

Chapter 14. Human Settlements and the North American Carbon Cycle

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KEY FINDINGS

- Human settlements occupy almost 5 % of the North American land area.
- There is currently insufficient information to determine the complete carbon balance of human settlements in North America. Fossil fuel emissions, however, very likely dominate carbon fluxes from settlements.
- An estimated 410 to 1679 Mt C are currently stored in the urban tree component of North American settlements. The growth of urban trees in North America produces a sink of approximately 16 to 49 Mt C yr⁻¹, which is 1 to 3% of the fossil fuel emissions from North America in 2003.
- Estimates of historical trends of the net carbon balance of North American settlements are not available. Fossil fuel emissions have likely gone up with the growth of urban lands but the net balance of carbon loss during conversion of natural to urban or suburban land cover and subsequent sequestration in lawns and urban trees is highly uncertain.
- The density and development patterns of human settlements are drivers of fossil fuel emissions, especially in the residential and transportation sectors. Biological carbon gains and losses are influenced by type of predevelopment land cover, post-development urban design and landscaping choices, soil and landscape management practices, and the time since land conversion.
- Projections of future trends in the net carbon balance of North American settlements are not available. However, the projected expansion of urban areas in North America will strongly impact the future North American carbon cycle as human settlements affect (1) the direct emission of CO₂ from fossil fuel combustion, (2) alter plant and soil carbon cycling in converting wild lands to residential and urban land cover.
- A number of municipalities in Canada, Mexico, and the U.S. have made commitments to voluntary GHG emission reductions under the Cities for Climate Protection program of International Governments for Local Sustainability [formerly the International Council for Local Environmental Initiatives (ICLEI)]. Reductions have in some cases been associated with improvements in air quality.

- Research is needed to improve comprehensive carbon inventories for settled areas, to improve understanding of how development processes relate to driving forces for the carbon cycle, and to improve linkages between understandings of human and environmental systems in settled areas.
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Activities in human settlements form the basis for much of North America's contribution to global CO₂ emissions. Settlements such as cities, towns, and suburbs vary widely in density, form, and distribution. Urban settlements, as they have been defined by the census bureaus of the United States, Canada, and Mexico, make up approximately 75 to 80% of the population of the continent, and this proportion is projected to continue to increase (United Nations, 2004). The density and forms of new development will strongly impact the future trajectory of the North American carbon cycle as human settlements affect the carbon cycle by (1) direct emission of CO₂ from fossil fuel combustion, (2) alterations to plant and soil carbon cycles in conversion of wildlands to residential and urban land cover, and (3) indirect effects of residential and urban land cover on energy use and ecosystem carbon cycling.

CARBON INVENTORIES OF HUMAN SETTLEMENTS

Conversion of agricultural and wildlands to settlements of varying densities is occurring at a rapid rate in North America, faster, in fact, than the rate of population growth. For example, according to U.S. Census Bureau estimates, urban land in the coterminous United States increased by 20% in the 1990s (Nowak *et al.*, 2005) while the population increased by 13%. Given these trends, it is important to determine the carbon balance of different types of settlements and how future urban policy and planning may impact the magnitude of CO₂ sources and sinks at regional, continental, and global scales. However, unlike many other types of common land cover, complete carbon inventories including fossil fuel emissions and biological sources and sinks of carbon have been conducted only rarely for settlements as a whole. Assessing the carbon balance of settlements is challenging, as they are characterized by large CO₂ emissions from fuel combustion and decomposition of organic waste as well as transformations to vegetation and soil that affect carbon sources and sinks.

Determining the extent of human settlements across North America also presents a challenge, as definitions of "developed," "built-up," and "urban" land vary greatly, particularly among nations. The U.S., Canadian, and Mexican census definitions are not consistent; in addition, several other classification schemes for defining and mapping settlements have been developed, such as the U.S. Department of Agriculture's National Resource Inventory categorization of developed land, which uses a variety of methods based on satellite imagery. One method of classifying settled land cover that has been consistently applied at a continental scale is the Global Rural-Urban Mapping Project conducted by a

1 consortium of institutions, including Columbia University and the World Bank (CIESIN *et al.*, 2004).
2 This estimate, which is based on nighttime lights satellite imagery, is 1,039,450 km², almost 5 % of the
3 total continental land area (Fig. 14-1).

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5 **Fig. 14-1. North America urban extents.**

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7 Currently, there is insufficient information to determine the complete current or historical carbon
8 balance of total continental land area. Fossil fuel emissions very likely dominate carbon fluxes from
9 settlements, just as settlement-related emissions likely dominate total fossil fuel consumption in North
10 America. However, specific estimates of the proportion of total fossil fuel emissions directly attributable
11 to settlements are difficult to make given current inventory methods, which are often conducted on a state
12 or province-wide basis. In addition, the biological component of the carbon balance of settlements is
13 highly uncertain, particularly with regard to the influence of urbanization on soil carbon pools and
14 biogenic greenhouse gas emissions.

15 For the urban tree component of the settlement carbon balance, carbon stocks and sequestration have
16 been estimated for urban land cover (as defined by the U.S. Census Bureau) in the coterminous United
17 States to be on the order of 700 Mt (335–980 Mt C) with sequestration rates of 22.8 Mt C yr⁻¹ (13.7–25.9
18 Mt C yr⁻¹) (Nowak and Crane, 2002). These estimates encompass a great deal of regional variability and
19 contain some uncertainty about differences in carbon allocation between urban and natural trees, as urban
20 trees have been less studied. However, to a first approximation, these estimates can be used to infer a
21 probable range of urban tree carbon stocks and gross sequestration on a continental basis. Nowak and
22 Crane (2002) estimated that urban tree carbon storage in the Canadian border states (excluding semi-arid
23 Montana, Idaho, and North Dakota) ranged from 24 to 45 t C ha⁻¹, and carbon sequestration ranged from
24 0.8 to 1.5 t C ha⁻¹ yr⁻¹. Applying these values to a range of estimates of the extent of urban land in Canada
25 (28,045 km² from the 1996 Canadian Census and 131,560 km² from CIESIN *et al.*, 2004), Canadian
26 urban forest carbon stocks are between 67 and 592 Mt while carbon sequestration rates are between 2.2
27 and 19.7 Mt C yr⁻¹. Similarly, for Mexico, Nowak and Crane (2002) estimated that urban carbon storage
28 and sequestration in the U.S. southwestern states varied from 4.4 to 10.5 t ha⁻¹ and 0.1 to 0.3 t ha⁻¹ yr⁻¹,
29 respectively, leading to estimates of 10 to 107 Mt C stored in urban trees in Mexico and 0.2 to 3.1 Mt C
30 yr⁻¹ sequestered. Estimates of historical trends are not available.

31 While complete national or continental-scale estimates of the carbon budget of settlements including
32 fossil fuels, vegetation, and soils are not available, several methods are available to assess the full carbon
33 balance of individual settlements and can be applied in the next several years toward constructing larger-
34 scale inventories. Atmospheric measurements can be used to determine the net losses of carbon from

1 settlements and urbanizing regions (Grimmond *et al.*, 2002; Grimmond *et al.*, 2004; Nemitz *et al.*, 2002;
2 Soegaard and Moller-Jensen, 2003). Specific sources of CO₂ can be determined from unique isotopic
3 signatures (Pataki *et al.*, 2003; Pataki *et al.*, 2006b) and from the relationship between CO₂ and carbon
4 monoxide (Lin *et al.*, 2004). Many of these techniques have been commonly applied to natural
5 ecosystems and may be easily adapted for settled regions. In addition, there have been several attempts to
6 quantify the “metabolism” of human settlements in terms of their inputs and outputs of energy, materials,
7 and wastes (Decker *et al.*, 2000) and the “footprint” of settlements in terms of the land area required to
8 supply their consumption of resources and to offset CO₂ emissions (Folke *et al.*, 1997). Often these
9 calculations include local flows and transformations of materials as well as upstream energy use and
10 carbon appropriation, such as remote electrical power generation and food production.

11 To conduct metabolic and footprint analyses of specific settlements, energy and fuel use statistics are
12 needed for individual municipalities, and these data are seldom made available at that scale.
13 Consequently, metabolic and footprint analyses of carbon flows and conversions associated with
14 metropolitan regions have been conducted for a relatively small number of cities. A metabolic analysis of
15 the Toronto metropolitan region showed per capita net CO₂ emissions of 14 t CO₂ yr⁻¹ (Sahely *et al.*,
16 2003), higher than analyses of other large metropolitan areas in developed countries (Newman, 1999;
17 Pataki *et al.*, 2006a; Warren-Rhodes and Koenig, 2001). In contrast, an analysis of Mexico City estimated
18 per capita CO₂ emissions of 3.4 t CO₂ yr⁻¹ (Romero Lankao *et al.*, 2004). Local emissions inventories can
19 provide useful supplements to national and global inventories in order to ensure that emissions reductions
20 policies are applied effectively and equitably (Easterling *et al.*, 2003).

21 Current projections for urban land development in North America highlight the importance of
22 improving carbon inventories of settlements and assessing patterns and impacts of future urban and rural
23 development. Projections for increases in the extent of developed land cover in the United States in the
24 next 25 years are as high as 79%, which would increase the proportion of developed land from 5.2% to
25 9.2% of total land cover (Alig *et al.*, 2004). The potential consequences of this increase for the carbon
26 cycle are significant in terms of CO₂ emissions from an expanded housing stock and transportation
27 network as well as from conversion of agricultural land, forest, rangeland, and other ecosystems to urban
28 land cover. Because the dynamics of carbon cycling in settled areas encompass a range of physical,
29 biological, social, and economic processes, studies of the potential impacts of future development on the
30 carbon cycle must be interdisciplinary. Large-scale research on what has been called the study “of cities
31 as ecosystems” (Pickett *et al.*, 2001) has begun only relatively recently, pioneered by interdisciplinary
32 studies such as the National Science Foundation’s Long-Term Ecological Research sites in the central
33 Arizona-Phoenix area and in Baltimore (Grimm *et al.*, 2000). Although there is not yet sufficient data to
34 construct a complete carbon inventory of settlements across North America, it is a feasible research goal

1 to do so in the next several years if additional studies in individual municipalities are conducted in a
2 variety of urbanizing regions.

3 4 **TRENDS AND DRIVERS**

5 Drivers of change in the carbon cycle associated with human settlements include (1) factors that
6 influence the rate of land conversion and urbanization, such as population growth and density, household
7 size, economic growth, and transportation infrastructure; (2) additional factors that influence fossil fuel
8 emissions, such as climate, residence and building characteristics, transit choices, and affluence; and
9 (3) factors that influence biological carbon gains and losses, including the type of predevelopment land
10 cover, post-development urban design and landscaping choices, soil and landscape management practices,
11 and the time since land conversion.

12 13 **Fossil Fuel Emissions**

14 The density and patterns of development of human settlements (i.e., their “form”) are drivers of the
15 magnitude of the fossil fuel emissions component of the carbon cycle. The size and number of residences
16 and households influence CO₂ emissions from the residential sector, and the spatial distribution of
17 residences, commercial districts, and transportation networks is a key influence in the vehicular and
18 transportation sectors. Many of the attributes of urban form that influence the magnitude of fossil fuel
19 emissions are linked to historical patterns of economic development, which have differed in Canada, the
20 United States, and Mexico. The future trajectory of development and associated levels of affluence and
21 technological and social change will strongly influence key aspects of urban form such as residence size,
22 vehicle miles traveled, and investment in urban infrastructure, along with associated fossil fuel emissions.
23 Whereas emissions from the transportation and residential sectors are discussed in detail in Chapters 7
24 and 9, respectively, this chapter discusses specific aspects of the form of human settlements that affect the
25 current continental carbon balance and its possible future trajectories.

26 Household size in terms of the number of occupants per household has been declining in North
27 America (Table 14-1) while the average size of new residences has been increasing. For example, the
28 average size of new, single family homes in the United States increased from 139 m² (1500 ft²) to more
29 than 214 m² (2300 ft²) between 1970 and 2004 (NAHB, 2005). These trends have contributed to increases
30 in per capita CO₂ emissions from the residential sector as well as increases in the consumption of land for
31 residential and urban development (Alig *et al.*, 2003; Ironmonger *et al.*, 1995; Liu *et al.*, 2003; MacKellar
32 *et al.*, 1995). In addition, when considering total emissions from settlements, the trajectory of the
33 transportation and residential sectors may be linked. There have been a number of qualitative discussions
34 of the role of “urban sprawl” in influencing fossil fuel and pollutant emissions from cities (CEC, 2001;

1 Gonzalez, 2005), although definitions of urban sprawl vary (Ewing *et al.*, 2003). Quantitative linkages
2 between urban form and energy use have been attempted by comparing datasets for a variety of cities, but
3 the results have been difficult to interpret due to the large number of factors that may affect transportation
4 patterns and energy consumption (Anderson *et al.*, 1996). For example, in a seminal analysis of data from
5 a variety of cities, Kenworthy and Newman (1990) found a negative correlation between population
6 density and per capita energy use in the transportation sector. However, their data have been reanalyzed
7 and reinterpreted in a number of subsequent studies that have highlighted other important driving
8 variables, such as income levels, employment density, and transit choice (Gomez-Ibanez, 1991; Gordon
9 and Richardson, 1989; Mindali *et al.*, 2004).

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11 **Table 14-1. Increases in number of households and the total population of the United States, Canada,**
12 **and Mexico between 1985 and 2000.** (United Nations, 2002; United Nations Habitat, 2003).

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14 Quantifying the nature and extent of the linkage between development patterns of human settlements
15 and greenhouse gas emissions is critical from the perspective of evaluating the potential impacts of land
16 use policy. One way forward is to further the application of integrated land use and transportation models
17 that have been developed to analyze future patterns of urban development in a variety of cities (Agarwal
18 *et al.*, 2000; EPA, 2000; Hunt *et al.*, 2005). Only a handful have been applied to date for generating fossil
19 fuel emissions scenarios from individual metropolitan areas (Jaccard *et al.*, 1997; Pataki *et al.*, 2006a),
20 such that larger-scale national or continental projections for human settlements are not currently available.
21 However, there is potential to add a carbon cycle component to these models that would assess the
22 linkages between land use and land cover change, residential and commercial energy use and emissions,
23 emissions from the transportation sector, and net carbon gains and losses in biological sinks following
24 land conversion. A critical feature of these models is that they may be used to evaluate future scenarios
25 and the potential impacts of policies to influence land use patterns and transportation networks in
26 individual settlements and developing regions.

27 28 **Vegetation and Soils in Human Settlements**

29 Human settlements contain vegetation and soils that are often overlooked in national inventories, as
30 they fall outside common classification schemes. Nevertheless, patterns of development affect the carbon
31 balance of biological systems, both in the replacement of natural ecosystems with rural, residential, or
32 urban land cover and in processes within settlements that affect constructed and managed land cover. In
33 the United States, satellite data and ecosystem modeling for the mid-1990s suggested that urbanization

1 occurred largely on productive agricultural land and therefore caused a net loss of carbon fixed by
2 photosynthesis of 40 Mt C yr⁻¹ (Imhoff *et al.*, 2004).

3 Urban forests and vegetation sequester carbon directly as described under carbon inventories. In
4 addition, urban trees influence the carbon balance of municipalities indirectly through their effects on
5 energy use. Depending on their placement relative to buildings, trees may cause shading and windbreak
6 effects, as well as evaporative cooling due to transpiration (Akbari, 2002; Oke, 1989; Taha, 1997). These
7 effects have been estimated in a variety of studies, mostly involving model calculations that suggest that
8 urban trees generally result in net reductions in energy use (Akbari, 2002; Akbari and Konopacki, 2005;
9 Akbari *et al.*, 1997; Akbari and Taha, 1992; Huang *et al.*, 1987). Taking into account CO₂ emissions
10 resulting from tree maintenance and decomposition of removed trees, “avoided” emissions from energy
11 savings were responsible for approximately half of the total net reduction in CO₂ emissions from seven
12 municipal urban forests, with the remainder attributable to direct sequestration of CO₂ (McPherson *et al.*,
13 2005). Direct measurements of the components of urban energy balance that quantify the contribution of
14 vegetation are needed to validate these estimates.

15 Like natural ecosystems, soils in human settlements contain carbon, although rates of sequestration
16 are much more uncertain in urban soils than in natural soils. In general, soil carbon is generally lost
17 following disturbances associated with conversion from natural to urban or suburban land cover (Pouyat
18 *et al.*, 2002). Soil carbon pools may subsequently increase at varying rates, depending on the soil and land
19 cover type, local climate, and management intensity (Golubiewski, 2006; Pouyat *et al.*, 2002; Qian and
20 Follet, 2002). In ecosystems with low rates of carbon sequestration in native soil such as arid and
21 semiarid ecosystems, conversion to highly managed, settled land cover can result in higher rates of carbon
22 sequestration and storage than pre-settlement due to large inputs of water, fertilizer, and organic matter
23 (Golubiewski, 2006). Pouyat *et al.* (2006) used urban soil organic carbon measurements to estimate the
24 total above- and below-ground carbon storage, including soil carbon, in U.S. urban land cover to be 2,640
25 Mt (1,890 to 3,300 Mt). This range does not include the uncertainty in classifying urban land cover, but
26 applies the range of uncertainty in aboveground urban carbon stocks reported in Nowak and Crane (2002)
27 and the standard deviation of urban soil carbon densities reported in Pouyat *et al.* (2006). In addition,
28 irrigated and fertilized urban soils have been associated with higher emissions of CO₂ and the potent
29 greenhouse gas N₂O relative to natural soils, offsetting some potential gains of sequestering carbon in
30 urban soils (Kaye *et al.*, 2004; Kaye *et al.*, 2005; Koerner and Klopatek, 2002). Finally, full carbon
31 accounting that incorporates fossil fuel emissions associated with soil management (e.g., irrigation and
32 fertilizer production and transport) has not yet been conducted. In general, additional data on soil carbon
33 balance in human settlements are required to assess the potential for managing urban and residential soils
34 for carbon sequestration.

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OPTIONS FOR MANAGEMENT

A number of municipalities in Canada, the United States, and Mexico have committed to voluntary programs of greenhouse gas emissions reductions. Under the Cities for Climate Protection program (CCP) of International Governments for Local Sustainability (ICLEI, formerly the International Council of Local Environmental Initiatives) 269 towns, cities, and counties in North America have committed to conducting emissions inventories, establishing a target for reductions, and monitoring the results of reductions initiatives (the current count of the number of municipalities participating in voluntary greenhouse gas reduction programs may be found on-line at <http://www.iclei.org>). Emissions reductions targets vary by municipality, as do the scope of reductions, which may apply to the municipality as a whole or only to government operations (i.e., emissions related to operation of government-owned buildings, facilities, and vehicle fleets).

Kousky and Schneider (2003) interviewed representatives from 23 participating CCP municipalities in the United States who indicated that cost savings and other co-benefits of greenhouse gas reductions in cities and towns were the most commonly cited reasons for participating in voluntary greenhouse gas reductions programs. Potential cost savings include reductions in energy and fuel costs from energy efficiency programs in buildings, street lights, and traffic lights; energy co-generation in landfills and sewage treatment plants; mass transit programs; and replacement of municipal vehicles and buses with alternative fuel or hybrid vehicles (ICLEI, 1993; 2000). Other perceived co-benefits include reductions in emissions of particulate and oxidant pollutants, alleviation of traffic congestion, and availability of lower-income housing in efforts to curb urban sprawl. These co-benefits are often “perceived” because many municipalities have not attempted to quantify them as part of their emissions reductions programs (Kousky and Schneider, 2003); however, it has been suggested that they play a key role in efforts to promote reductions of municipal-scale greenhouse gas emissions because local constituents regard them as an issue of interest (Betsill, 2001).

Of the co-benefits of municipal programs to reduce CO₂ emissions, improvements in air quality are perhaps the most well studied. Cifuentes (2001) analyzed the benefits of reductions in atmospheric particulate matter measuring less than 10 µm in diameter (PM₁₀) and ozone concentrations in four cities in North and South America. Using a greenhouse gas reduction of 13% of 2000 levels by 2020 from energy efficiency and fuel substitution programs, Cifuentes (2001) estimated that PM₁₀ and ozone concentrations would decline by 10% of 2000 levels. Estimated health benefits from such a reduction included avoidance of 64,000 (18,000–116,000) premature deaths associated with air quality-related health problems as well as avoidance of 91,000 (28,000–153,000) hospital admissions and 787,000 (136,000–1,430,000) emergency room visits. However, using calculations for co-control of CO₂ and air pollutants

1 in Mexico City, West *et al.* (2004) found that in practice, if electrical energy is primarily generated in
2 remote locations relative to the urban area, cost-effective energy efficiency programs may have a
3 relatively small effect on air quality. In that case, options for reducing greenhouse gas emissions would
4 have to be implemented primarily in the transportation sector to appreciably affect air quality.

6 RESEARCH NEEDS

7 Additional studies of the carbon balance of settlements of varying densities, geographical location,
8 and patterns of development are needed to quantify the potential impacts of various policy and planning
9 alternatives on net greenhouse gas emissions. While it may seem intuitive that policies to curb urban
10 sprawl or enhance tree planting programs will result in emissions reductions, different aspects of urban
11 form (e.g., housing density, availability of public transportation, type and location of forest cover) may
12 have different net effects on carbon sources and sinks, depending on the location, affluence, economy,
13 and geography of various settlements. It is possible to develop quantitative tools to take many of these
14 factors into account. To facilitate development and application of integrated urban carbon cycle models
15 and to extrapolate local studies to regional, national, and continental scales, useful additional data include:

- 16 • common land cover classifications appropriate for characterizing a variety of human settlements
17 across North America,
- 18 • emissions inventories at small spatial scales such as individual neighborhoods and municipalities,
- 19 • expansion of the national carbon inventory and flux measurement networks to include land cover
20 types within human settlements,
- 21 • comparative studies of processes and drivers of development in varying regions and nations, and
- 22 • interdisciplinary studies of land use change that evaluate socioeconomic as well as biophysical drivers
23 of carbon sources and sinks.

24
25 In general, there has been a focus in carbon cycle science on measuring carbon stocks and fluxes in
26 natural ecosystems, and consequently highly managed and human-dominated systems such as settlements
27 have been underrepresented in many regional and national inventories. To assess the full carbon balance
28 of settlements ranging from rural developments to large cities, a wide range of measurement techniques
29 and scientific, economic, and social science disciplines are required to understand the dynamics of urban
30 expansion, transportation, economic development, and biological sources and sinks. An advantage to an
31 interdisciplinary focus on the study of human settlements from a carbon cycle perspective is that human
32 activities and biological impacts in and surrounding settled areas encompass many aspects of
33 perturbations to atmospheric CO₂, including a large proportion of national CO₂ emissions and changes in
34 carbon sinks resulting from land use change.

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REFERENCES

- Agarwal C, Green GM, Grove JM, Evans TP, Schweik CM (2000) A review and assessment of land-use change models: Dynamics of space, time and human choice. CIPEC Collaborative Report Series No. 1, Center for the Study of Institutions, Populations, and Environmental Change, Indiana University and the USDA Forest Service.
- Akbari H (2002) Shade trees reduce building energy use and CO₂ emissions from power plants. *Environmental Pollution* 116:S119–S126.
- Akbari H, Konopacki S (2005) Calculating energy-saving potentials of heat-island reduction strategies. *Energy Policy* 33:721–756.
- Akbari H, Kurn DM, Bretz SE, Hanford JW (1997) Peak power and cooling energy savings of shade trees. *Energy and Buildings* 25:139–148.
- Akbari H, Taha H (1992). The impact of trees and white surfaces on residential heating and cooling energy use in four Canadian cities. *Energy* 17:141–149.
- Alig RJ, Kline JD, Lichtenstein M (2004) Urbanization on the U.S. landscape: Looking ahead in the 21st century. *Landscape and Urban Planning* 69:219–234.
- Alig RJ, Plantinga A, Ahn S, Kline JD (2003) Land use changes involving forestry for the United States: 1952 to 1997, with projections to 2050. USDA Forest Service, Pacific Northwest Research Station, Portland, OR. Gen. Tech. Report 587.
- Anderson WP, Kanaroglou PS, Miller EJ (1996). Urban form, energy and the environment: A review of issues, evidence and policy. *Urban Studies* 33:7–35.
- Betsill MM (2001) Mitigating climate change in U.S. cities: opportunities and obstacles. *Local Environment* 6:393–406.
- CEC (2001). *The North American Mosaic: A State of the Environment Report*. Commission for Environmental Cooperation, Montreal, Canada.
- Center for International Earth Science Network (CIESIN) CU, International Food Policy Research Institute (IPFRI), the World Bank, Centro Internacional de Agricultura Tropical (CIAT) (2004) Global Rural-Urban Mapping Project (GRUMP): Urban extents., <http://sedac.ciesin.columbia.edu/gpw>, last accessed 3 Dec 2005.
- Cifuentes L, Borja-Aburto VH, Gouveia N, Thurston G, Davis DL (2001) Assessing health benefits of urban air pollution reductions associated with climate change mitigation (2000–2020): Santiago, Sao Paulo, Mexico City, and New York City. *Environmental Health Perspectives* 109:419–425.
- Decker EH, Elliot S, Smith FA, Blake DR, Rowland FS (2000) Energy and material flow through the urban ecosystem. *Annual Review of Energy and the Environment* 25:685–740.
- Easterling WE, Polsky C, Goodin DG, Mayfield MW, Muraco WA, Yarnal B (2003) Changing places and changing emissions: comparing local, state, and United States emissions. In: Team AoAGGR (ed) *Global change and local places: Estimating, understanding and reducing greenhouse gases*. Cambridge University Press, Cambridge, pp 143–157.

- 1 EPA (2000) Projecting land-use change: A summary of models for assessing the effects of community growth and
2 change on land-use patterns. U.S. Environmental Protection Agency, Washington, D.C. EPA/600/R-00/098.
- 3 Ewing R, Pendall R, Chen D (2003) Measuring sprawl and its transportation impacts. *Transportation Research*
4 *Record* 1831:175–183.
- 5 Folke C, Jansson A, Larsson J, Costanza R (1997) Ecosystem appropriation by cities. *Ambio* 26:167–172.
- 6 Golubiewski NE (2006) Urbanization transforms prairie carbon pools: Effects of landscaping in Colorado's Front
7 Range. *Ecological Applications* 16(2): 555-51.
- 8 Gomez-Ibanez JA (1991) A global view of automobile dependence: review of "Cities and automobile dependence:
9 An international sourcebook" by P.W.G. Newman and J.R. Kenworthy". *Journal of the American Planning*
10 *Association* 57:376–379.
- 11 Gonzalez GA (2005) Urban sprawl, global warming and the limits of ecological modernisation. *Environmental*
12 *Politics* 14:344–362.
- 13 Gordon P, Richardson HW (1989) Gasoline consumption and cities: A reply. *Journal of the American Planning*
14 *Association* 55:342–346.
- 15 Grimm NB, Grove JM, Pickett STA, Redman CL (2000) Integrated approaches to long-term studies of urban
16 ecological systems. *Bioscience* 50:571–584.
- 17 Grimmond CSB, King TS, Cropley FD, Nowak DJ, Souch C (2002) Local-scale fluxes of carbon dioxide in urban
18 environments: methodological challenges and results from Chicago. *Environmental Pollution* 116:S243–S254.
- 19 Grimmond CSB, Salmond JA, Oke TR, Offerle B, Lemonsu A (2004) Flux and turbulence measurements at a
20 densely built-up site in Marseille: heat, mass (water and carbon dioxide), and momentum. *Journal of*
21 *Geophysical Research–Atmospheres* 109:DOI: 10.1029/2004JD004936.
- 22 Huang YJ, Akbari H, Taha H, Rosenfeld H (1987) The potential of vegetation in reducing summer cooling loads in
23 residential buildings. *Journal of Climate and Applied Meteorology* 26:1103–1116.
- 24 Hunt JD, Kriger DS, Miller EJ (2005) Current operation urban land-use-transport modelling frameworks: A review.
25 *Transport Reviews* 25:329–376.
- 26 ICLEI (1993) Cities for climate protection: An international campaign to reduce urban emissions of greenhouse
27 gases. <http://www.iclei.org/index.php?id=1651>, last accessed 30 Mar 2006.
- 28 ICLEI (2000) Best practices for climate protection: A local government guide. ICLEI, Berkeley, CA.
- 29 Imhoff ML, Bounoua L, DeFries RS, Lawrence WT, Stutzer D, Compton JT, Ricketts T (2004) The consequences
30 of urban land transformations on net primary productivity in the United States. *Remote Sensing of the*
31 *Environment* 89:434–443.
- 32 Ironmonger DS, Aitken CK, Erbas B (1995) Economies of scale in energy use in adult-only households. *Energy*
33 *Economics* 17:301–310.
- 34 Jaccard M, Failing L, Berry T (1997) From equipment to infrastructure: community energy management and
35 greenhouse gas emission reduction. *Energy Policy* 25:1065–1074.
- 36 Kaye JP, Burke IC, Mosier AR, Guerschman JP (2004) Methane and nitrous oxide fluxes from urban soils to the
37 atmosphere. *Ecological Applications* 14:975–981.

- 1 Kaye JP, McCulley RL, Burke IC (2005) Carbon fluxes, nitrogen cycling, and soil microbial communities in
2 adjacent urban, native and agricultural ecosystems. *Global Change Biology* 11:575–587.
- 3 Kenworthy JR, Newman PWG (1990) Cities and transport energy: lessons from a global survey. *Ekistics* 34:258–
4 268.
- 5 Koerner B, Klopatek J (2002) Anthropogenic and natural CO₂ emission sources in an arid urban environment.
6 *Environmental Pollution* 116:S45–S51.
- 7 Kousky C, Schneider SH (2003) Global climate policy: will cities lead the way? *Climate Policy* 3:359–372.
- 8 Lin JC, Gerbig C, Wofsy SC, Andrews AE, Daube BC, Grainger BC, Stephens BB, Bakwin PS, Hollinger DY
9 (2004) Measuring fluxes of trace gases at regional scales by Lagrangian observations: Application to the CO₂
10 budget and rectification airborne (COBRA study). *Journal of Geophysical Research–Atmospheres*
11 109:DOI:10.1029/2004JD004754.
- 12 Liu J, Daily GC, Ehrlich PR, Luck GW (2003) Effects of household dynamics on resource consumption and
13 biodiversity. *Nature* 421:530–533.
- 14 MacKellar FL, Lutz W, Prinz C, Goujon A (1995) Population, households, and CO₂ emissions. *Population and*
15 *Development Review* 21:849–865.
- 16 McPherson EG, Simpson JR, Peper PF, Maco SE, Xiao Q (2005) Municipal forest benefits and costs in five U.S.
17 cities. *Journal of Forestry* In press.
- 18 Mindali O, Raveh A, Saloman I (2004) Urban density and energy consumption: A new look at old statistics.
19 *Transportation Research Record* 38A:143–162.
- 20 NAHB (2005) Housing facts, figures and trends. National Association of Home Builders, Washington, DC.
- 21 Nemitz E, Hargreaves K, McDonald AG, Dorsey JR, Fowler D (2002) Micrometeorological measurements of the
22 urban heat budget and CO₂ emissions on a city scale. *Environmental Science and Technology* 36:3139–3146.
- 23 Newman PWG (1999) Sustainability and cities: extending the metabolism model. *Landscape and Urban Planning*
24 44:219–226.
- 25 Nowak DJ, Crane DE (2002) Carbon storage and sequestration by urban trees in the USA. *Environmental Pollution*
26 116:381–389.
- 27 Nowak DJ, Walton JT, Dwyer JF, Kaya LG, Myeong S (2005) The increasing influence of urban environments on
28 U.S. forest management. *Journal of Forestry* In press.
- 29 Oke TR (1989) The micrometeorology of the urban forest. *Phil. Trans. R. Soc. Lond. B* 324:335–349.
- 30 Pataki DE, Alig RJ, Fung AS, Golubiewski NE, Kennedy CA, McPherson EG, Nowak DJ, Pouyat RV, Romero
31 Lankao P (2006a) Urban ecosystems and the North American carbon cycle. *Global Change Biology* In press.
- 32 Pataki DE, Bowling DR, Ehleringer JR (2003) The seasonal cycle of carbon dioxide and its isotopic composition in
33 an urban atmosphere: anthropogenic and biogenic effects. *Journal of Geophysical Research* 108:4735.
- 34 Pataki DE, Bowling DR, Ehleringer JR, Zobitz JM (2006b) High resolution monitoring of urban carbon dioxide
35 sources. *Geophysical Research Letters* 33, L03813, doi:10.1029/2005GL024822.

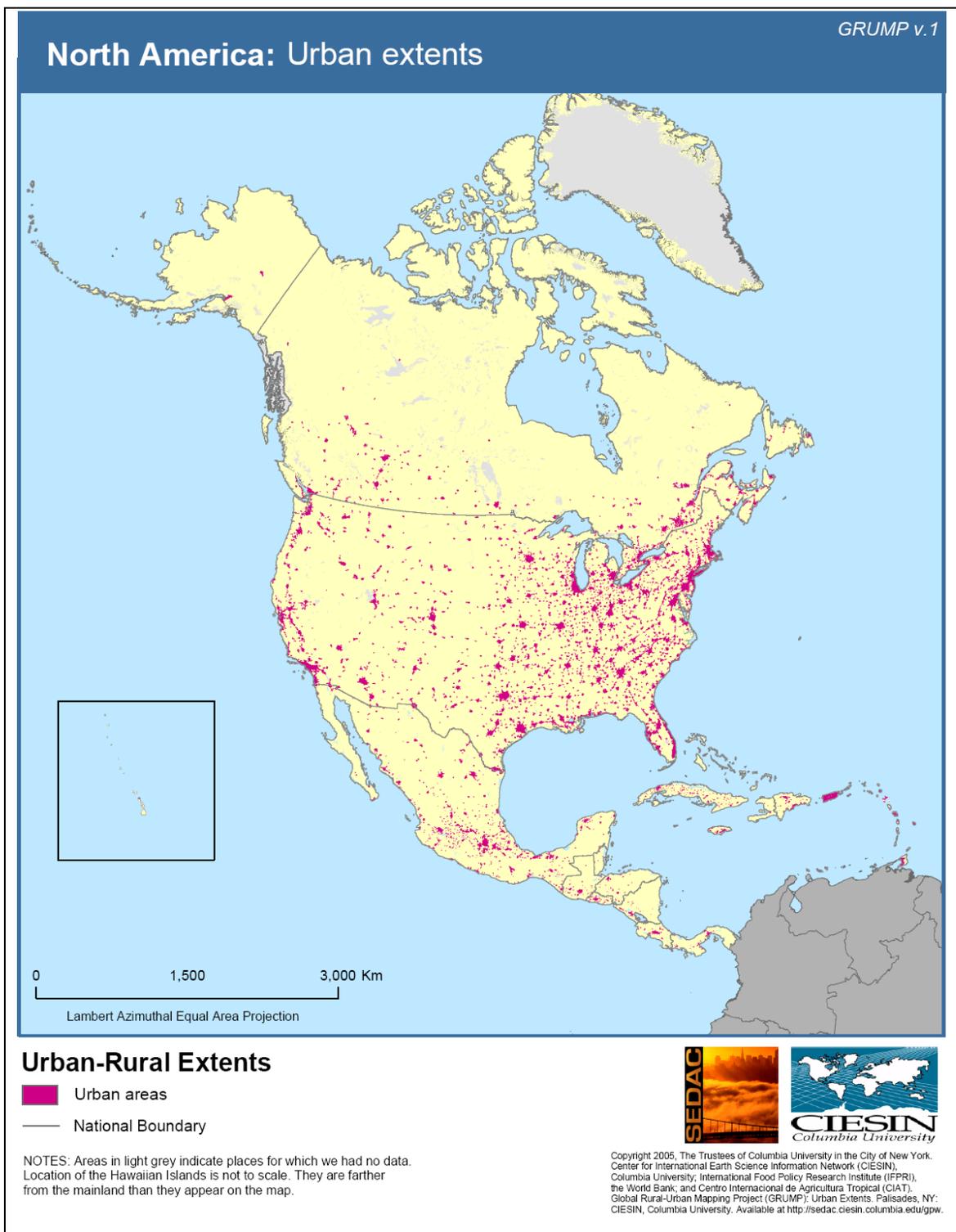
- 1 Pickett STA, Cadenasso ML, Grove JM, Nilon CH, Pouyat RV, Zipperer WC, Costanza R (2001) Urban ecological
2 systems: linking terrestrial ecological, physical, and socioeconomic components of metropolitan areas. *Annual*
3 *Review of Ecology and Systematics* 32:127–157.
- 4 Pouyat R, Groffman P, Yesilonis I, Hernandez L (2002) Soil carbon pools and fluxes in urban ecosystems.
5 *Environmental Pollution* 116:S107–S118.
- 6 Pouyat RV, Yesilonis I, Nowak DJ (2006) Carbon storage by urban soils in the USA. *Journal of Environmental*
7 *Quality* In press.
- 8 Qian Y, Follet RF (2002) Assessing soil carbon sequestration in turfgrass systems using long-term soil testing data.
9 *Agronomy Journal* 94:930–935.
- 10 Romero Lankao P, Lopez H, Rosas A, Gunther G, Correa Z (2004) Can cities reduce global warming? Urban
11 development and the carbon cycle in Latin America. IAI, UAM-X, IHDP, GCP, Mexico.
- 12 Sahely HR, Dudding S, Kennedy CA (2003) Estimating the urban metabolism of Canadian cities: Greater Toronto
13 Area case study. *Canadian Journal of Civil Engineering* 30:468–483.
- 14 Soegaard H, Moller-Jensen L (2003) Toward a spatial CO₂ budget of metropolitan region based on textural image
15 classification and flux measurements. *Remote Sensing of the Environment* 87:283–294.
- 16 Taha H (1997) Urban climates and heat islands: albedo, evapotranspiration, and anthropogenic heat. *Energy and*
17 *Buildings* 25:99–103.
- 18 United Nations (2002) *Demographic Yearbook*, <http://unstats.un.org/unsd/demographic/products/dyb/default.htm>.
- 19 United Nations (2004) *World urbanization prospects: The 2003 Revision*. U.N. Dept. of Economic and Social
20 Affairs, Population Division, New York. E.04.XIII.6.
- 21 United Nations Habitat (2003) *Global Observatory Database*, <http://www.unchs.org/programmes/guo>, last accessed
22 10 Nov 2005.
- 23 Warren-Rhodes K, Koenig A (2001) Ecosystem appropriation by Hong Kong and its implications for sustainable
24 development. *Ecological Economics* 39:347–359.
- 25 West JJ, Osnaya P, Laguna I, Martinez J, Fernandez A (2004) Co-control of urban air pollutants and greenhouse
26 gases in Mexico City. *Environmental Science and Technology* 38:3474–3481.

1 **Table 14-1. Increases in number of households and the total population of the United States, Canada, and**
 2 **Mexico between 1985 and 2000.** (United Nations, 2002; United Nations Habitat, 2003).

	Total population (%)	Households (%)
Canada	19	39
Mexico	33	60
United States	15	25

3

1 Figure 14-1. North America urban extents.



2

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