Carbon Sequestration in Urban Ecosystems

Rattan Lal • Bruce Augustin
Editors

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Foreword

Urbanization, a principal land use during the twenty-first century, is an anthropogenically driven and a rapid transformation of ecosystems. While more than 50% of the world's population already lives in urban centers, urban encroachment of prime farmlands is caused by a rapid population growth. By 2050, as much as 69% of the world population may live in urban centers. It is estimated that providing accommodation and the supporting infrastructure to one million people requires 40,000 ha of land. Thus, the estimated global population growth rate of 70–80 million people per year needs an additional land area of three million hectares (Mha). Total land area in urban centers in the U.S. is estimated at 24 Mha or 2.62% of the total land area. Such a rapid urbanization has also increased demand for natural resources, with a large ecologic foot print. Further, continued loss of prime farmland may exacerbate food prices, create agricultural shortages across the world, and lead to food price inflation. Urban encroachment has numerous social, economic, political and ecologic implications, including reduction in ability of agroecosystems to produce adequate amount of food and fiber for the ever increasing world population.

Megacities and growing urban centers also use numerous resources including energy, minerals, transport fuel, water and food, and generate a large amount of waste. This drastic ecologic transformation and consumption of natural resources is a principal anthropogenic driver of global change including the global warming. Of the total earth's ice-free land area of 11.3 billion ha, about 3% (338 Mha) is under urban land use. However, these areas are major sources of emission of greenhouse gases. Yet, judicious management and restoration of urban ecosystems can off-set some anthropogenic emissions and also generate essential ecosystem services.

Urban centers consist of build up areas (under buildings, concrete and asphalt) and also green areas (under lawns, shrubs, trees, forests and agriculture or horticultural gardens). While efficient use of energy, water, and minerals in build up areas is extremely important, sustainable management of green areas is essential to restoring the ecosystems C budget. Improved management of green areas can sequester C in the above and below-ground biomass, increase soil organic C pool and improve its depth distribution in favor of translocation of C into the sub-soil layers, reduce emissions of N_2O and CH_4, and off-set some anthropogenic emissions.

It is argued that the twenty-first century is the Century of the Cities, because of their major impact on global process and significant issues of the twenty-first century. Therefore, a workshop was organized at the campus of The Ohio State University (OSU) entitled, "Carbon Sequestration in Urban Ecosystems" on 14th April 2010. Jointly organized and sponsored by OSU and Scotts Co., the workshop was attended by about 50 participants from around the country. This volume is based on papers presented at the workshop. In addition, some other renowned researchers/authors were invited to contribute additional chapters to address regions or themes not covered by the workshop participants. Principal objectives of the workshop, and of this volume, are to:

- Assess the effects of urbanization on national and global C pools and fluxes,
- Determine credible estimates of C pool and fluxes in turf grass, home lawns, urban agriculture and gardens, urban forests and trees and other land use,
- Evaluate the role of turf grass and lawns on emissions of greenhouse gases (CO_2, CH_4, N_2O),
- Study coupled cycling of C with that of H_2O, N, P, etc. in relation to soil quality in lawns and turf grass systems,
- Identify best management practices for diverse land uses within urban green spaces,
- Develop strategies which promote adoption of best management practices to enhance sequestration of C within green areas of urban ecosystems, and
- Identify management systems which reduce emissions of greenhouse gases from urban land systems, and enhance use efficiency of inputs.

These objectives have been summarized into some basic questions which need to be addressed. Some important questions are:

- How much and by what processes does the urbanization influence the global carbon cycle?
- What is the quantitative estimate of diverse green areas (i.e., lawns, turfs, forests, agriculture) in urban centers, and how can the green areas be sustainably managed?
- How does management influence C budget of the "green city areas" within urban ecosystems?

The 19-chapter volume specifically addresses the objectives and question listed above. Specific topics addressed include: (i) adapting urban land use to climate change, (ii) managing urban forests and lawns to sequester carbon, (iii) assessing C pools, and gaseous fluxes in urban ecosystems, and (iv) promoting urban agriculture.

The editors thank all the authors for their outstanding contributions to this volume. Thanks are also due to the staff of Springer Verlag for their timely efforts in publishing this information, and making it available to scientists, practitioners, and general public. Editors specifically acknowledge support received from the staff and students of the Carbon Management and Sequestration Center of The Ohio State University, and the staff of the Scotts Co. for their help and support. We especially thank Ms. Theresa L. Colson for her efforts in handling the flow of the chapters

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Contents

Part V Sustainable Management of Urban Ecosystems

Part I
Urban Ecosystems and Climate Change

Chapter 1
Urban Ecosystems and Climate Change

Rattan Lal

Abstract More than 50% of the world population (~3.5 billion) lives in urban areas, and the relative magnitude will increase to 60% by 2030. The highest rate of urbanization in the world is in Latin America, and in the emerging economies of China and India. Urban ecosystems, covering ~3% of the terrestrial land area, strongly influence biogeochemical cycles of elements (C, N) and water, and alter regional and global climate through gaseous emissions. Yet, urban lands are an important C pool with a C density as high as 20–40 kg C m^{-2}. Because of intensive management, the above ground net primary productivity can be 300–400 g C m^{-2} $year^{-1}$. Principal components of the ecosystem C pool include urban forests, lawns and turfs and recreational grounds, and soil C pool. The net ecosystem C pool can be enhanced by reducing the hidden C costs associated with management. Urban agriculture is gaining importance and adds to multifunctionality of urban landscapes. Urban ecosystems have a large technical potential to sequester C in soils and biota through judicious management. While sources of gaseous emissions must be reduced, C sink capacity of urban lands can be enhanced through adoption of recommended management practices.

Keywords Urban agriculture • Soil carbon in urban land • Green roofs • Urban soil quality • Urban forests

List of Abbreviations

ACC	abrupt climate change
ANPP	above-ground net primary productivity
C	carbon

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GCC global carbon cycle
GHGs greenhouse gases
HCC hidden carbon costs
NEE net ecosystem exchange
NPP net primary productivity
SOC soil organic carbon
USDA United States Department of Agriculture

1.1 Introduction and Rationale

The world population increased from 2.53 billion in 1950 to 6.91 billion in 2010, an increase of 173% (UN 2008). Between 2010 and 2050, the world population will increase by another 32% to 9.15 billion. In comparison, world's urban population increased from 165 to 215 million in 1900 to 729 million in 1950 and 3.486 billion in 2010, 21 times compared with 1900 and 3.8 times in comparison with 1950. Between 2010 and 2050, world's urban population will increase by another 80% to 6.29 billion. By 2050, 68.7% of the world population will live in urban centers (Fig. 1.1a, b; UNPD 2011). These trends indicate a drastic shift to urban living since 1900 (Grimm et al. 2008; Seto and Satterthwaite 2010). Urban population, as a percentage of the world total population, was 10–13% in 1900, 28.8% in 1950, 50% in 2009, and is projected to be 60% in 2030 and 68.7% in 2050 (Fig. 1.1c; UNPD 2011). The rate of urbanization is very rapid in less developed and developing countries (Seto and Shepherd 2009; Table 1.1). Similar trends in urbanization are observed in USA and North America. The urban population had increased from 130 million in 1960 to 259 million in 2010 in the U.S.A., and 143 million to 281 million in North America (Table 1.2). The urban population in the state of Ohio increased from 5.6 million (70.2%) in 1950 to 8.9 million (77.4%) in 2009 (Table 1.3).

Concentration of world population in large urban centers or mega cities (i.e., Mexico, Rio, Mumbai, Kolkata) strongly impacts regional and global climate (Tollefson 2010a, b) because of drastic perturbations of land use and the attendant changes in biogeochemical cycles of H_2O and elements (C, N, P, S), energy use, radiation budget, and the heat island effect (Buckley 2010). Urban population growth and export of agricultural products are also major factors causing tropical deforestation (DeFries et al. 2010). Thus, the objective of this chapter is to outline the impact of urbanization on ecosystem functions, but specifically on the global C cycle in relation to climate change adaptation and mitigation (Table 1.4).

1.2 Urban Ecosystems and Climate Change

Urban lands constitute an important component of the global land use and area change matrix (Holmgren 2006), thus, must be considered in all climate and environmental issues. Global urban centers cover ~3% of the terrestrial land area

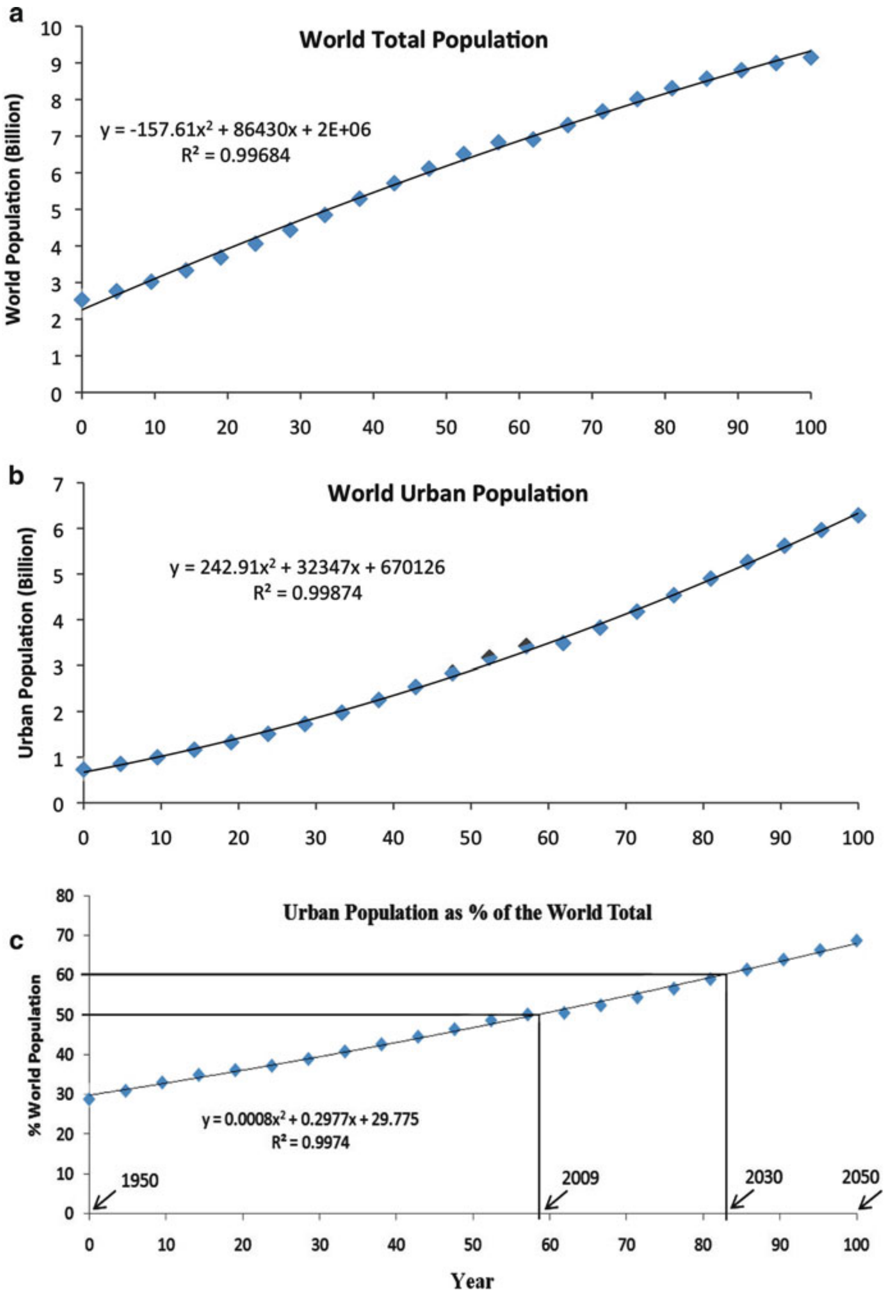

Fig. 1.1 (**a**) trends in world population (**b**) world urban population (**c**) % urban population from 1950 to 2050 (Redrawn from UNPD 2011)

Table 1.1 Continental distribution of urban population (UN 2008)

Region	Urban population (10^9) 2007	2025	2050
World	3.29	4.58	6.40
Africa	0.37	0.66	1.23
Developed regions	0.91	0.99	1.07
Less developed regions	2.38	3.59	5.33
China	0.56	0.83	1.01

Table 1.2 Urban population in North America (10^9) (UN 2008)

Year	USA	North America
1960	130	143
1970	155	171
1980	170	189
1990	193	214
2000	225	150
2010	259	286
2020	291	321
2030	318	351
2040	343	378
2050	364	401

Table 1.3 Urban population in Ohio (Ohio Data Center 2010)

	Population (10^9)		
Year	Total	Urban	Urban (% of total)
1950	7.9	5.6	70.2
1960	9.7	7.1	73.4
1970	10.7	8.0	75.3
1980	10.8	7.9	73.3
1990	10.8	8.0	74.1
2000	11.4	8.8	77.4
2009	11.5	8.9	77.4

Table 1.4 Energy use in urban households (Williams 2008)

			Residential energy use (10^6 BTU)			
Unit	Parameter	Area (ft^2)	Heating	Cooling	Other	Total
Single-family	Detached	2,368	45.7	8.0	44.0	89.7
Single-family	Attached	1,121	36.6	6.1	36.7	79.4
Apartment	Multifamily	1,067	24.5	6.4	28.3	59.2

(Grimm et al. 2008). However, urban ecosystems are the major source of global emissions including 78% of total C emission. Urban centers also use 60% of the residential water consumption and 76% of industrial wood consumption (Grimm et al. 2008). Consequently, there is a drastic transformation in resource use because of the strong impacts of urbanization on the environment (Fig. 1.2). Principal among these impacts are physical alteration because of (i) transformation of landscape,

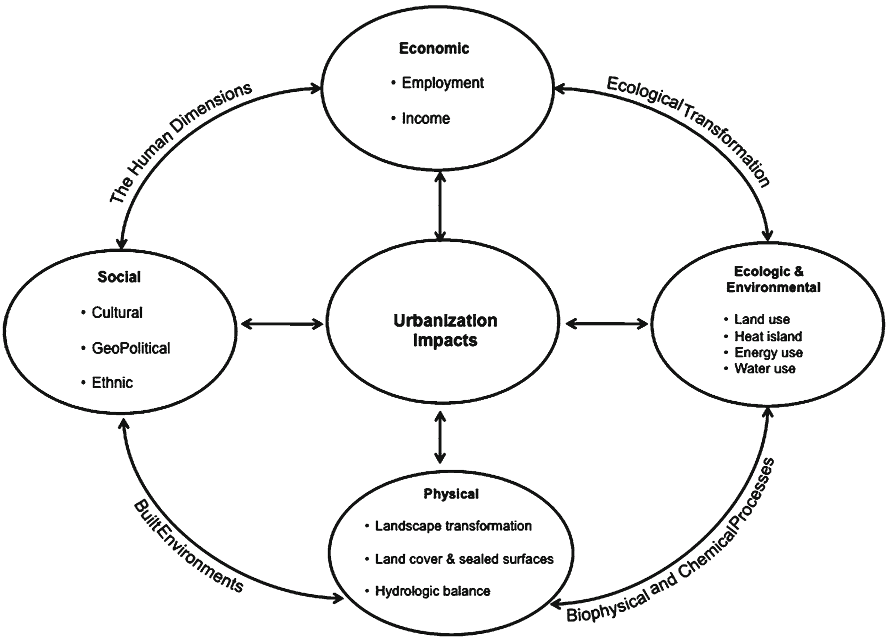

Fig. 1.2 Ecologic, economical, physical and social impacts of urbanization in the context of climate change

(ii) changes in land cover and sealed surfaces, and (iii) alternations in the hydrologic balance. Urbanization in the desert or dry regions is a principal challenge of water sustainability because urban cities are vulnerable to water scarcity (Gober 2010). There is a distinct water–energy relationship in desert urban centers. These physical changes lead to ecologic and environmental impacts including those on land use, heat island, and energy and water use. These impacts are also related to the human dimensions or social issues as influenced by job opportunities and employment, and thus to changes in income or economic affluence of the urban population. Another important aspect of the human dimensions of the urbanization involves changes in social and community structure encompassing those related to cultural, geopolitical and ethnic mix in urban population. These impacts, outlined in Fig. 1.2, strongly alter the biogeochemical cycles, especially the C cycle, with an attendant changes in both regional and global climate.

1.3 Urban Land Use and Climate Change

In comparison with natural and agroecosystems or forest plantations, urban ecosystems have a distinct biogeochemistry (Kaye et al. 2006). Principal biogeochemical controls include impervious surfaces, engineered aqueous flow paths, drastic

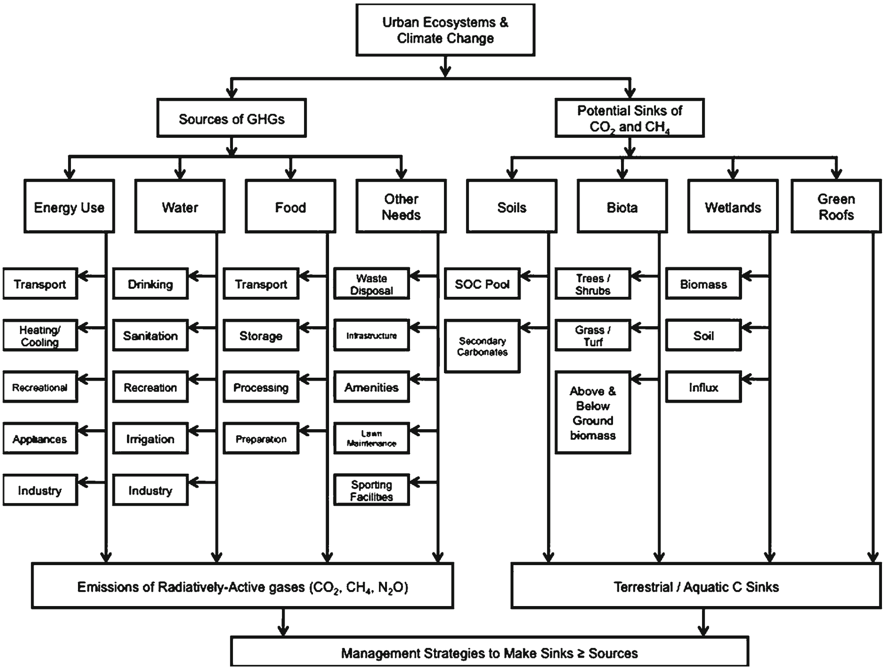

Fig. 1.3 Sources and potential sinks of greenhouse gases in urban ecosystems (*SOC* soil organic carbon)

landscape alterations, and perturbed ecological processes (Jenerette et al. 2006). Thus, urbanization influences the global C cycle (GCC) through alterations in sources and sinks of C (Fig. 1.3). Urbanization changes the characteristics of the vegetation and soils, both of which are a distinct component of the GCC (Svirejeva-Hopkins et al. 2004). Through alteration of C pools and their dynamics (flows), it influences the climate at local, regional and global scales. Urbanization is a process of ecological transformation (Huang et al. 2010).

The principal sources of CO_2 and other greenhouse gases (GHGs) in urban ecosystems are attributed to the concentration of transport and industry in these sites. The poor air quality in megacities (Parrish and Zhu 2009) is attributed to emission of a wide range of trace gases from industrial sources. Important among these traces gases are NO, NO_2, O_3. SO_2, HNO_3 and a range of organic acids (Grimm et al. 2008). There are also elevated concentrations of CO_2, CH_4 and O_3 compared with rural areas. Air pollution also affects the net primary productivity (NPP) and indirectly influences the GCC. Other principal sources of GHGs in urban ecosystems are from infra-structure, sporting facilities, lawn maintenance, and other amenities.

It is estimated that by 2015, there will be 236 cities in the world with a population of 10 million or more. A city of this size requires about 6,000 tons of food per day. Thus, a large number of plant nutrients are transferred into the cities, which

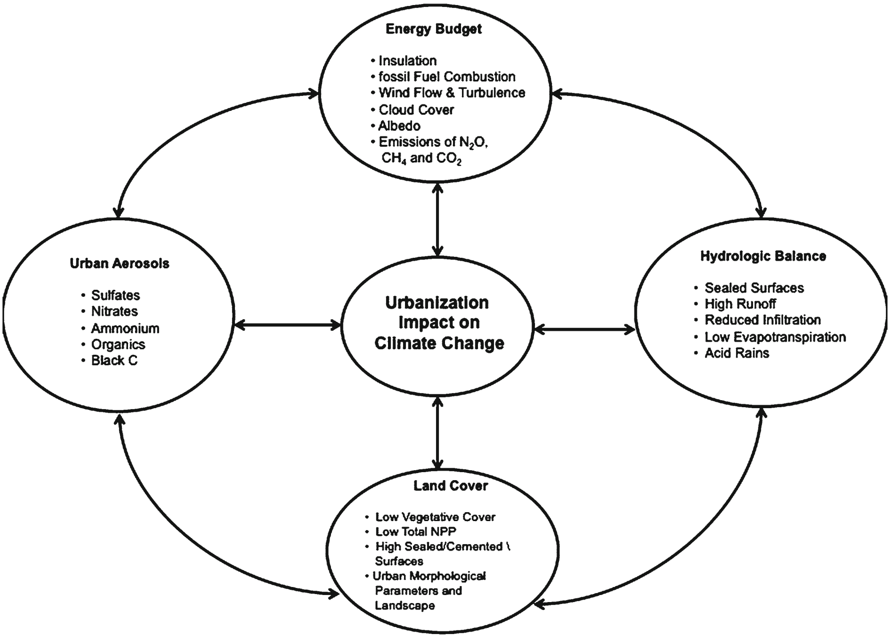

Fig. 1.4 Urbanization effects on climate change through alterations in energy budget, hydrologic balance, land cover and aerosols

accumulate N, P, metals and other pollutants. Megacities are considered similar to an organism that consumes a large amount of food and generates a considerable quantity of waste (Walsh 2002), and the latter is a principal cause of environmental pollution and of the abrupt climate change (ACC). Waste disposal is an important factor, and landfills are a major source of GHGs.

There are also numerous potential sinks of GHGs within the urban ecosystems (Fig. 1.3). Important among these are soils, biota, wetlands and green roofs. With judicious management of soils and trees (along with wetlands and green roofs etc.), urban ecosystems can be a major sink of CO_2 and other atmospheric constituents.

The overall effects of urbanization on climate change, outlined in Fig. 1.4, include those due to drastic alterations in the energy budget, hydrologic balance, land cover and NPP, and the aerosols. The effects of aerosols on climate are complex (Seto and Shepherd 2009) and can be positive or negative, and direct or indirect. Some aerosols have a cooling effect (i.e., sulfates). Most urbanization occurs on highly fertile lands/soils. Thus, there is a strong negative effect of urban encroachment on NPP and the ecosystem C budget. High emissions of N_2O (and CH_4 from waste and sewage) create high radiative forcing in urban environments. The reduction in NPP through urbanization is exacerbated by increase in deforestation (DeFries et al. 2010). Indeed, there are numerous interactions between urbanization and climate change and other environmental factors (Seto and Satterthwaite 2010).

Creation of sealed surfaces has buried a considerable amount of soil C beneath the cemented or covered surfaces. Yet the terrestrial C stored in human settlements has not been adequately quantified. Churkina et al. (2009) estimated that the amount of terrestrial C stored in urban settlements can be as much as 23–42 kg C m^{-2} compared with 7–16 kg C m^{-2} in rural areas and 4–25 kg C m^{-2} in tropical rainforests. In 2000, the terrestrial C pool in urban lands in the contiguous USA was 18 Pg or 10% of the total C pool (Churkina et al. 2009). Of this, 11.5 Pg (64%) was stored in the urban soils. Thus, management of soil C pool in urban ecosystems is important to the GCC and ecosystem C budget (Pavao-Zuckerman 2008). Thus, protecting and enhancing the terrestrial C pool in urban ecosystems is an important strategy to mitigating its average impacts on the environment, and for sustainable development (Rodriguez and Bonilla 2007).

1.4 Sources of Gaseous Emissions

Two principal aspects of urbanization, as major sources of gaseous emissions, are: consumption of natural resources (i.e., fossil fuel, forest products, water), and transformation of land and ecosystems (i.e., deforestation, drainage of wet lands, landscaping, etc.). It is the large demand for energy and natural resources which exacerbate emissions of CO_2, CH_4, N_2O and other trace gases into the atmosphere. Urban sprawl as a result of human population growth is an important source of increased atmospheric CO_2 (Shao et al. 2008).

Urban centers, and especially the megacities, are major sources of GHGs. A wide range of emission sources in urban ecosystems include use of electricity and natural gas for residential, commercial and industrial activities. City growth affects the environment directly and indirectly (Bettencourt and West 2010), and has been a source of much pollution. In addition, there is a large consumption of petro-fuels (diesel, gasoline, jet fuel, etc.) for vehicles (cars, trucks) used in transport (Hillman and Ramaswami 2010). Trucking is a dominant freight mode in North America and elsewhere. In addition, a vast amount of cement used in urban centers is also a major source of CO_2.

1.5 Urban Land Use and Carbon Sinks

Management of urban landscape is important to moderating the GCC. Urbanization affects the sustainable use of natural resources (Lyons 1997). The twenty first century is considered as The Century of the City, and cities are leading the way in climate-change action plan (Armstrong and Spiller 2010; Rosenzweig et al. 2010; van Noorden 2010c), and in institutions (Butler 2010). The United States Department of Agriculture (USDA) also has a program in urban ecosystem management. With a large proportion of the terrestrial C pool stored in urban settlements (both pedologic and biotic), a sustainable management of this pool is essential to moderating the GCC, and mitigating ACC through enhancement and sequestration of C in urban