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GHG emissions from urbanization and opportunities for urban carbon mitigation

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A large body of literature has been published on urban carbon emissions and management in the last few years. This paper searches for answers to two broad questions: what do we know about the GHG emissions from urbanization at multiple scales and what are the key opportunities to mitigate GHG from cities and their efficient governance? The review suggests that the quantification of urban contribution to global, regional and national GHGs are limited to few regions and for CO_2 only. The GHG emissions of urban areas differ widely for the accounting methods, scope of GHGs, emission sources and urban definition, thus, making place-based comparisons difficult. The urban system has large indirect carbon flows across the administrative and agglomeration boundaries with important policy implications. We also observed that an integrated system perspective is needed in future studies to integrate all sources, sinks, and opportunities for infrastructure and technology for carbon management. In particular, the multiple benefit assessment of climate change mitigation in cities including the potentials for combined response to the mitigation and adaptation are necessary and the research related to efficient urban carbon governance by ascertaining who can influence the urban carbon mitigation by what extent is important.

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Introduction

3.3 billion or 49.4% of the global population lived in urban areas in 2007. By 2050, this will increase to 6.4 billion or 70% of the global population [1]. Thus, the present and future levels of urbanization, particularly the rapid urbanization of developing countries, have clear linkages to the global greenhouse gas (GHG) emissions [2•,3••,4•]. However, in earlier decades, only a few studies on GHGs in urban areas, mostly in the west, were undertaken [5–7]. Earlier, few city authorities were active in the climate change agenda [8,9•] and the scientific community was not sufficiently challenged for more knowledge. In the last seven to eight years, research and policy communities are placing greater importance on urban GHGs. The Intergovernmental Panel on Climate Change had pointed out the need to cover urban carbon mitigation more vigorously for the Fifth Assessment Report [10]. Similarly, for city authorities, developing long-term urban carbon scenarios and identifying the potential urban development pathways are necessitating more scientific inputs [11–13]. The policy community too is debating on urban carbon governance and the responsibilities of cities [14•,15•].

In this context, this paper synthesizes the existing literature on the GHG emissions from urbanization to answer two broad questions. First, what do we know about the GHG emissions from urbanization at multiple scales? and second, what do we know on opportunities to mitigate GHG from cities and their efficient governance? This paper is divided into three sections after this introduction. The following two sections address these questions followed by a section on conclusions and future research needs. This review does not include the sectoral carbon mitigation issues in transport, buildings and waste and is limited to the holistic urban issues in view of the space limitations.

GHG emissions from urbanization at multiple scales

This section illustrates what we know about the GHG emissions from urbanization at global, regional and city scales.

Global and regional GHG emissions from urbanization

International Energy Agency (IEA) estimated that the urban areas contributed 67% and 71%, respectively, to the global primary energy demand and energy-related CO_2 emissions for the year 2006 [3••]. CO_2 is estimated to increase to 76% by 2030. This remains the only published global estimate. On a national and regional scale, carbon emissions from urban energy usage for China, USA and Europe are estimated to 85%, 80% and 69% respectively [2•,3••,4•]. In China, urban areas contributed 75% to the national primary energy demand and 85% to the national commercial energy demand [2•]. These studies highlight the importance of paying attention to the definitions of the urban population, the urban extent, and the city. Depending on the definition used, the urban energy and carbon estimates can vary substantially. The estimate by IEA is compatible with the United Nations (UN) urban population, in principle. However, one has to note that UN itself accepts the national definitions that vary widely across countries.[1] For example, for the US, 76% of the direct final energy consumption occurs in 'census urban areas', 59% occurs in 'urbanized areas' and 17% occurs in 'urban clusters' [4•]. Furthermore, the difference of urban contribution to the primary energy demand for the US in Parshall *et al.* [4•] and IEA estimate [3••], in the order of about 4% (80% versus 76%), is dependent on how out-of-boundary electricity is treated. Such energy and CO_2 estimations also depend on the energy accounting method and the GHG allocation principles. Some argue that the actual urban contribution is lower because urban areas are merely production hubs to meet demands of other areas, the electricity comes from outside urban areas, and the urban areas provide through-traffic and other through-services [14•,15•].

For GHGs other than CO_2, urban areas' contributions are still unknown. One study has estimated that urban CH_4 emissions may contribute to 7–15% of the global anthropogenic methane emissions [16•]. However, this is only an extension of analyses done in Southern California to the globe based on the assumption that similar correlation upholds between CO_2 and CH_4 globally. Nevertheless, despite the lack of full GHG accounting of urban areas, it can be fairly said that the urban GHG contribution globally would be far lesser than 71% as in the case of energy-related global CO_2. This is because the annual average share of energy-related CO_2 emissions globally for 2000–2008 is about 85% only; the remaining 15% is from land use change [17] to which urban areas are not expected to contribute much. Although being far from accurate, Wunch *et al.* [16•] show that the urban contributions of methane are far lesser. This is essentially a production-based approach; however, if one attributes all GHGs to the consumption side, then the urban areas may have significantly higher global share. Unfortunately, such studies in urban contexts are not available and are done for only countries [18,19].

GHG emissions in cities

At the urban scale, most of the GHG emission estimates are available for the administrative boundaries. This is true for climate change action plans devised by the city governments [11–13,20,21] as well as for a majority of the research literature [2•,5,23,24•,25–29]. These literature address GHG emission sources in varying degree; some cover only CO_2 from energy use while others cover GHGs other than CO_2 (for detailed analyses on GHG emissions, emission sources, emission types, and methodological differences of 44 cities, see [30••]). CO_2 estimates for urban agglomerations are largely not available but a few papers have shown the urban agglomeration and CO_2 picture in the context of higher resolution spatial global [31] and regional [32] fossil fuel emission maps. A recent study from Brookings Institute estimated and ranked CO_2 emissions from 100 metropolitan cities in the United States covering the transport and residential sectors [33•].

In China, the 35 largest and key cities (as mentioned in China's National Plan) representing 18% of the nation's population, account for 40% of its energy-related CO_2 emissions. In the United States, 20% of the nation's transportation and residential carbon emissions come from the 10 largest metro areas [33•]. In Thailand, Bangkok City with 9% of the country's population emitted 26% of the nation's CO_2 emissions from energy use in 2005 [3••,26]. Tokyo with about 10% of the country's population emitted 4% of the nation's total GHG emissions and 4.7% of fossil fuel combustion related GHG emissions [34]. From the existing literature the role of large-size cities seems to be important, especially in developing country cities where they have disproportionately higher emission share as compared to their population. Across cities, existing studies point to a large variation in the scale of the total and the per capita emissions. Comparison of over 50 cities [23,25,24•,30••] points that such differences emerge from the nature of emission sources, urban economic structures (balance of manufacturing versus service domination), local climate and geography, stage of economic development, fuel mix, state of public transport, and others [36]. In the United States, for only transport and residential sectors, per capita carbon emissions were highest in Lexington (3.5 tons) and lowest in Honolulu (1.4 tons) in 2005 within 100 metropolitan areas [33]. Big cities also seem to evade the usual developing and developed country substantiation for the above reasons. Thus, per capita CO_2 emissions of cities in the developing world such as Beijing, Shanghai, Tianjin and Bangkok are higher than those of Tokyo, New York City, and Greater London [2•,12,34,26,37]. As a result, it is often difficult to devise criteria and to compare the GHG emissions and GHG performance of cities globally.

The city-based studies have used a variety of methods and data to account GHGs. These include a combination of sales data (for oil, gas and electricity, e.g.), estimated levels of activities (trip surveys and household surveys to generate average activity levels), scaling from regional

[1] Out of 228 countries, the criteria to allocate urban population vary widely. 83 countries use administrative boundary, 57 use population size, 1 uses economic criteria, 4 use urban characteristics and 48 use a combination of the above. However, 6 use entire country population, 3 have no urban population, 25 have no definition, and 1 has no clear definition (Personal communications with UN Population Statistics Division).

and national information, and modeling. Their treatment to aviation, marine and road transport, those sectors which interact beyond city boundaries, vary from city to city adding to the existing complexities [30••]. Methodologically, existing studies differ, and thus there is an inconsistency in regard to firstly, gases measured; secondly, emission sources covered; thirdly, sector definitions; fourthly, scopes of the measurement; fifthly, global warming potential; and sixthly, IPCC Tier methods [30••,38]. However, in contrast to the IPCC's territorial accounting principles, city action plans and the research literature allocate the electricity related CO_2 emissions to the city's carbon estimates. The recent international conferences and workshops[2] have witnessed the need to standardize the scope, protocol and methods of urban GHG accounting.

Determining urban system boundaries of carbon emissions and their implications

All studies mentioned in previous sections attribute CO_2 to the point of production other than for electricity. However, cities consume materials produced elsewhere [19] and the input of the material into most cities surpasses the output by large [22]. Large energy and GHG emissions could be embedded in goods and service flows depending on the nature of cities. The embedded energy usage (a proxy for CO_2 emission) in Tokyo was 2.8 times in 1995 compared to direct energy usage [39]. In London, CO_2 emission from consumption approach is two times (90 $MtCO_2$ compared to 44 $MtCO_2$) as that of production approach [40]. In Sydney, the indirect energy requirement of households is 2.3 times of its direct energy requirement [41]. In Brazilian cities, indirect energy requirement of households were 1.6–1.9 times compared to the direct energy requirements [42]. Literature shows that the embedded emissions in goods and services could overwhelm the total urban carbon flows of cities. Consideration to embedded emissions might attribute more carbon mitigation burdens to commercial cities (because of their consumption and service demand, Tokyo and London being unique case) and relieve industrial cities where CO_2 is emitted to produce goods and services for other cities. Then the question arises what should be operational system boundary of carbon emission mitigation of a city and whether a city should be responsible only for its direct emissions within its physical boundary or also for the consumptions, actions and decisions that urban dwellers make which impact emissions in the long chain from consumption to production. This has implications for finding an efficient management regime including institutional set-ups. Recent papers support carbon footprint for policy applications [40,43•,44,30••]. The policy community is already developing carbon emission reporting with embedded emissions included. ICLEI's new revised guideline has embedded emissions as supplementary information. World Bank, UNEP and Habitat recently released a guideline for reporting cities GHG emissions including embedded emissions.[3] Despite such developments, many studies as of yet are household-based [41,42] and the urban level studies are utterly limited to understand and illustrate the various complexities in indirect emission and responsibility attribution. A large volume of literature on embodied energy has been published using Input–Output analyses, material flows, and life cycle assessment at national, sectoral and product levels, but their application to study the carbon footprint of cities is less [40,43•,41,45••,44].

Urban carbon mitigation opportunities

This section illustrates what we know on opportunities to mitigate GHG from cities and their efficient governance.

Above, we noted that cities' global and national GHG emissions are high. These are opportunities for climate change mitigation. Studies for the City of Shanghai showed that only an extension of already planned policies under the 11th Five year Plan to beyond 2010 will reduce 49% of CO_2 from do-nothing scenario by 2020 [25]. In Kyoto, Gomi *et al.* [28], using back-casting scenarios, found opportunities to reduce the city's CO_2 by 50% by 2030 compared with 1990, maintaining 1.3% per year economic growth rates. They found that energy efficiency improvements in the household and commercial sectors have large potentials. City-based research literature, cited in earlier sections, is in broad agreement that the energy efficiency improvement in urban transport and building sectors has large potentials to address carbon mitigation. However, a key gap in the existing literature remains on analyses involving the opportunity to optimize the urban system as a whole in an integrated fashion. Going beyond the conventional carbon management opportunities in cities, few studies have explored, separately, the opportunities to sequester carbon in urban systems too. Renforth *et al.* [46] show that urban soils may be able to capture 300 tons of carbon/ha if designed with calcium-rich minerals, and others have analyzed the role of urban forestry in sequestering carbon despite being small [47,48]. In Canberra, the 400 000 planted trees are estimated to have a combined energy reduction, pollution mitigation and carbon sequestration of the value of US$ 20–67 million (30 200 tons carbon sequestration) during the period 2008–2012 [49]. Studies have shown that the mean carbon uptake per ha by woody plants for urban

[2] 5th Urban Research Symposium on Cities and Climate Change: Responding to an Urgent Agenda, 28–30 June 2009, Marseille, France; A Dialogue in Cities and Climate Change, 21–23 September, The World Bank, Washington DC; International Symposium on Cities and Carbon Management: Towards Enhancing Science, Policy Linkages, 16 November 2009, Tokyo International Forum, Tokyo; ICLEI World Congress 2009, 14–18 June 2009, Edmonton, Canada.

[3] Draft International Standard for Determining Greenhouse Gas Emissions for Cities, 5th World Urban Forum, available from http://www.unep.org/urban_environment/PDFs/InternationalStd-GHG.pdf.

lands was 0.56 tons/year in Chuncheon (Korea), 0.71 tons/year in Kangleung (Korea), 0.53 tons/year in Kangnam (Korea), 0.8 tons/year in Junglang (Korea), and 0.7 tons/year in a residential district in Chicago [50]. In summary, integrated analysis, not only limiting to the efficiency gains in traditional sectors but also covering all infrastructure, technology, urban design and sinks (noting their other ecosystem services as co-benefits too) can provide a comprehensive picture of carbon management opportunities. A better understanding of carbon budge of cities helps in this [51]. From consumption side, cities also offer opportunities to influence large embedded carbon flows. Mitigation of embedded emissions from cities is related to the behavior and lifestyle issues. However, these aspects are less studied in general for climate change and the urban carbon case is not an exception [52,53].

For cities, priorities are essentially local, such as energy security, air pollution reduction, urban greening, waste management, and local economy [9•,23]. Therefore, the multiple benefits (or co-benefits) are an important element of mitigation opportunities in cities [54]. City action plans cited earlier essentially address local priorities and GHGs simultaneously and try to harmonize benefits on both fronts. Additionally, the research and actions for mitigation and adaptation in cities are often disconnected. In cities and climate change context there is need to connect them for urban development [55]. Thus costs to mitigate carbon could be minimized by simultaneously addressing local needs, mitigation and adaptation in an integrated fashion. This would also assist to efficiently utilize the local resources and the mitigation and adaptation related funding schemes for assisting developing country cities. However, one has to note that local needs and climate change mitigation and adaptation are not always synergistic. Literature with detailed studies of such opportunities at urban level and often are limited to sectors such as transport and buildings. Comprehensive urban level analyses and assessment of the extent of synergies and conflicts for multiple benefits are important to explore opportunities for urban carbon management.

In order to plan and implement carbon mitigation opportunities, appropriate forms of carbon governance are critical [9•]. A large body of literature has analyzed urban carbon governance from multiple levels [8,9•,56–59,60•,61,62,63••]. The urban climate change mitigation debate has been led by municipalities and municipal-related networks and associations. The growing role of city governments in climate change actions can be attributed to a variety of factors: requirements to shoulder national climate targets (such as in the case of Japan and others mandated by Law); lack of federal government leaderships (in the case of US); the willingness of global cities to be connected to global issues without obligatory commitment (Bangkok, Jakarta, Rio, Sao Paulo, etc.); expectation of new funding and technology from climate regimes (developing countries); and, new business prospects for local economy. In many cases, strong political leadership of Mayor is a key to devise city actions as seen from cases of Bogota, Mexico City, Malmo, Tokyo, Chicago, London and New York, but not always, especially in developing country cities, where international donors, local scholar and civil society groups can push agenda much faster (see additionally [64,65]). It is clear that the ability of the local governments to gather resources and the legislative power to devise plans and enforce them are crucial factors for carbon governance which vary substantially across the cities. The literature points out that the local government can govern climate change mitigation in four ways: self-governing (reducing GHG from municipal actions and activities), governing through legislating, governing by provisioning and governing by enabling [56]. The rising interest of local governments to assume more responsibility to govern city seems a positive trend for urban carbon mitigation. Nevertheless, the academic literature and policy debates over-emphasizes the role of municipal government and fails to take into account the limited ability of municipal governments in influencing substantial amounts of emissions from urban activities because of the several structural factors in cities (city playing a role of facilitator rather than an actor, provisioning of municipal utility services to private sectors, limited authorities, crumbling financial performance, etc.). In developing countries, the capacity, resources and jurisdiction of city governments are further limited. Thus, the role of municipal government is absolutely necessary but not sufficient for urban carbon management. Therefore, future research is needed to understand who can influence how much of cities' carbon emissions within major urban governance stakeholders, and to understand the opportunities and challenges to streamline existing modes of governance to match with such influence or the intended one.

Conclusions and future research needs

About half of the world's population lives in urban areas and the future population growth will happen mostly in urban areas. How urban dwellers choose their infrastructure (including efficient transport, green buildings, and cleaner energy supply), technology, consumption and lifestyle will determine the global GHG emissions. To support the global GHG mitigation, several new strands of research for developing a better understanding of mitigation opportunities, governance and incentives systems for urban areas are necessary. The goals of research and actions in urban areas should be to reduce the overall urban carbon footprint, taking into a broader system perspective.

In order to advance the urban research agenda on global GHG mitigation, we identify a number of key research issues. First, a better understanding and quantification of

GHG emissions and mitigation potential under the different definitions of urban areas and allocation principles globally and nationally is necessary. Second, urban system is essentially an open system with extensive cross boundary interactions for food, water, energy, mobility, material and services. Therefore, in urban regions, a clear understanding of the concept of urban carbon footprints is needed. This should take into account the direct GHG emissions and indirect GHG emissions (means, upstream GHG emissions from energy and heat import/export and embedded GHG emission from import/export of goods and services). This would also require developing new type of methodologies going beyond product-based life-cycle assessments, Input–Output analyses and household income–expenditure surveys. Third, of the cities' total carbon footprints, how much GHG the municipal governments and other urban institutions and stakeholders respectively can mitigate or should aim for is necessary. In urban setting, municipal governments have often limited role in managing many key drivers of even direct GHG emissions. Mobility, food and material flow are difficult to influence. In this context, research advances are needed in determining the efficient and innovative ways of governing urban GHGs for reducing overall GHG footprint. City authorities can effectively act as a facilitator if not actor in many cases and such roles need a better understanding. Fourth, a sound understanding of urban development pathways and their GHG consequences are needed for various urban typologies. Such understanding can be generated from a set of well coordinated comparative studies across cities. Global scientific programs can help to foster research protocols and facilitate such comparative studies. Fifth, a better understanding of the prospects for optimizing GHG mitigations with multiple benefits locally for issues such as air pollution, transport, and waste management are essential. In addition, the mitigation and adaptation needs to be connected for urban development planning to optimize urban infrastructure system and financial resources.

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