K. Mays, J. Whetstone, J. Huang, I. Razlivanov, N. L. Miles, and S. J. Richardson, 2014: Assessment of uncertainties of an aircraft-based mass balance approach for quantifying urban greenhouse gas emissions. *Atmospheric Chemistry and Physics*, **14**(17), 9029-9050, doi: 10.5194/acp-14-9029-2014.

Cambaliza, M. O. L., P. B. Shepson, J. Bogner, D. R. Caulton, B. Stirm, C. Sweeney, S. A. Montzka, K. R. Gurney, K. Spokas, O. E. Salmon, T. N. Lavoie, A. Hendricks, K. Mays, J. Turnbull, B. R. Miller, T. Lauvaux, K. Davis, A. Karion, B. Moser, C. Miller, C. Obermeyer, J. Whetstone, K. Prasad, N. Miles, and S. Richardson, 2015: Quantification and source apportionment of the methane emission flux from the city of Indianapolis. *Elementa: Science of the Anthropocene*, **3**, 000037, doi: 10.12952/journal.elementa.000037.

Carney, S., and S. Shackley, 2009: The Greenhouse Gas Regional Inventory Project (GRIP): Designing and employing a regional greenhouse gas measurement tool for stakeholder use. *Energy Policy*, **37**(11), 4293-4302, doi: 10.1016/j.enpol.2009.05.028.

Castan Broto, V., and H. Bulkeley, 2013: A survey of urban climate change experiments in 100 cities. *Global Environmental Change*, **23**(1), 92-102, doi: 10.1016/j.gloenvcha.2012.07.005.

CCSP, 2007: *First State of the Carbon Cycle Report (SOCCR): The North American Carbon Budget and Implications for the Global Carbon Cycle. A Report by the U.S. Climate Change Science Program and the Subcommittee on Global Change Research.* [A. W. King, L. Dilling, G. P. Zimmerman, D. M. Fairman, R. A. Houghton, G. Marland, A. Z. Rose, and T. J. Wilbanks (eds.)]. National Oceanic and Atmospheric Administration, National Climatic Data Center, Asheville, NC, USA, 242 pp.

CEC, 2015: *CEC Strategic Plan 2015-2020*. Commission for Environmental Cooperation, 24 pp. [http://www.cec.org/sites/default/files/documents/strategic_plans/strategic_plan_2015_2020.pdf]

Chavez-Baeza, C., and C. Sheinbaum-Pardo, 2014: Sustainable passenger road transport scenarios to reduce fuel consumption, air pollutants and GHG (greenhouse gas) emissions in the Mexico City metropolitan area. *Energy*, **66**, 624-634, doi: 10.1016/j.energy.2013.12.047.

Chavez, A., and A. Ramaswami, 2011: Progress toward low carbon cities: Approaches for transboundary GHG emissions' footprinting. *Carbon Management*, **2**(4), 471-482, doi: 10.4155/cmt.11.38.

Chester, M., S. Pincetl, Z. Elizabeth, W. Eisenstein, and J. Matute, 2013: Infrastructure and automobile shifts: Positioning transit to reduce life-cycle environmental impacts for urban sustainability goals. *Environmental Research Letters*, **8**(1), 015041, doi: 10.1088/1748-9326/8/1/015041.

Chester, M. V., J. Sperling, E. Stokes, B. Allenby, K. Kockelman, C. Kennedy, L. A. Baker, J. Keirstead, and C. T. Hendrickson, 2014: Positioning infrastructure and technologies for low-carbon urbanization. *Earth's Future*, **2**(10), 533-547, doi: 10.1002/2014ef000253.

Christen, A., 2014: Atmospheric measurement techniques to quantify greenhouse gas emissions from cities. *Urban Climate*, **10**, 241-260, doi: 10.1016/j.uclim.2014.04.006.

Churkina, G., D. G. Brown, and G. Keoleian, 2010: Carbon stored in human settlements: The conterminous United States. *Global Change Biology*, **16**(1), 135-143, doi: 10.1111/j.1365-2486.2009.02002.x.

City of Toronto, 2007: *Greenhouse Gases and Air Pollutants in the City of Toronto: Towards a Harmonized Strategy for Reducing Emissions*. I.C.F. International.

City of Toronto, 2013: *Summary of Toronto's 2011 Greenhouse Gas and Air Quality Pollutant Emissions Inventory*.

City of Toronto, 2015: *Toronto's 2013 Greenhouse Gas Inventory*.

Clark, S. S., and M. V. Chester, 2017: A hybrid approach for assessing the multi-scale impacts of urban resource use: Transportation in Phoenix, Arizona. *Journal of Industrial Ecology*, **21**(1), 136-150, doi: 10.1111/jiec.12422.

Cox, M., M. A. Brown, and X. J. Sun, 2013: Energy benchmarking of commercial buildings: A low-cost pathway toward urban sustainability. *Environmental Research Letters*, **8**(3), 035018, doi: 10.1088/1748-9326/8/3/035018.

Crawford, B., and A. Christen, 2014: Spatial source attribution of measured urban eddy covariance CO_2 fluxes. *Theoretical and Applied Climatology*, **119**(3-4), 733-755, doi: 10.1007/s00704-014-1124-0.

Crawford, B., C. S. B. Grimmond, and A. Christen, 2011: Five years of carbon dioxide fluxes measurements in a highly vegetated suburban area. *Atmospheric Environment*, **45**(4), 896-905, doi: 10.1016/j.atmosenv.2010.11.017.

Creutzig, F., 2014: How fuel prices determine public transport infrastructure, modal shares and urban form. *Urban Climate*, **10**, 63-76, doi: 10.1016/j.uclim.2014.09.003.

Creutzig, F., G. Baiocchi, R. Bierkandt, P. P. Pichler, and K. C. Seto, 2015a: Global typology of urban energy use and potentials for an urbanization mitigation wedge. *Proceedings of the National Academy of Sciences USA*, **112**(20), 6283-6288, doi: 10.1073/pnas.1315545112.

Creutzig, F., P. Jochem, O. Y. Edelenbosch, L. Mattauch, D. P. van Vuuren, D. McCollum, and J. Minx, 2015b: Transport: A roadblock to climate change mitigation? *Science*, **350**(6263), 911-912, doi: 10.1126/science.aac8033.

Creutzig, F., P. Agoston, J. C. Minx, J. G. Canadell, R. M. Andrew, C. L. Quéré, G. P. Peters, A. Sharifi, Y. Yamagata, and S. Dhakal, 2016: Urban infrastructure choices structure climate solutions. *Nature Climate Change*, **6**(12), 1054-1056, doi: 10.1038/nclimate3169.

Davis, K. J., A. Deng, T. Lauvaux, N. L. Miles, S. J. Richardson, D. P. Sarmiento, K. R. Gurney, R. M. Hardesty, T. A. Bonin, W. A. Brewer, B. K. Lamb, P. B. Shepson, R. M. Harvey, M. O. Cambaliza, C. Sweeney, J. C. Turnbull, J. Whetstone, and A. Karion, 2017: The Indianapolis Flux Experiment (INFLUX): A test-bed for developing urban greenhouse gas emission measurements. *Elementa: Science of the Anthropocene*, **5**(0), 21, doi: 10.1525/elementa.188.

Decina, S. M., L. R. Hutyra, C. K. Gately, J. M. Getson, A. B. Reinmann, A. G. Short Gianotti, and P. H. Templer, 2016: Soil respiration contributes substantially to urban carbon fluxes in the greater Boston area. *Environmental Pollution*, **212**, 433-439, doi: 10.1016/j.envpol.2016.01.012.

Dixit, M. K., J. L. Fernandez-Solis, S. Lavy, and C. H. Culp, 2010: Identification of parameters for embodied energy measurement: A literature review. *Energy and Buildings*, **42**(8), 1238-1247, doi: 10.1016/j.enbuild.2010.02.016.

Djuricin, S., D. E. Pataki, and X. Xu, 2010: A comparison of tracer methods for quantifying CO_2 sources in an urban region. *Journal of Geophysical Research*, **115**(D11), doi: 10.1029/2009jd012236.

Dodman, D., 2009: Blaming cities for climate change? An analysis of urban greenhouse gas emissions inventories. *Environment and Urbanization*, **21**(1), 185-201, doi: 10.1177/0956247809103016.

Duren, R. M., and C. E. Miller, 2012: Measuring the carbon emissions of megacities. *Nature Climate Change*, **2**(8), 560-562, doi: 10.1038/nclimate1629.

Ehrlich, P. R., and J. P. Holdren, 1971: Impact of population growth. *Science*, **171**(3977), 1212-1217, doi: 10.1126/science.171.3977.1212.

Erickson, P., S. Kartha, L. Michael, and K. Tempest, 2015: Assessing carbon lock-in. *Environmental Research Letters*, **10**:1–7, doi: 10.1088/1748-9326/10/8/084023.

Escobedo, F., S. Varela, M. Zhao, J. E. Wagner, and W. Zipperer, 2010: Analyzing the efficacy of subtropical urban forests in offsetting carbon emissions from cities. *Environmental Science and Policy*, **13**(5), 362-372, doi: 10.1016/j.envsci.2010.03.009.

Ewing-Thiel, J., and X. Manarolla, 2011: ICLEI USA draft framework for measuring and reporting community GHG emissions. *Carbon Management*, **2**(4), 371-375, doi: 10.4155/Cmt.11.41.

Ewing, R., and F. Rong, 2008: The impact of urban form on U.S. residential energy use. *Housing Policy Debate*, **19**, 1-30.

Fan, H., and D. Sailor, 2005: Modeling the impacts of anthropogenic heating on the urban climate of Philadelphia: A comparison of implementations in two PBL schemes. *Atmospheric Environment*, **39**(1), 73-84, doi: 10.1016/j.atmosenv.2004.09.031.

Feng, S., T. Lauvaux, S. Newman, P. Rao, R. Ahmadov, A. Deng, L. I. Díaz-Isaac, R. M. Duren, M. L. Fischer, C. Gerbig, K. R. Gurney, J. Huang, S. Jeong, Z. Li, C. E. Miller, apos, D. Keeffe, R. Patarasuk, S. P. Sander, Y. Song, K. W. Wong, and Y. L. Yung, 2016: Los Angeles megacity: A high-resolution land–atmosphere modelling system for urban CO_2 emissions. *Atmospheric Chemistry and Physics*, **16**(14), 9019-9045, doi: 10.5194/acp-16-9019-2016.

Fischel, W. A., 2015: *Zoning Rules! The Economics of Land Use Regulation*. Lincoln Institute of Land Policy.

Florida, R., 2010: *The Great Reset.* Harper Collins.

Fong, W. K., M. Sotos, M. Doust, S. Schultz, A. Marques, and C. Deng-Beck, 2014: *Global Protocol for Community-Scale Greenhouse Gas Emissions Inventories: An Accounting and Reporting Standard for Cities*. World Resources Institute, C40 Cities Climate Leadership, and ICLEL Local Governments for Sustainability.

Fragkias, M., J. Lobo, D. Strumsky, and K. C. Seto, 2013: Does size matter? Scaling of CO_2 emission and U.S. urban areas. *PLOS One*, **8**(6), e64727, doi: 10.1371/journal.pone0064727.

Frankenberg, C., A. K. Thorpe, D. R. Thompson, G. Hulley, E. A. Kort, N. Vance, J. Borchardt, T. Krings, K. Gerilowski, C. Sweeney, S. Conley, B. D. Bue, A. D. Aubrey, S. Hook, and R. O. Green, 2016: Airborne methane remote measurements reveal heavy-tail flux distribution in Four Corners region. *Proceedings of the National Academy of Sciences USA*, **113**(35), 9734-9739, doi: 10.1073/pnas.1605617113.

Fraser, A., and M. V. Chester, 2016: Environmental and economic consequences of permanent roadway infrastructure commitment: City road network lifecycle assessment and Los Angeles county. *Journal of Infrastructure Systems*, **22**(1), 04015018, doi: 10.1061/(asce)is.1943-555x.0000271.

Fujita, M., 1989: *Urban Economic Theory.* Cambridge University Press.

Fujita, M., P. R. Krugman, and A. J. Venables, 1999: *The Spatial Economy: Cities, Regions, and International Trade.* The MIT Press, Cambridge, Mass., USA. 367 pp.

Gan, L., G. S. Eskeland, and H. H. Kolshus, 2007: Green electricity market development: Lessons from Europe and the U.S. *Energy Policy*, **35**(1), 144-155, doi: 10.1016/j.enpol.2005.10.008.

Gately, C. K., L. R. Hutyra, and I. Sue Wing, 2015: Cities, traffic, and CO_2: A multidecadal assessment of trends, drivers, and scaling relationships. *Proceedings of the National Academy of Sciences USA*, **112**(16), 4999-5004, doi: 10.1073/pnas.1421723112.

Gately, C. K., L. R. Hutyra, I. S. Wing, and M. N. Brondfield, 2013: A bottom up approach to on-road CO_2 emissions estimates: Improved spatial accuracy and applications for regional planning. *Environmental Science and Technology*, **47**(5), 2423-2430, doi: 10.1021/es304238v.

Georgescu, M., P. E. Morefield, B. G. Bierwagen, and C. P. Weaver, 2014: Urban adaptation can roll back warming of emerging megapolitan regions. *Proceedings of the National Academy of Sciences USA*, **111**(8), 2909-2914, doi: 10.1073/pnas.1322280111.

Gill, S. E., J. F. Handley, A. R. Ennos, and S. Pauleit, 2007: Adapting cities for climate change: The role of the green infrastructure. *Built Environment*, **33**(1), 115-133, doi: 10.2148/benv.33.1.115.

Glaeser, E. L., and M. E. Kahn, 2010: The greenness of cities: Carbon dioxide emissions and urban development. *Journal of Urban Economics*, **67**(3), 404-418, doi: 10.1016/j.jue.2009.11.006.

Gore, C. D., 2010: The limits and opportunities of networks: Municipalities and Canadian climate change policy. *Review of Policy Research*, **27**(1), 27-46, doi: 10.1111/j.1541-1338.2009.00425.x.

Grazi, F., and J. C. J. M. van den Bergh, 2008: Spatial organization, transport, and climate change: Comparing instruments of spatial planning and policy. *Ecological Economics*, **67**(4), 630-639, doi: 10.1016/j.ecolecon.2008.01.014.

Griego, D., M. Krarti, and A. Hernández-Guerrero, 2012: Optimization of energy efficiency and thermal comfort measures for residential buildings in Salamanca, Mexico. *Energy and Buildings*, **54**, 540-549, doi: 10.1016/j.enbuild.2012.02.019.

Grimmond, C. S. B., T. S. King, F. D. Cropley, D. J. Nowak, and C. Souch, 2002: Local-scale fluxes of carbon dioxide in urban environments: Methodological challenges and results from Chicago. *Environmental Pollution*, **116**, S243-S254, doi: 10.1016/s0269-7491(01)00256-1.

Grubler A., X. Bai, T. Buettner, S. Dhakal, D. Fisk, T. Ichinose, J. Keirstead, G. Sammer, D. Satterthwaite, N. Schulz, N. Shah, J. Steinberger, and H. Weisz, 2012. Urban energy systems. In: *Global Energy Assessment: Toward a Sustainable Future*. Cambridge University Press, Cambridge, UK, and New York, NY, USA and the International Institute for Applied Systems Analysis, Laxenburg, Austria, pp. 1307–1400.

Gurney, K. R., 2014: Recent research quantifying anthropogenic CO_2 emissions at the street scale within the urban domain. *Carbon Management*, **5**(3), 309-320, doi: 10.1080/17583004.2014.986849.

Gurney, K. R., J. Huang, and K. Coltin, 2016: Bias present in U.S. federal agency power plant CO_2 emissions data and implications for the U.S. clean power plan. *Environmental Research Letters*, **11**(6), 064005, doi: 10.1088/1748-9326/11/6/064005.

Gurney, K. R., I. Razlivanov, Y. Song, Y. Zhou, B. Benes, and M. Abdul-Massih, 2012: Quantification of fossil fuel CO_2 emissions on the building/street scale for a large U.S. city. *Environmental Science and Technology*, **46**(21), 12194-12202, doi: 10.1021/es3011282.

Gurney, K. R., D. L. Mendoza, Y. Zhou, M. L. Fischer, C. C. Miller, S. Geethakumar, and S. de la Rue du Can, 2009: High resolution fossil fuel combustion CO_2 emission fluxes for the United States. *Environmental Science and Technology*, **43**(14), 5535-5541, doi: 10.1021/es900806c.

Gurney, K. R., J. Liang, R. Patarasuk, D. O'Keeffe, J. Huang, M. Hutchins, T. Lauvaux, J. C. Turnbull, and P. B. Shepson, 2017: Reconciling the differences between a bottom-up and inverse-estimated $FFCO_2$ emissions estimate in a large U.S. urban area. *Elementa: Science of the Anthropocene*, **5**, 44, doi: 10.1525/elementa.137.

Gurney, K. R., P. Romero-Lankao, K. C. Seto, L. R. Hutyra, R. Duren, C. Kennedy, N. B. Grimm, J. R. Ehleringer, P. Marcotullio, S. Hughes, S. Pincetl, M. V. Chester, D. M. Runfola, J. J. Feddema, and J. Sperling, 2015: Climate change: Track urban emissions on a human scale. *Nature*, **525**(7568), 179-181, doi: 10.1038/525179a.

Hakkarainen, J., I. Ialongo, J. Tamminen, 2016: Direct space-based observations of anthropogenic CO_2 emission 12 areas from OCO-2. *Geophysical Research Letters*, **43**, 11400-11406, doi: 10.1002/2016GL070885.

Hamin, E. M., and N. Gurran, 2009: Urban form and climate change: Balancing adaptation and mitigation in the U.S. and Australia. *Habitat International*, **33**(3), 238-245, doi: 10.1016/j.habitatint.2008.10.005.

Hammond, G. P., and C. I. Jones, 2008: Embodied energy and carbon in construction materials. *Proceedings of the Institution of Civil Engineers - Energy*, **161**(2), 87-98, doi: 10.1680/ener.2008.161.2.87.

Harlan, S. L., and D. M. Ruddell, 2011: Climate change and health in cities: Impacts of heat and air pollution and potential co-benefits from mitigation and adaptation. *Current Opinion in Environmental Sustainability*, **3**(3), 126-134, doi: 10.1016/j.cosust.2011.01.001.

Hendrick, M. F., S. Cleveland, and N. G. Phillips, 2016: Unleakable carbon. *Climate Policy*, 1-8, doi: 10.1080/14693062.2016.1202808.

Hertwich, E. G., and G. P. Peters, 2009: Carbon footprint of nations: A global, trade-linked analysis. *Environmental Science and Technology*, **43**(16), 6414-6420, doi: 10.1021/es803496a.

Hillman, T., and A. Ramaswami, 2010: Greenhouse gas emission footprints and energy use benchmarks for eight U.S. cities. *Environmental Science and Technology*, **44**(6), 1902-1910, doi: 10.1021/es9024194.

Hodson, M., and S. Marvin, 2010: Can cities shape socio-technical transitions and how would we know if they were? *Research Policy*, **39**(4), 477-485, doi: 10.1016/j.respol.2010.01.020.

Hoesly, R., M. Blackhurst, H. S. Matthews, J. F. Miller, A. Maples, M. Pettit, C. Izard, and P. Fischbeck, 2012: Historical carbon footprinting and implications for sustainability planning: A case study of the Pittsburgh region. *Environmental Science and Technology*, **46**(8), 4283-4290, doi: 10.1021/es203943q.

Hoffmann, M. J., 2011: *Climate Governance at the Crossroads: Experimenting with a Global Response After Kyoto.* Oxford University Press. 224 pp.

Homsy, G. C., and M. E. Warner, 2014: Cities and sustainability: Polycentric action and multilevel governance. *Urban Affairs Review*, **51**(1), 46-73, doi: 10.1177/1078087414530545.

Hoornweg, D., L. Sugar, C. Lorena, and T. Gomez, 2011: Cities and greenhouse gas emissions: Moving forward. *Environment and Urbanization*, **23**(1), 207-227.

Hopkins, F. M., J. R. Ehleringer, S. E. Bush, R. M. Duren, C. E. Miller, C.-T. Lai, Y.-K. Hsu, V. Carranza, and J. T. Randerson, 2016: Mitigation of methane emissions in cities: How new measurements and partnerships can contribute to emissions reduction strategies. *Earth's Future*, **4**(9), 408-425, doi: 10.1002/2016ef000381.

Hsu, A., A. S. Moffat, A. J. Weinfurter, and J. D. Schwartz, 2015: Commentary: Towards a new climate diplomacy. *Nature Climate Change*, **5**(6), 501-503, doi: 10.1038/nclimate2594.

Hsu, A., Y. Cheng, A. Weinfurter, K. Xu, and C. Yick, 2016: Track climate pledges of cities and companies. *Nature*, **532**(7599), 303-306, doi: 10.1038/532303a.

Huang, C., A. G. Barnett, Z. Xu, C. Chu, X. Wang, L. R. Turner, and S. Tong, 2013: Managing the health effects of temperature in response to climate change: Challenges ahead. *Environmental Health Perspectives*, **121**(4), 415-419, doi: 10.1289/ehp.1206025.

Huang, J., and K. R. Gurney, 2016: Impact of climate change on U.S. building energy demand: Sensitivity to spatiotemporal scales, balance point temperature, and population distribution. *Climatic Change*, **137**(1-2), 171-185, doi: 10.1007/s10584-016-1681-6.

Huang, W., A. Swatantran, K. Johnson, L. Duncanson, H. Tang, J. O'Neil Dunne, G. Hurtt, and R. Dubayah, 2015: Local discrepancies in continental scale biomass maps: A case study over forested and non-forested landscapes in Maryland, USA. *Carbon Balance Management*, **10**, 19, doi: 10.1186/s13021-015-0030-9.

Hughes, S., 2017: The politics of urban climate change policy: Toward a research agenda. *Urban Affairs Review*, **53**(2), 362-380, doi: 10.1177/1078087416649756.

Hughes, S., and P. Romero-Lankao, 2014: Science and institution building in urban climate-change policymaking. *Environmental Politics*, **23**(6), 1023-1042, doi: 10.1080/09644016.2014.921459.

Hutyra, L. R., B. Yoon, J. Hepinstall-Cymerman, and M. Alberti, 2011: Carbon consequences of land cover change and expansion of urban lands: A case study in the Seattle metropolitan region. *Landscape and Urban Planning*, **103**(1), 83-93, doi: 10.1016/j.landurbplan.2011.06.004.

Hutyra, L. R., R. Duren, K. R. Gurney, N. Grimm, E. A. Kort, E. Larson, and G. Shrestha, 2014: Urbanization and the carbon cycle: Current capabilities and research outlook from the natural sciences perspective. *Earth's Future*, **2**(10), 473-495, doi: 10.1002/2014ef000255.

Ibrahim, N., L. Sugar, D. Hoornweg, and C. Kennedy, 2012: Greenhouse gas emissions from cities: Comparison of international inventory frameworks. *Local Environment*, **17**(2), 223-241, doi: 10.1080/13549839.2012.660909.

IEA, 2008: *World Energy Outlook 2008.* International Energy Agency. 578 pp. [https://www.iea.org/media/weowebsite/2008-1994/WEO2008.pdf]

IEA, 2015: IEA Building Energy Efficiency Policies Database: United States. International Energy Agency. [https://www.iea.org/beep/]

INECC, 2012: *México, Quinta Comunicación Nacional Ante la Convención Marco de las Naciones Unidas Sobre el Cambio Climático*. Instituto Nacional de Ecología y Cambio Climático.

Jackson, R. B., A. Down, N. G. Phillips, R. C. Ackley, C. W. Cook, D. L. Plata, and K. Zhao, 2014: Natural gas pipeline leaks across Washington, DC. *Environmental Science and Technology*, **48**(3), 2051-2058, doi: 10.1021/es404474x.

Jacobson, M. Z., and J. E. Ten Hoeve, 2012: Effects of urban surfaces and white roofs on global and regional climate. *Journal of Climate*, **25**(3), 1028-1044, doi: 10.1175/jcli-d-11-00032.1.

Jacoby, H. D., A. C. Janetos, R. Birdsey, J. Buizer, K. Calvin, F. de la Chesnaye, D. Schimel, I. S. Wing, R. Detchon, J. Edmonds, L. Russell, and J. West, 2014: Mitigation. In: *Climate Change Impacts in the United States: the Third National Climate Assessment.* [J. M. Melillo, T. T. C. Richmond, and G. W. Yohe (eds.)]. U.S. Global Change Research Program, pp . 648-669.

Jeong, S., X. G. Cui, D. R. Blake, B. Miller, S. A. Montzka, A. Andrews, A. Guha, P. Martien, R. P. Bambha, B. LaFranchi, H. A. Michelsen, C. B. Clements, P. Glaize, and M. L. Fischer, 2017: Estimating methane emissions from biological and fossil-fuel sources in the San Francisco Bay Area. *Geophysical Research Letters*, **44**(1), 486-495, doi: 10.1002/2016gl071794.

Jones, C., and D. M. Kammen, 2014: Spatial distribution of U.S. household carbon footprints reveals suburbanization undermines greenhouse gas benefits of urban population density. *Environmental Science and Technology*, **48**(2), 895-902, doi: 10.1021/es4034364.

Kammen, D. M., and D. A. Sunter, 2016: City-integrated renewable energy for urban sustainability. *Science*, **352**(6288), 922-928, doi: 10.1126/science.aad9302.

Karathodorou, N., D. J. Graham, and R. B. Noland, 2010: Estimating the effect of urban density on fuel demand. *Energy Economics*, **32**(1), 86-92, doi: 10.1016/j.eneco.2009.05.005.

Kennedy, C., 2015: Key threshold for electricity emissions. *Nature Climate Change*, **5**(3), 179-181, doi: 10.1038/nclimate2494.

Kennedy, C., S. Demoullin, and E. Mohareb, 2012: Cities reducing their greenhouse gas emissions. *Energy Policy*, **49**, 774-777, doi: 10.1016/j.enpol.2012.07.030.

Kennedy, C., J. Steinberger, B. Gasson, Y. Hansen, T. Hillman, M. Havranek, D. Pataki, A. Phdungsilp, A. Ramaswami, and G. Villalba Mendez, 2009: Greenhouse gas emissions from global cities. *Environmental Science and Technology*, **43**(19), 7297-7302, doi: 10.1021/es900213p.

Kennedy, C., J. Steinberger, B. Gasson, Y. Hansen, T. Hillman, M. Havranek, D. Pataki, A. Phdungsilp, A. Ramaswami, and G. V. Mendez, 2010: Methodology for inventorying greenhouse gas emissions from global cities. *Energy Policy*, **38**(9), 4828-4837, doi: 10.1016/j.enpol.2009.08.050.

Kennedy, C. A., N. Ibrahim, and D. Hoornweg, 2014: Low-carbon infrastructure strategies for cities. *Nature Climate Change*, **4**(5), 343-346, doi: 10.1038/Nclimate2160.

Kennedy, C. A., I. Stewart, A. Facchini, I. Cersosimo, R. Mele, B. Chen, M. Uda, A. Kansal, A. Chiu, K. G. Kim, C. Dubeux, E. Lebre La Rovere, B. Cunha, S. Pincetl, J. Keirstead, S. Barles, S. Pusaka, J. Gunawan, M. Adegbile, M. Nazariha, S. Hoque, P. J. Marcotullio, F. Gonzalez Otharan, T. Genena, N. Ibrahim, R. Farooqui, G. Cervantes, and A. D. Sahin, 2015: Energy and material flows of megacities. *Proceedings of the National Academy of Sciences USA*, **112**(19), 5985-5990, doi: 10.1073/pnas.1504315112.

Kenworthy, J. R., 2006: The eco-city: Ten key transport and planning dimensions for sustainable city development. *Environment and Urbanization*, **18**(1), 67-85, doi: 10.1177/0956247806063947.

Kern, K., and G. Alber, 2009: Governing climate change in cities: Modes of urban climate governance in multi-level systems. *The International Conference on Competitive Cities and Climate Change, OECD Conference Proceedings, Milan, Italy*, pp. 171-196.

Kern, K., and H. Bulkeley, 2009: Cities, Europeanization and multi-level governance: Governing climate change through transnational municipal networks. *JCMS: Journal of Common Market Studies*, **47**(2), 309-332, doi: 10.1111/j.1468-5965.2009.00806.x.

Kim, B. J., J. W. Kwon, J. H. Seo, H. B. Kim, S. Y. Lee, K. S. Park, J. Yu, H. C. Kim, J. H. Leem, J. Sakong, S. Y. Kim, C. G. Lee, D. M. Kang, M. Ha, Y. C. Hong, H. J. Kwon, and S. J. Hong, 2011: Association of ozone exposure with asthma, allergic rhinitis, and allergic sensitization. *Annals of Allergy, Asthma and Immunology*, **107**(3), 214-219 e211, doi: 10.1016/j.anai.2011.05.025.

Knaap, G.-J., Z. Nedović-Budić, and A. Carbonell, 2015: *Planning for States and Nation-States in the U.S. and Europe*. Lincoln Land Institute.

Koerner, B., and J. Klopatek, 2002: Anthropogenic and natural CO_2 emission sources in an arid urban environment. *Environmental Pollution*, **116**, S45-S51.

Kort, E. A., C. Frankenberg, C. E. Miller, and T. Oda, 2012: Space-based observations of megacity carbon dioxide. *Geophysical Research Letters*, **39**(17), doi: 10.1029/2012gl052738.

Koski, C., 2010: Greening America's skylines: The diffusion of low-salience policies. *Policy Studies Journal*, **38**(1), 93-117, doi: 10.1111/j.1541-0072.2009.00346.x.

Krause, R. M., 2011: Policy innovation, intergovernmental relations, and the adoption of climate protection initiatives by U.S. cities. *Journal of Urban Affairs*, **33**(1), 45-60, doi: 10.1111/j.1467-9906.2010.00510.x.

Krause, R. M., 2012: An assessment of the impact that participation in local climate networks has on cities' implementation of climate, energy, and transportation policies. *Review of Policy Research*, **29**(5), 585-604, doi: 10.1111/j.1541-1338.2012.00582.x.

Krause, R. M., 2015: How U.S. cities dropped climate protection commitments in response to mainstream political opposition and programmatic stagnation. *USAPP – American Politics and Policy*. [http://bit.ly/1Ty8pUr]

Lal, R., and B. Augustin, 2012: *Carbon Sequestration in Urban Ecosystems.* Springer. 388 pp.

Lamb, B. K., S. L. Edburg, T. W. Ferrara, T. Howard, M. R. Harrison, C. E. Kolb, A. Townsend-Small, W. Dyck, A. Possolo, and J. R. Whetstone, 2015: Direct measurements show decreasing methane emissions from natural gas local distribution systems in the United States. *Environmental Science and Technology*, **49**(8), 5161-5169, doi: 10.1021/es505116p.

Lamb, B. K., M. O. Cambaliza, K. J. Davis, S. L. Edburg, T. W. Ferrara, C. Floerchinger, A. M. Heimburger, S. Herndon, T. Lauvaux, T. Lavoie, D. R. Lyon, N. Miles, K. R. Prasad, S. Richardson, J. R. Roscioli, O. E. Salmon, P. B. Shepson, B. H. Stirm, and J. Whetstone, 2016: Direct and indirect measurements and modeling of methane emissions in Indianapolis, Indiana. *Environmental Science and Technology*, **50**(16), 8910-8917, doi: 10.1021/acs.est.6b01198.

Lariviere, I., and G. Lafrance, 1999: Modelling the electricity consumption of cities: Effect of urban density. *Energy Economics*, **21**(1), 53-66.

Larsson, N. K., 1999: Development of a building performance rating and labelling system in Canada. *Building Research and Information*, **27**(4-5), 332-341, doi: 10.1080/096132199369444.

Lauvaux, T., N. L. Miles, S. J. Richardson, A. Deng, D. R. Stauffer, K. J. Davis, G. Jacobson, C. Rella, G.-P. Calonder, and P. L. DeCola, 2013: Urban emissions of CO_2 from Davos, Switzerland: The first real-time monitoring system using an atmospheric inversion technique. *Journal of Applied Meteorology and Climatology*, **52**(12), 2654-2668, doi: 10.1175/jamc-d-13-038.1.

Lauvaux, T., N. L. Miles, A. Deng, S. J. Richardson, M. O. Cambaliza, K. J. Davis, B. Gaudet, K. R. Gurney, J. Huang, D. O'Keefe, Y. Song, A. Karion, T. Oda, R. Patarasuk, I. Razlivanov, D. Sarmiento, P. Shepson, C. Sweeney, J. Turnbull, and K. Wu, 2016: High-resolution atmospheric inversion of urban CO_2 emissions during the dormant season of the Indianapolis Flux Experiment (INFLUX). *Journal of Geophysical Research: Atmospheres*, **121**(10), 5213-5236, doi: 10.1002/2015jd024473.

Lavoie, T. N., P. B. Shepson, C. A. Gore, B. H. Stirm, R. Kaeser, B. Wulle, D. Lyon, and J. Rudek, 2017: Assessing the methane emissions from natural gas-fired power plants and oil refineries. *Environmental Science and Technology*, **51**(6), 3373-3381, doi: 10.1021/acs.est.6b05531.

Lenzen, M., 2014: An outlook into a possible future of footprint research. *Journal of Industrial Ecology*, **18**(1), 4-6, doi: 10.1111/jiec.12080.

Lenzen, M., and G. M. Peters, 2009: How city dwellers affect their resource hinterland. *Journal of Industrial Ecology*, **14**(1), 73-90, doi: 10.1111/j.1530-9290.2009.00190.x.

Lenzen, M., R. Wood, and B. Foran, 2008: Direct versus embodied energy: The need for urban lifestyle transitions. In *Urban Energy Transition: From Fossil Fuels to Renewable Power.* [P. Droege (ed.)]. Elsevier, pp. 91-120.

Li, D., and E. Bou-Zeid, 2013: Synergistic interactions between urban heat islands and heat waves: The impact in cities is larger than the sum of its parts. *Journal of Applied Meteorology and Climatology*, **52**(9), 2051-2064, doi: 10.1175/jamc-d-13-02.1.

Li, M., J. Shi, J. Guo, J. Cao, J. Niu, and M. Xiong, 2015: Climate impacts on extreme energy consumption of different types of buildings. *PLOS One*, **10**(4), e0124413, doi: 10.1371/journal.pone.0124413.

Liddle, B., 2014: Impact of population, age structure and urbanization on carbon emissions/energy consumption: Evidence from macro-level, cross-country analyses. *Population and Environment*, **35**(3), 286-304.

Lin, J. Y., Y. C. Hu, S. H. Cui, J. F. Kang, and A. Ramaswami, 2015: Tracking urban carbon footprints from production and consumption perspectives. *Environmental Research Letters*, **10**(5), doi: 10.1088/1748-9326/10/5/054001.

Litvak, E., H. R. McCarthy, and D. E. Pataki, 2017: A method for estimating transpiration of irrigated urban trees in California. *Landscape and Urban Planning*, **158**, 48-61, doi: 10.1016/j.landurbplan.2016.09.021.

Liu, C. F., and X. M. Li, 2012: Carbon storage and sequestration by urban forests in Shenyang, China. *Urban Forestry & Urban Greening*, **11**(2), 121-128, doi: 10.1016/j.ufug.2011.03.002.

Lutsey, N., and D. Sperling, 2008: America's bottom-up climate change mitigation policy. *Energy Policy*, **36**(2), 673-685, doi: 10.1016/j.enpol.2007.10.018.

Marcotullio, P. J., A. Sarzynski, J. Albrecht, N. Schulz, and J. Garcia, 2013: The geography of global urban greenhouse gas emissions: An exploratory analysis. *Climatic Change*, **121**(4), 621-634, doi: 10.1007/s10584-013-0977-z.

Marcotullio, P. J., S. Hughes, A. Sarzynski, S. Pincetl, L. S. Pena, P. Romero-Lankao, D. Runfola, and K. C. Seto, 2014: Urbanization and the carbon cycle: Contributions from social science. *Earth's Future*, **2**(10), 496-514, doi: 10.1002/2014ef000257.

Markolf, S. A., H. S. Matthews, I. L. Azevedo, and C. Hendrickson, 2017: An integrated approach for estimating greenhouse gas emissions from 100 U.S. metropolitan areas. *Environmental Research Letters*, **12**(2), 024003, doi: 10.1088/1748-9326/aa5731.

Martinez-Fernandez, C., I. Audirac, S. Fol, and E. Cunningham-Sabot, 2012: Shrinking cities: Urban challenges of globalization. *International Journal of Urban and Regional Research*, **36**(2), 213-225, doi: 10.1111/j.1468-2427.2011.01092.x.

Mattauch, L., M. Ridgway, and F. Creutzig, 2016: Happy or liberal? Making sense of behavior in transport policy design. *Transportation Research Part D: Transport and Environment*, **45**, 64-83, doi: 10.1016/j.trd.2015.08.006.

McHale, M. R., S. J. Hall, A. Majumdar, and N. B. Grimm, 2017: Carbon lost and carbon gained: A study of vegetation and carbon trade-offs among diverse land uses in Phoenix, Arizona. *Ecological Applications*, **27**(2), 644-661, doi: 10.1002/eap.1472.

McKain, K., S. C. Wofsy, T. Nehrkorn, J. Eluszkiewicz, J. R. Ehleringer, and B. B. Stephens, 2012: Assessment of ground-based atmospheric observations for verification of greenhouse gas emissions from an urban region. *Proceedings of the National Academy of Sciences USA*, **109**(22), 8423-8428, doi: 10.1073/pnas.1116645109.

McKain, K., A. Down, S. M. Raciti, J. Budney, L. R. Hutyra, C. Floerchinger, S. C. Herndon, T. Nehrkorn, M. S. Zahniser, R. B. Jackson, N. Phillips, and S. C. Wofsy, 2015: Methane emissions from natural gas infrastructure and use in the urban region of Boston, Massachusetts. *Proceedings of the National Academy of Sciences USA*, **112**(7), 1941-1946, doi: 10.1073/pnas.1416261112.

McPherson, G., J. R. Simpson, P. J. Peper, S. E. Maco, and Q. F. Xiao, 2005: Municipal forest benefits and costs in five US cities. *Journal of Forestry*, **103**(8), 411-416.

Melaas, E. K., J. A. Wang, D. L. Miller, and M. A. Friedl, 2016: Interactions between urban vegetation and surface urban heat islands: A case study in the Boston metropolitan region. *Environmental Research Letters*, **11**(5), doi: 10.1088/1748-9326/11/5/054020.

Menzer, O., W. Meiring, P. C. Kyriakidis, and J. P. McFadden, 2015: Annual sums of carbon dioxide exchange over a heterogeneous urban landscape through machine learning based gap-filling. *Atmospheric Environment*, **101**, 312-327, doi: 10.1016/j.atmosenv.2014.11.006.

Middel, A., N. Chhetri, and R. Quay, 2015: Urban forestry and cool roofs: Assessment of heat mitigation strategies in Phoenix residential neighborhoods. *Urban Forestry and Urban Greening*, **14**(1), 178-186, doi: 10.1016/j.ufug.2014.09.010.

Middel, A., K. Hab, A. J. Brazel, C. A. Martin, and S. Guhathakurta, 2014: Impact of urban form and design on mid-afternoon microclimate in Phoenix local climate zones. *Landscape and Urban Planning*, **122**, 16-28, doi: 10.1016/j.landurbplan.2013.11.004.

Miles, N. L., S. J. Richardson, T. Lauvaux, K. J. Davis, A. Deng, J. C. Turnbull, C. Sweeney, K. R. Gurney, R. Patarasuk, I. Razlivanov, M. Obiminda, L. Cambaliza, and P. B. Shepson, 2017: Quantification of urban atmospheric boundary layer greenhouse gas dry mole fraction enhancements in the dormant season: Results from the Indianapolis Flux Experiment (INFLUX). *Elementa: Science of the Anthropocene*, **5**, 27, doi: 10.1525/elementa.127.

Miller, C. A., A. Iles, and C. F. Jones, 2013: The social dimensions of energy transitions. *Science as Culture*, **22**(2), 135-148, doi: 10.1080/09505431.2013.786989.

Mills, B., and J. Schleich, 2012: Residential energy-efficient technology adoption, energy conservation, knowledge, and attitudes: An analysis of European countries. *Energy Policy*, **49**, 616-628, doi: 10.1016/j.enpol.2012.07.008.

Milner, J., M. Davies, and P. Wilkinson, 2012: Urban energy, carbon management (low carbon cities) and co-benefits for human health. *Current Opinion in Environmental Sustainability*, **4**(4), 398-404, doi: 10.1016/j.cosust.2012.09.011.

Mindali, O., A. Raveh, and I. Salomon, 2004: Urban density and energy consumption: A new look at old statistics. *Transportation Research Part A: Policy and Practice*, **38**(2), 143-162, doi: 10.1016/j.tra.2003.10.004.

Minx, J., G. Baiocchi, T. Wiedmann, J. Barrett, F. Creutzig, K. S. Feng, M. Forster, P. P. Pichler, H. Weisz, and K. Hubacek, 2013: Carbon footprints of cities and other human settlements in the UK. *Environmental Research Letters*, **8**(3), doi: 10.1088/1748-9326/8/3/035039.

Minx, J. C., T. Wiedmann, R. Wood, G. P. Peters, M. Lenzen, A. Owen, K. Scott, J. Barrett, K. Hubacek, G. Baiocchi, A. Paul, E. Dawkins, J. Briggs, D. Guan, S. Suh, and F. Ackerman, 2009: Input–output analysis and carbon footprinting: An overview of applications. *Economic Systems Research*, **21**(3), 187-216, doi: 10.1080/09535310903541298.

Mohareb, E., and C. Kennedy, 2012: Greenhouse gas emission scenario modeling for cities using the PURGE model: A case study of the Greater Toronto Area. *Journal of Industrial Ecology*, **16**(6), 875-888, doi: 10.1111/j.1530-9290.2012.00563.x.

Mohareb, E. A., and A. K. Mohareb, 2014: A comparison of greenhouse gas emissions in the residential sector of major Canadian cities. *Canadian Journal of Civil Engineering*, **41**(4), 285-293, doi: 10.1139/cjce-2013-0465.

Monahan, J., and J. C. Powell, 2011: An embodied carbon and energy analysis of modern methods of construction in housing: A case study using a lifecycle assessment framework. *Energy and Buildings*, **43**(1), 179-188, doi: 10.1016/j.enbuild.2010.09.005.

Müller, D. B., G. Liu, A. N. Løvik, R. Modaresi, S. Pauliuk, F. S. Steinhoff, and H. Brattebø, 2013: Carbon emissions of infrastructure development. *Environmental Science and Technology*, **47**(20), 11739-11746, doi: 10.1021/es402618m.

Newman, L., and Y. Herbert, 2009: The use of deep water cooling systems: Two Canadian examples. *Renewable Energy*, **34**(3), 727-730, doi: 10.1016/j.renene.2008.04.022.

Newman, P., and J. Kenworthy, 1999: *Sustainability and Cities: Overcoming Automobile Dependence.* Island Press, Washington, DC, USA. 442 pp.

Newman, P. W. G., and J. R. Kenworthy, 1989: Gasoline consumption and cities. *Journal of the American Planning Association*, **55**(1), 24-37, doi: 10.1080/01944368908975398.

Newman, S., X. M. Xu, K. R. Gurney, Y. K. Hsu, K. F. Li, X. Jiang, R. Keeling, S. Feng, D. O'Keefe, R. Patarasuk, K. W. Wong, P. Rao, M. L. Fischer, and Y. L. Yung, 2016: Toward consistency between trends in bottom-up CO_2 emissions and top-down atmospheric measurements in the Los Angeles megacity. *Atmospheric Chemistry and Physics*, **16**(6), 3843-3863, doi: 10.5194/acp-16-3843-2016.

Nowak, D. J., 1993: Atmospheric carbon reduction by urban trees. *Journal of Environmental Management*, **37**(3), 207-217, doi: 10.1006/jema.1993.1017.

Nowak, D. J., and J. T. Walton, 2005: Projected urban growth (2000-2050) and its estimated impact on the U.S. forest resource. *Journal of Forestry*, **103**(8), 383-389.

Nowak, D. J., and E. J. Greenfield, 2010: Evaluating the national land cover database tree canopy and impervious cover estimates across the conterminous United States: A comparison with photo-interpreted estimates. *Environmental Management*, **46**(3), 378-390, doi: 10.1007/s00267-010-9536-9.

Nowak, D. J., E. J. Greenfield, R. E. Hoehn, and E. Lapoint, 2013: Carbon storage and sequestration by trees in urban and community areas of the United States. *Environmental Pollution*, **178**, 229-236, doi: 10.1016/j.envpol.2013.03.019.

Oke, T. R., 1982: The energetic basis of the urban heat-island. *Quarterly Journal of the Royal Meteorological Society*, **108**(455), 1-24, doi: 10.1002/qj.49710845502.

Oleson, K. W., G. B. Bonan, J. Feddema, and M. Vertenstein, 2008: An urban parameterization for a global climate model. Part II: Sensitivity to input parameters and the simulated urban heat island in offline simulations. *Journal of Applied Meteorology and Climatology*, **47**, 1061-1076, doi: 10.1175/2007JAMC1598.1.

Ostro, B., S. Rauch, and S. Green, 2011: Quantifying the health impacts of future changes in temperature in California. *Environmental Research*, **111**(8), 1258-1264, doi: 10.1016/j.envres.2011.08.013.

Parshall, L., K. Gurney, S. A. Hammer, D. Mendoza, Y. Y. Zhou, and S. Geethakumar, 2010: Modeling energy consumption and CO_2 emissions at the urban scale: Methodological challenges and insights from the United States. *Energy Policy*, **38**(9), 4765-4782, doi: 10.1016/j.enpol.2009.07.006.

Pataki, D. E., P. C. Emmi, C. B. Forster, J. I. Mills, E. R. Pardyjak, T. R. Peterson, J. D. Thompson, and E. Dudley-Murphy, 2009: An integrated approach to improving fossil fuel emissions scenarios with urban ecosystem studies. *Ecological Complexity*, **6**(1), 1-14, doi: 10.1016/j.ecocom.2008.09.003.

Pataki, D. E., R. J. Alig, A. S. Fung, N. E. Golubiewski, C. A. Kennedy, E. G. McPherson, D. J. Nowak, R. V. Pouyat, and P. R. Lankao, 2006: Urban ecosystems and the North American carbon cycle. *Global Change Biology*, **12**(11), 2092-2102, doi: 10.1111/j.1365-2486.2006.01242.x.

Patarasuk, R., K. R. Gurney, D. O'Keeffe, Y. Song, J. Huang, P. Rao, M. Buchert, J. C. Lin, D. Mendoza, and J. R. Ehleringer, 2016: Urban high-resolution fossil fuel CO_2 emissions quantification and exploration of emission drivers for potential policy applications. *Urban Ecosystems*, **19**(3), 1013-1039, doi: 10.1007/s11252-016-0553-1.

Peters, G. P., J. C. Minx, C. L. Weber, and O. Edenhofer, 2011: Growth in emission transfers via international trade from 1990 to 2008. *Proceedings of the National Academy of Sciences USA*, **108**(21), 8903-8908, doi: 10.1073/pnas.1006388108.

Phillips, N. G., R. Ackley, E. R. Crosson, A. Down, L. R. Hutyra, M. Brondfield, J. D. Karr, K. Zhao, and R. B. Jackson, 2013: Mapping urban pipeline leaks: Methane leaks across Boston. *Environmental Pollution*, **173**, 1-4, doi: 10.1016/j.envpol.2012.11.003.

Pincetl, S., M. Chester, and D. Eisenman, 2016: Urban heat stress vulnerability in the U.S. Southwest: The role of sociotechnical systems. *Sustainability*, **8**(9), 842, doi: 10.3390/su8090842.

Pincetl, S., M. Chester, G. Circella, A. Fraser, C. Mini, S. Murphy, J. Reyna, and D. Sivaraman, 2014: Enabling future sustainability transitions an urban metabolism approach to Los Angeles. *Journal of Industrial Ecology*, **18**(6), 871-882, doi: 10.1111/jiec.12144.

Pitt, D. R., 2010: Harnessing community energy: The keys to climate mitigation policy adoption in US municipalities. *Local Environment*, **15**(8), 717-729, doi: 10.1080/13549839.2010.509388.

Porse, E., J. Derenski, H. Gustafson, Z. Elizabeth, and S. Pincetl, 2016: Structural, geographic, and social factors in urban building energy use: Analysis of aggregated account-level consumption data in a megacity. *Energy Policy*, **96**, 179-192, doi: 10.1016/j.enpol.2016.06.002.

Portney, K. E., 2013: *Taking Sustainable Cities Seriously: Economic Development, the Environment, and Quality of Life in American Cities*. 2nd ed., MIT Press.

Raciti, S. M., L. R. Hutyra, and J. D. Newell, 2014: Mapping carbon storage in urban trees with multi-source remote sensing data: Relationships between biomass, land use, and demographics in Boston neighborhoods. *Science of the Total Environment*, **500-501**, 72-83, doi: 10.1016/j.scitotenv.2014.08.070.

Raciti, S. M., L. R. Hutyra, P. Rao, and A. C. Finzi, 2012: Inconsistent definitions of "urban" result in different conclusions about the size of urban carbon and nitrogen stocks. *Ecological Applications*, **22**(3), 1015-1035, doi: 10.1890/11-1250.1.

Raji, B., M. J. Tenpierik, and A. van den Dobbelsteen, 2015: The impact of greening systems on building energy performance: A literature review. *Renewable and Sustainable Energy Reviews*, **45**, 610-623, doi: 10.1016/j.rser.2015.02.011.

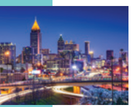
Ramaswami, A., and A. Chavez, 2013: What metrics best reflect the energy and carbon intensity of cities? Insights from theory and modeling of 20 US cities. *Environmental Research Letters*, **8**(3), 035011, doi: 10.1088/1748-9326/8/3/035011.

Ramaswami, A., T. Hillman, B. Janson, M. Reiner, and G. Thomas, 2008: A demand-centered, hybrid life-cycle methodology for city-scale greenhouse gas inventories. *Environmental Science and Technology*, **42**(17), 6455-6461, doi: 10.1021/es702992q.

Reinmann, A., and L. Hutyra, 2017: Effects of forest fragmentation on carbon storage and uptake in an urbanizing landscape. *Proceedings of the National Academy of Sciences USA*, **114**(1), 107-112.

Reyna, J. L., and M. V. Chester, 2015: The growth of urban building stock unintended lock-in and embedded environmental effects. *Journal of Industrial Ecology*, **19**(4), 524-537, doi: 10.1111/jiec.12211.

Roberts, D., 2015: California communities seize contol of their energy future. *Grist*. [http://grist.org/climate-energy/california-communities-seize-control-of-their-energy-futures/]



Robinson, P., and C. Gore, 2011: The spaces in between: A comparative analysis of municipal climate governance and action. *SSRN Electronic Journal*, doi: 10.2139/ssrn.1921095.

Romero-Lankao, P., 2007: Are we missing the point? Particularities of urbanization, sustainability and carbon emissions in Latin American cities. *Environment and Urbanization*, **19**(1), 159-175, doi: 10.1177/0956247807076915.

Romero-Lankao, P., T. McPhearson, and D. J. Davidson, 2017: The food-energy-water nexus and urban complexity. *Nature Climate Change*, **7**(4), 233-235, doi: 10.1038/nclimate3260.

Romero-Lankao, P., S. Hughes, A. Rosas-Huerta, R. Borquez, and D. M. Gnatz, 2013: Institutional capacity for climate change responses: An examination of construction and pathways in Mexico City and Santiago. *Environment and Planning C: Government and Policy*, **31**(5), 785-805, doi: 10.1068/c12173.

Romero-Lankao, P., J. Hardoy, S. Hughes, A. Rosas-Huerta, R. Borquez, and D. M. Gnatz, 2015: Multilevel governance and institutional capacity for climate change responses in Latin American cities. *The Urban Climate Challenge Rethinking the Role of Cities in the Global Climate Regime*. [C. Johnson, N. Toly, and H. Schroeder (eds.)]. Cities and Global Governance. Routledge, pp. 179-204.

Romero-Lankao, P., K. R. Gurney, K. C. Seto, M. Chester, R. M. Duren, S. Hughes, L. R. Hutyra, P. Marcotullio, L. Baker, N. B. Grimm, C. Kennedy, E. Larson, S. Pincetl, D. Runfola, L. Sanchez, G. Shrestha, J. Feddema, A. Sarzynski, J. Sperling, and E. Stokes, 2014: A critical knowledge pathway to low-carbon, sustainable futures: Integrated understanding of urbanization, urban areas, and carbon. *Earth's Future*, **2**(10), 515-532, doi: 10.1002/2014ef000258.

Rosenzweig, C., W. Solecki, S. A. Hammer, and S. Mehrotra, 2010: Cities lead the way in climate-change action. *Nature*, **467**(7318), 909-911, doi: 10.1038/467909a.

Rosenzweig, C., W. Solecki, P. Romero-Lankao, S. Mehrotra, S. Dhakal, and S. Ali Ibrahim, 2016: Pathways to urban transformation. In: *Climate Change and Cities: Second Assessment Report of the Urban Climate Change Research Network*. [C. Rosenzweig, W. Solecki, P. Romero-Lankao, S. Mehrotra, S. Dhakal, and S. A. Ibrahim (eds.)]. Cambridge University Press.

Ryan, D., 2015: From commitment to action: A literature review on climate policy implementation at city level. *Climatic Change*, **131**(4), 519-529, doi: 10.1007/s10584-015-1402-6.

Sailor, D. J., 1998: Simulations of annual degree day impacts of urban vegetative augmentation. *Atmospheric Environment*, **32**(1), 43-52, doi: 10.1016/s1352-2310(97)00178-7.

Sailor, D. J., M. Georgescu, J. M. Milne, and M. A. Hart, 2015: Development of a national anthropogenic heating database with an extrapolation for international cities. *Atmospheric Environment*, **118**, 7-18, doi: 10.1016/j.atmosenv.2015.07.016.

Salat, S., and L. Bourdic, 2012: *Urban Complexity, Efficiency and Resilience, Energy Efficiency — A Bridge to Low Carbon Economy*. [Z. Morvaj (ed.)]. [https://www.intechopen.com/books/energy-efficiency-a-bridge-to-low-carbon-economy]

Sarofim, M. C., S. Saha, M. D. Hawkins, D. M. Mills, J. Hess, R. Horton, P. Kinney, J. Schwartz, and A. S. Juliana, 2016: Temperature-related death and illness. In: *The Impacts of Climate Change on Human Health in the United States: A Scientific Assessment*. U.S. Global Change Research Program. pp. 43-68.

Schiller, G., 2007: Urban infrastructure: Challenges for resource efficiency in the building stock. *Building Research and Information*, **35**(4), 399-411, doi: 10.1080/09613210701217171.

Schreurs, M. A., 2008: From the bottom up. *Journal of Environment and Development*, **17**(4), 343-355, doi: 10.1177/1070496508326432.

Seto, K. C., S. J. Davis, R. B. Mitchell, E. C. Stokes, G. Unruh, and D. Ürge-Vorsatz, 2016: Carbon lock-in: Types, causes, and policy implications. *Annual Review of Environment and Resources*, **41**, 425-452, doi: 10.1146/annurev-environ-110615-085934.

Seto, K. C., S. Dhakal, A. Bigio, H. Blanco, G. C. Delgado, D. Dewar, L. Huang, A. Inaba, A. Kansal, S. Lwasa, J. E. McMahon, D. B. Müller, J. Murakami, H. Nagendra, and A. Ramaswami, 2014: Human settlements, infrastructure and spatial planning. In: *Climate Change 2014: Mitigation of Climate Change. Contribution of Working Group III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change* [O. Edenhofer, R. Pichs-Madruga, Y. Sokona, E. Farahani, S. Kadner, K. Seyboth, A. Adler, I. Baum, S. Brunner, P. Eickemeier, B. Kriemann, J. Savolainen, S. Schlömer, C. von Stechow, T. Zwickel, and J.C. Minx (eds.)]. Cambridge University Press, Cambridge, UK, and New York, NY, USA, 923-1000.

Seto, K. C., B. Guneralp, and L. R. Hutyra, 2012: Global forecasts of urban expansion to 2030 and direct impacts on biodiversity and carbon pools. *Proceedings of the National Academy of Sciences USA*, **109**(40), 16083-16088, doi: 10.1073/pnas.1211658109.

Sharp, E. B., D. M. Daley, and M. S. Lynch, 2010: Understanding local adoption and implementation of climate change mitigation policy. *Urban Affairs Review*, **47**(3), 433-457, doi: 10.1177/1078087410392348.

Shashua-Bar, L., D. Pearlmutter, and E. Erell, 2009: The cooling efficiency of urban landscape strategies in a hot dry climate. *Landscape and Urban Planning*, **92**(3-4), 179-186, doi: 10.1016/j.landurbplan.2009.04.005.

Sheller, M., and J. Urry, 2000: The city and the car. *International Journal of Urban and Regional Research*, **24**(4), 737-757, doi: 10.1111/1468-2427.00276.

Shu, Y., and N. S. N. Lam, 2011: Spatial disaggregation of carbon dioxide emissions from road traffic based on multiple linear regression model. *Atmospheric Environment*, **45**(3), 634-640, doi: 10.1016/j.atmosenv.2010.10.037.

Shui, B., and R. Harriss, 2005: Carbon-dioxide embodiment in North American trade. *Journal of Energy and Development*, **31**(1), 101-110.

Sovacool, B. K., and M. A. Brown, 2010: Twelve metropolitan carbon footprints: A preliminary comparative global assessment. *Energy Policy*, **38**(9), 4856-4869, doi: 10.1016/j.enpol.2009.10.001.

St. John, J., 2014: Dueling charts of the day: Peaker plants vs. green power. GTM Research. [https://www.greentechmedia.com/articles/read/dueling-charts-of-the-day-peaker-plants-vs.-green-power]

Sun, X., M. A. Brown, M. Cox, and R. Jackson, 2015: Mandating better buildings: A global review of building codes and prospects for improvement in the United States. *Wiley Interdisciplinary Reviews: Energy and Environment*, **5**(2), 188-215, doi: 10.1002/wene.168.

Susca, T., S. R. Gaffin, and G. R. Dell'Osso, 2011: Positive effects of vegetation: Urban heat island and green roofs. *Environmental Pollution*, **159**(8-9), 2119-2126, doi: 10.1016/j.envpol.2011.03.007.

Tang, Y., A. Chen, and S. Zhao, 2016: Carbon storage and sequestration of urban street trees in Beijing, China. *Frontiers in Ecology and Evolution*, **4**, doi: 10.3389/fevo.2016.00053.

Tang, Z., S. D. Brody, C. Quinn, L. Chang, and T. Wei, 2010: Moving from agenda to action: Evaluating local climate change action plans. *Journal of Environmental Planning and Management*, **53**(1), 41-62, doi: 10.1080/09640560903399772.

Tanikawa, H., and S. Hashimoto, 2009: Urban stock over time: Spatial material stock analysis using 4d-GIS. *Building Research and Information*, **37**(5-6), 483-502, doi: 10.1080/09613210903169394.

Templer, P. H., J. W. Toll, L. R. Hutyra, and S. M. Raciti, 2015: Nitrogen and carbon export from urban areas through removal and export of litterfall. *Environmental Pollution*, **197**, 256-261, doi: 10.1016/j.envpol.2014.11.016.

Thompson, D. R., A. K. Thorpe, C. Frankenberg, R. O. Green, R. Duren, L. Guanter, A. Hollstein, E. Middleton, L. Ong, and S. Ungar, 2016: Space-based remote imaging spectroscopy of the Aliso Canyon CH_4 superemitter. *Geophysical Research Letters*, **43**(12), 6571-6578, doi: 10.1002/2016gl069079.

Townsend-Small, A., and C. I. Czimczik, 2010: Carbon sequestration and greenhouse gas emissions in urban turf. *Geophysical Research Letters*, **37**(2), doi: 10.1029/2009gl041675.

Tozer, L., 2013: Community energy plans in Canadian cities: Success and barriers in implementation. *Local Environment*, **18**(1), 20-35, doi: 10.1080/13549839.2012.716406.

Tuckett, D., A. Mandel, D. Mangalagiu, A. Abramson, J. Hinkel, K. Katsikopoulos, A. Kirman, T. Malleret, I. Mozetic, P. Ormerod, R. E. Smith, T. Venturini, and A. Wilkinson, 2015: Uncertainty, decision science, and policy making: A manifesto for a research agenda. *Critical Review*, **27**(2), 213-242, doi: 10.1080/08913811.2015.1037078.

Turnbull, J. C., C. Sweeney, A. Karion, T. Newberger, S. J. Lehman, P. P. Tans, K. J. Davis, T. Lauvaux, N. L. Miles, S. J. Richardson, M. O. Cambaliza, P. B. Shepson, K. Gurney, R. Patarasuk, and I. Razlivanov, 2015: Toward quantification and source sector identification of fossil fuel CO_2 emissions from an urban area: Results from the INFLUX experiment. *Journal of Geophysical Research: Atmospheres*, **120**(1), 292-312, doi: 10.1002/2014jd022555.

UN DESA, 2015: *World Urbanization Prospects: The 2014 Revision*. United Nations, Department of Economic and Social Affairs, Population Division. ST/ESA/SER.A/366.

Unruh, G. C., 2000: Understanding carbon lock-in. *Energy Policy*, **28**(12), 817-830, doi: 10.1016/S0301-4215(00)00070-7.

Valavanidis, A., T. Vlachogianni, K. Fiotakis, and S. Loridas, 2013: Pulmonary oxidative stress, inflammation and cancer: Respirable particulate matter, fibrous dusts and ozone as major causes of lung carcinogenesis through reactive oxygen species mechanisms. *International Journal of Environmental Research and Public Health*, **10**(9), 3886-3907, doi: 10.3390/ijerph10093886.

VandeWeghe, J. R., and C. Kennedy, 2007: A spatial analysis of residential greenhouse gas emissions in the Toronto census metropolitan area. *Journal of Industrial Ecology*, **11**(2), 133-144, doi: 10.1162/jie.2007.1220.

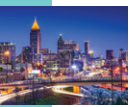
Velasco, E., and M. Roth, 2010: Cities as net sources of CO_2: Review of atmospheric CO_2 exchange in urban environments measured by eddy covariance technique. *Geography Compass*, **4**(9), 1238-1259, doi: 10.1111/j.1749-8198.2010.00384.x.

Velasco, E., M. Roth, L. Norford, and L. T. Molina, 2016: Does urban vegetation enhance carbon sequestration? *Landscape and Urban Planning*, **148**, 99-107, doi: 10.1016/j.landurbplan.2015.12.003.

Velasco, E., S. Pressley, E. Allwine, H. Westberg, and B. Lamb, 2005: Measurements of CO_2 fluxes from the Mexico City urban landscape. *Atmospheric Environment*, **39**(38), 7433-7446, doi: 10.1016/j.atmosenv.2005.08.038.

Velasco, E., S. Pressley, R. Grivicke, E. Allwine, T. Coons, W. Foster, B. T. Jobson, H. Westberg, R. Ramos, F. Hernández, L. T. Molina, and B. Lamb, 2009: Eddy covariance flux measurements of pollutant gases in urban Mexico City. *Atmospheric Chemistry and Physics*, **9**(19), 7325-7342, doi: 10.5194/acp-9-7325-2009.

Viguié, V., and S. Hallegatte, 2012: Trade-offs and synergies in urban climate policies. *Nature Climate Change*, **2**(5), 334-337, doi: 10.1038/nclimate1434.



Virote, J., and R. Neves-Silva, 2012: Stochastic models for building energy prediction based on occupant behavior assessment. *Energy and Buildings*, **53**, 183-193, doi: 10.1016/j.enbuild.2012.06.001.

von Fischer, J. C., D. Cooley, S. Chamberlain, A. Gaylord, C. J. Griebenow, S. P. Hamburg, J. Salo, R. Schumacher, D. Theobald, and J. Ham, 2017: Rapid, vehicle-based identification of location and magnitude of urban natural gas pipeline leaks. *Environmental Science and Technology*, **51**(7), 4091-4099, doi: 10.1021/acs.est.6b06095.

Wachs, M., 1993: Learning from Los Angeles: Transport, urban form, and air quality. *Transportation*, **20**(4), 329-354, doi: 10.1007/bf01100463.

Wang, R., 2012: Leaders, followers, and laggards: Adoption of the U.S. Conference of Mayors climate protection agreement in California. *Environment and Planning C: Government and Policy*, **30**(6), 1116-1128, doi: 10.1068/c1122.

Wang, X., D. Chen, and Z. Ren, 2010: Assessment of climate change impact on residential building heating and cooling energy requirement in Australia. *Building and Environment*, **45**(7), 1663-1682, doi: 10.1016/j.buildenv.2010.01.022.

Wennberg, P. O., W. Mui, D. Wunch, E. A. Kort, D. R. Blake, E. L. Atlas, G. W. Santoni, S. C. Wofsy, G. S. Diskin, S. Jeong, and M. L. Fischer, 2012: On the sources of methane to the Los Angeles atmosphere. *Environmental Science and Technology*, **46**(17), 9282-9289, doi: 10.1021/es301138y.

While, A., A. E. G. Jonas, and D. Gibbs, 2010: From sustainable development to carbon control: Eco-state restructuring and the politics of urban and regional development. *Transactions of the Institute of British Geographers*, **35**(1), 76-93, doi: 10.1111/j.1475-5661.2009.00362.x.

Wilby, R. L., and G. L. W. Perry, 2006: Climate change, biodiversity and the urban environment: A critical review based on London, UK. *Progress in Physical Geography*, **30**(1), 73-98, doi: 10.1191/0309133306pp470ra.

Wilson, C., and H. Dowlatabadi, 2007: Models of decision making and residential energy use. *Annual Review of Environment and Resources*, **32**(1), 169-203, doi: 10.1146/annurev.energy.32.053006.141137.

Wilson, J., J. Spinney, H. Millward, D. Scott, A. Hayden, and P. Tyedmers, 2013: Blame the exurbs, not the suburbs: Exploring the distribution of greenhouse gas emissions within a city region. *Energy Policy*, **62**, 1329-1335, doi: 10.1016/j.enpol.2013.07.012.

Wong, C. K., T. J. Pongetti, T. Oda, P. Rao, K. R. Gurney, S. Newman, R. M. Duren, C. E. Miller, Y. L. Yung, and S. P. Sander, 2016: Monthly trends of methane emissions in Los Angeles from 2011 to 2015 inferred by CLARS-FTS observations. *Atmospheric Chemistry and Physics*, **16**(20), 13121-13130, doi: 10.5194/acp-16-13121-2016.

Wong, K. W., D. Fu, T. J. Pongetti, S. Newman, E. A. Kort, R. Duren, Y. K. Hsu, C. E. Miller, Y. L. Yung, and S. P. Sander, 2015: Mapping CH_4:CO_2 ratios in Los Angeles with CLARS-FTS from Mount Wilson, California. *Atmospheric Chemistry and Physics*, **15**(1), 241-252, doi: 10.5194/acp-15-241-2015.

WRI/WBCSD, 2004: *The Greenhouse Gas Protocol: A Corporate Accounting and Reporting Standard.* World Business Council for Sustainable Development and the World Resources Institute. [http://www.ghgprotocol.org/corporate-standard]

Wright, L. A., J. Coello, S. Kemp, and I. Williams, 2011: Carbon footprinting for climate change management in cities. *Carbon Management*, **2**(1), 49-60, doi: 10.4155/cmt.10.41.

Wunch, D., P. O. Wennberg, G. C. Toon, G. Keppel-Aleks, and Y. G. Yavin, 2009: Emissions of greenhouse gases from a North American megacity. *Geophysical Research Letters*, **36**(15), doi: 10.1029/2009gl039825.

Wunch, D., G. C. Toon, J. K. Hedelius, N. Vizenor, C. M. Roehl, K. M. Saad, J. F. L. Blavier, D. R. Blake, and P. O. Wennberg, 2016: Quantifying the loss of processed natural gas within California's South Coast Air Basin using long-term measurements of ethane and methane. *Atmospheric Chemistry and Physics*, **16**(22), 14091-14105, doi: 10.5194/acp-16-14091-2016.

Zahran, S., S. D. Brody, A. Vedlitz, H. Grover, and C. Miller, 2008: Vulnerability and capacity: Explaining local commitment to climate-change policy. *Environment and Planning C: Government and Policy*, **26**(3), 544-562, doi: 10.1068/c2g.

Zhang, X., M. A. Friedl, C. B. Schaaf, A. H. Strahler, and A. Schneider, 2004: The footprint of urban climates on vegetation phenology. *Geophysical Research Letters*, **31**(12), doi: 10.1029/2004gl020137.

Zhang, X. Y., M. A. Friedl, and C. B. Schaaf, 2006: Global vegetation phenology from Moderate Resolution Imaging Spectroradiometer (MODIS): Evaluation of global patterns and comparison with in situ measurements. *Journal of Geophysical Research: Biogeosciences*, **111**(G4), doi: 10.1029/2006jg000217.

Zhao, S., S. Liu, and D. Zhou, 2016: Prevalent vegetation growth enhancement in urban environment. *Proceedings of the National Academy of Sciences USA*, **113**(22), 6313-6318, doi: 10.1073/pnas.1602312113.

Zhou, Y. Y., and K. R. Gurney, 2011: Spatial relationships of sector-specific fossil fuel CO_2 emissions in the United States. *Global Biogeochemical Cycles*, **25**, GB3002, doi: 10.1029/2010gb003822.