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ENERGY AND MATERIAL FLOW THROUGH THE URBAN ECOSYSTEM

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■ **Abstract** This paper reviews the available data and models on energy and material flows through the world's 25 largest cities. Throughput is categorized as stored, transformed, or passive for the major flow modes. The aggregate, fuel, food, water, and air cycles are all examined. Emphasis is placed on atmospheric pathways because the data are abundant. Relevant models of urban energy and material flows, demography, and atmospheric chemistry are discussed. Earth system–level loops from cities to neighboring ecosystems are identified. Megacities are somewhat independent of their immediate environment for food, fuel, and aggregate inputs, but all are constrained by their regional environment for supplying water and absorbing wastes. We elaborate on analogies with biological metabolism and ecosystem succession as useful conceptual frameworks for addressing urban ecological problems. We conclude that whereas data are numerous for some individual cities, cross-cutting compilations are lacking in biogeochemical analysis and modeling. Synthesis of the existing information will be a crucial first step. Cross-cutting field research and integrated, multidisciplinary simulations will be necessary.

CONTENTS

1. INTRODUCTION

The growth and urbanization of the global human population over the past 300 years has resulted in the construction of cities of unprecedented size and form. The world's megacities [those estimated to contain more than 10 million inhabitants by 2010 (1)] offer the most striking examples of the environmental and energy problems that accompany intense urbanization. Although megacities in developed countries appear to have solved the most pressing health and economic problems, rapid growth in developing countries has led to extreme shortages of basic social services, a glaring lack of infrastructure, chronic air and water pollution, and questions about the future for urban residents. Simultaneously, the human species has come to dominate the ecology of the entire planet (2). The roles played by large settlements in the global biosphere and in geochemical cycling remain understudied.

As cities grow, the flow of energy and material through them increases. This occurs through human socioeconomic activities of transforming and transferring food, goods, energy, and services. It is unclear whether there are qualitative, quantitative, or categorical differences among megacities or between smaller and larger cities in terms of energy and material fluxes. Most summaries of energy use refer to the country level (3), and most analyses of cities address either human health or environmental pollution (1).

Here we examine the energy and material flows through the 25 largest cities of the world. For the most part they consist of a densely populated core and its heavily-built surroundings. Whereas the central city might have 2 million residents, each metropolitan area contains between 7 and 28 million people, depending on how the metropolitan region is defined (4–6). For example, Manhattan (New York County) had a 1990 population of 1,487,536 (7). New York City—including Manhattan, the Bronx, Brooklyn, Queens, and Staten Island—contained 7,322,564 people. The population of the New York Primary Metropolitan Statistical Area (PMSA) was 8,546,846 (8). The New York-Northern New Jersey-Long Island Consolidated MSA, which includes parts of four states (New York, New Jersey, Connecticut, and Pennsylvania), had a 1990 population of 19,549,649.

Similar variation occurs with measures of city area, as different agencies adopt their own criteria. Using New York as an example again, the five borough area of New York City covers 787 km^2, whereas the CMSA covers 3,585 km^2 (1). Based on satellite images of the earth at night, New York is part of a continuous cluster of light that stretches 9,706 km^2 within New York State and 43,448 km^2 across the eastern seaboard (9). Because all cities are symbiotic with the agricultural lands that feed their populations, the term metro-agro-plex has recently been used to describe contiguous, continental-scale, industrial-agricultural systems (10).

For the purposes of this review, megacities are defined as by the UN (1). This definition is also reasonable considering that the globalization of food and fuel supplies is loosening the dependence of cities on their immediate surroundings for their resources (11, 12). Much of the available data, however, are based on other definitions of urban area. Therefore, measures that are sensitive to city size, either in population or area, may have considerable error; furthermore, they may not correspond to measures of other variables even for the same city if they are not calculated for identical areas.

We begin with a summary of climate and geography of megacities, describing the major large-scale features of urban environments. Available data are reviewed on energy and material inputs and outputs, focusing on fuels, water and air chemistry, and transport. Inputs are categorized as either stored (e.g. construction materials for urban infrastructure and solid waste in landfills), transformed (e.g. food, fuel, and water), or passive (e.g. air, water, and solar radiation). Outputs are classified as atmospheric or aquatic and marine, as exported goods only comprise a small fraction of urban flows. Our emphasis is on atmospheric outputs and processes, with particular attention to Mexico City, because more data are available. Linkages among inputs and outputs are made, as well as connections to the larger-scale earth system processes that affect and are affected by those at the level of the city. We then discuss relevant models of urban energy and material fluxes, demography, and atmospheric chemistry.

To synthesize available data and models within a conceptual, biological, and geophysical framework, we utilize two analogies: biological metabolism and ecosystem succession. Energy and material flows through human settlements are conceived as urban metabolism (13), in which material inputs are transformed into useful energy, physical structure, and waste. Principles of ecosystem succession are used to explore ways in which city development differs from that of wild ecosystems (14). We use the term wild, as opposed to natural, to distinguish ecosystems not managed by humans from those that have been domesticated to serve human needs. Human-dominated ecosystems are still “natural”. Each analogy offers options for synthesis of current knowledge and suggests future areas of research. Finally, several open areas of investigation are delineated, and anecdotal examples of potential future study strategies are drawn from recent work in Asia and the Americas.

2. URBAN SETTINGS

The world’s largest cities are primarily found in mid-latitude regions (Figure 1; see color insert). For the most part, they lie near large sources of water. Most megacities are port towns near large river mouths and within 100 km of a coast.

There are several exceptions, however. Moscow and Delhi are both inland river towns, and Mexico City and Tehran currently have no major body of water nearby. Mexico City actually began as Tenochtitlan, the island capital of the Aztec empire, situated in the middle of Lake Texcoco. When the conquistadores arrived in 1519, Tenochtitlan could only be reached by causeways several kilometers long. Hydrological reengineering has removed all but a small remnant of the lake and has caused the downtown area to undergo rapid sinkage (15, 16). Excluding Mexico City and Tehran (which are outliers at 2,240 m and 1,138 m, respectively), the mean elevation of the megacities is 121 m (Table 1).

Beyond these generalizations, megacities are found in a variety of settings. Regional topography varies from extremely flat to complex terrain. Mountains, if present, generally border the city and most construction is on flat land. Nine megacities are classified as temperate (Buenos Aires, Delhi, London, Los Angeles, Mexico City, Osaka, São Paulo, Shanghai, Tokyo), eight are tropical (Bangkok, Bombay, Calcutta, Dhaka, Jakarta, Lagos, Manila, Rio de Janeiro), four are arid (Cairo, Karachi, Tehran, Tianjin), and four are cold (Beijing, Moscow, New York, Seoul) (17). Annual precipitation varies dramatically from 25 mm in Cairo to 2,129 mm in Bombay, with a mean of 1,092 mm (18). Monthly mean temperature also varies greatly, as does climate equability (Table 1). Seasonal temperatures vary by only 1°C in Jakarta, for example, but differ by 31°C in Beijing (−5 to 26°C).

The distribution of the world's largest metropolises, like that of population in general, is strongly skewed toward the Northern Hemisphere. This mainly reflects arrangement of the major land masses and distribution of arable land (19). However, the point is crucial to the role human population centers play in climate and earth system evolution (20). Atmospheric and aquatic emissions of pollutants mainly take place north of the equator and the inter tropical convergence zone (21). Interesting special cases are constituted by the urban areas of India. Because they lie in the path of the Asian monsoon, their plumes spill either over the Himalaya or out into the central Indian Ocean. Aerosol hazes in and around the Indian subcontinent are only beginning to be studied (22, 23). Other cities in the North inject their atmospheric effluent into the familiar trade winds and geostrophic westerlies of the global general circulation.

Few demographic and economic generalities can be made about the countries in which megacities are found (Table 2). They are not limited to, or even more common in the most populous countries, for example, but are found even in relatively small ones. Argentina, with a 1998 population of only 36 million, contains Buenos Aires, the twelfth largest city in the world. The percent of the national population found in one or more megacities varies greatly among countries and probably reflects a combination of historical events and physical constraints (24). Approximately 30% of the national population of both Argentina and Japan are found in one or more megacities, for instance, but for very different reasons. As an island nation with restricted land area and a high national population, it is not surprising that a high percentage of Japan's inhabitants are found in megacities. Argentina, however, is fairly large and has the smallest national population of any country containing a megacity. In fact, Buenos Aires is a classic example of a geopolitical primate urban area, dominating the culture and economy of Argentina. Primate cities tend to arise most often under colonial governments (25). Both Central and South America remained under Iberian sway until relatively recently.

Economic performance as measured by GDP or other factors varies widely among countries containing megacities (Table 2). In 1997, for example, per capita GDP ranged from US$286 in Bangladesh to US$33,265 in Japan (26). Whether megacity inhabitants performed better or worse than the country average is unclear. Although these data may be collected by urban agencies or national census bureaus, they are not widely disseminated. Socioeconomic data are typically only freely available for the national level. Consequently, very little cross-cutting analysis has been possible.

3. INPUTS

Urban systems gain matter and energy both actively (through human work) and passively. Active inputs include materials that are stored or transformed, or both. Stored materials become part of the urban built environment—such as stone, wood, and metals—or are used until they become waste products "stored" in landfills. Transformed materials include water, food, and fuel, which are converted to another form and then exported from the urban system as waste. Urban systems also passively gain a variety of substances. Water and waterborne materials come into the city through precipitation and surface flow. Gases and various airborne particulates enter through regional meteorological fluxes. Solar radiation inputs heat. Finally, living plants and animals migrate into the city (27).

This categorization may not be as natural as one based on cycles of major nutrients such as carbon and nitrogen. Nevertheless, we define these categories because of their pedagogical expedience. Active and passive inputs are not mutually exclusive, but materials are often perceived and used quite differently depending on how they enter the city. For example, actively imported water is a clear asset, whereas water passively input via precipitation is usually perceived as a nuisance. Also, the distinction between storage and transformation is clearly dependent on time scale; material turnover in the human component of the urban ecosystem requires on the order of weeks to months. However, classification of material as stored or transformed is useful for examining major pathways and components of urban material fluxes. Storage and transformation can also entail leakage. This is discussed below with particular reference to hydrocarbons and fossil fuels.

3.1 Stored Inputs: Construction and Waste

Humans actively import a huge variety of energy and materials into urban systems. Many of these substances, such as aggregates (stone, sand, and gravel), tar, wood, glass, metals, and plastics, become part of permanent structures. Excluding water,

TABLE 1 Climatic features of world's megacities[a]

City	Elev. (m)	Precip. (mm)	Tmin (C)	Tmax (C)	Climate zone Major	Climate zone Minor	Nearest body of water	Topo.
Karachi	20	231	18	31	Arid	Desert	Ocean	Level
Cairo	74	25	14	28	Arid	Desert, hot summer	River	Level
Tehran	1138	241	3	30	Arid	Steppe	Landlocked	Level
Tianjin	6	525	−4	27	Arid	Steppe	River	Level
Beijing	44	635	−5	26	Cold	Hot summer	River	Level
Seoul	50	1365	−4	25	Cold	Hot summer	River	Mountains
Moscow	156	601	−10	19	Cold	Moist, cool summer	River	Level
New York	10	1054	0	25	Cold	Moist, hot summer	Delta	Level
Delhi	216	706	14	34	Temperate	Dry winter	River	Level
London	5	589	5	19	Temperate	Humid, cool summer	Delta	Level
Buenos Aires	25	1005	10	25	Temperate	Humid, hot summer	Delta	Level
Shanghai	5	1144	3	28	Temperate	Humid, hot summer	River	Level
Osaka	597	1342	4	28	Temperate	Humid, hot summer	Delta	Level
Tokyo	100	1523	4	26	Temperate	Humid, hot summer	Delta	Level

Los Angeles	113	343	13	22	Temperate	Mediterranean	Ocean	Mountains
Mexico City	2240	634	13	19	Temperate		Landlocked	Mountains
São Paulo	800	1387	15	21	Tropical	Rainforest	River	Mountains
Rio de Janeiro	400	1101	21	26	Tropical	Rainforest	Delta	Mountains
Lagos	34	1740	25	28	Tropical	Rainforest	Ocean	Level
Jakarta	7	1821	26	27	Tropical	Rainforest	Delta	Level
Dhaka	4	1997	18	29	Tropical	Rainforest	Delta	Level
Manila	5	2051	25	29	Tropical	Rainforest	Ocean	Level
Bangkok	7	1476	25	30	Tropical	Savanna	River	Level
Calcutta	6	1634	20	31	Tropical	Savanna	River	Level
Bombay	11	2129	24	30	Tropical	Savanna	Ocean	Level

[a]Elev., elevation; Precip., annual precipitation; Tmin, monthly mean minimum temperature; Tmax, monthly mean maximum temperature; Topo., topography (17, 18).

TABLE 2 Economic indicators of countries with megacities

Country	Population[a] (10^6)	Weight[b] (%)	GDP[c] (US $)	EP[d]
Japan	126.28	8.4, 22.10	33,265	High
Rep. of Korea	46.11	26.68	9,677	High
Thailand	60.30	12.11	2,576	High
Indonesia	206.34	6.83	1,055	High
China	1255.70	1.0–1.37	745	High
U.S.	274.03	4.8, 6.08	28,789	Medium
U.K.	58.65	12.45	21,921	Medium
Russian Fed.	147.43	6.31	3,028	Medium
Iran	65.76	11.10	2,466	Medium
Philippines	72.94	14.81	1,151	Medium
Pakistan	148.17	8.17	466	Medium
India	982.22	1.2–1.84	402	Medium
Bangladesh	124.77	8.18	286	Medium
Argentina	36.12	31.56	9,070	Low
Brazil	165.85	6.1, 10.70	4,930	Low
Mexico	95.83	17.11	4,265	Low
Nigeria	106.41	12.69	1,376	Low
Egypt	65.98	16.22	1,168	Low

[a]1998 country population. Source, Reference 24.

[b]Weight, % of national population living in megacity. Range reported for countries with several megacities.

[c]GDP, per capita 1997. Source, Reference 26.

[d]EP, economic performance. Source, Reference 274.

fuel, and food, nearly 75% of all materials consumed in the United States are aggregates (28). Of the remainder, industrial minerals such as cement and gypsum predominate, followed by plastics and other petroleum products.

Massive input of construction materials is ubiquitous across megacities. In Shanghai, 20 million square meters of floor space were built from 1990–1993 (29). New house construction is estimated to consume on average 450 kg of material per square meter of floor space, or 5.8 gigajoules when converted to energy and including direct and indirect energy expenditures (30). Thus, roughly 9.27 million tons of material (119.5 petajoules) were incorporated into Shanghai just through construction of new buildings. Further, the construction of high-rise buildings, which are very energy-intensive per square meter, increased exponentially during the 1980s from 3 to 45 new high-rises per year (31).

The social and environmental costs of building can compare with normal maintenance and turnover. A typical megacity consumes on the order of 100 to 1000 petajoules of energy per year to operate its transportation, electrical, and climate control infrastructures (1). From the standpoint of global climate change, this ultimately translates to emission and buildup of atmospheric CO_2 and to the release of a variety of gaseous, particulate, and aqueous pollutants. Although megacities in developing countries are expanding faster than those in developed areas (32), economically advanced nations usually have higher per capita rates of material consumption (3). Little is known about comparative quantity and type of material inputs across the larger urban areas or whether inputs scale linearly with city size.

Some construction materials, as well as remnants of food and textiles, ultimately end up being stored in landfills or incinerated. The solids and liquids in such waste repositories consist, crudely speaking, of aggregate, wood (paper), glass, metals, food refuse, and plastic (3). In Mexico City, 43% of solid waste is food refuse; the rest is largely paper products, glass, and diapers (33). However, urban solid waste data are not routinely collected or compiled by metropolitan or international agencies.

In many megacities, less than half of the population is served by municipal solid waste services (Table 3). Lack of service is particularly severe in squatter and tenement communities on the urban perimeter, some of which contain millions of residents (34). These communities are being settled much faster than municipal services can be extended to them. Estimates of solid waste production and destination are therefore difficult to construct and fraught with uncertainty and unrealistic precision. Where estimates account only for the city center, generation rates for the entire metropolis will be underestimated and collection rates will be overestimated. Furthermore, estimates may be biased by municipal agencies that inflate rates of waste collection and sanitary disposal.

Rates of solid waste generation vary widely across megacities, generally increasing with level of development (Table 3). Waste destination also varies greatly, from dumping in unlined landfills to incineration for electricity generation. In Mexico City, over 29% of solid waste ends up in illegal dumps (33). In Los Angeles, 10% is recycled (35). And in Tokyo, remarkably, over 60% is recycled (36). However, urban waste management is a serious problem in the space-limited metropolis. Because of the lack of open land in the Tokyo area, islands of waste are being built in Tokyo Bay (37).

Though recycling rates are otherwise generally low, a large proportion of solid waste is recyclable. In New York City, up to 75% is recyclable or compostable (38), though all urban waste goes to landfill. Recycling processes appear to shift from informal systems of scavenging to formal municipal programs as development increases (39, 40).

Waste destination also has direct consequences for leakage rates for various pollutants. Labile organics leach into the ground or surface waters or enter the atmosphere. Globally, landfills are a major source of the greenhouse gas methane (21). Ethane and other hydrocarbons are also generated, and their atmospheric

TABLE 3 Solid waste and water fluxes for megacities[a]

City	Solid waste generation (tons/day)	Solid waste collection (%)	Landfill (%)	Piped water (%)	Water use (kilotons/ day)	Sewerage (%)	Sewage treated (%)
Bangkok	6,000[b]	90[b]	90[c]	65[c]	—	2[b]	0[b]
Beijing	—	—	—	—	—	—	—
Bombay	5,000[c]	90	94[c]	55	1,900	51	10
Buenos Aires	—	—	—	—	—	—	—
Cairo	4,800	65	—	89	—	91	98
Calcutta	—	55[c]	—	50[c]	—	45[c]	—
Delhi	12,000	77	—	57	1,300	40	69
Dhaka	780	50	—	25[d]–80	900	18[c]–44	55
Jakarta	13,400[c]	60[e]	99[c]	15	2,200	0	16
Karachi	—	33[c]	—	40[c]	1,540[f]	16[f]	—
Lagos	3,100	8	—	65	720	2	2
London	—	—	—	—	—	—	—
Los Angeles	20,360[g]	100[g]	89[g]	—	—	—	—
Manila	6,500	85	—	95	—	11[c]–80	—
Mexico City	15,046[h]	70[c]	—	—	27–45[c]	32[h]–80[c]	—
Moscow	4,490[j]	100	—	100	5,100	100	100
New York	13,000[k]	100[k]	100[k]	100	7,600	99	100
Osaka	—	—	—	—	—	—	—
Rio de Janeiro	10,900	88	—	95	3,000	87	23
Sao Paulo	20,200[c]	90[c]	95[c]	95[c]	—	36[c]	Low[c]
Seoul	—	99[c]	—	94[c]	—	86[c]	—
Shanghai	12,000	—	—	100	4,100	58	3[m]–58
Tehran	—	100	—	99	—	—	—
Tianjin	16,800[n]	93[n]	35[n]	—	—	—	—
Tokyo	66,000[p]	99[p]	33[q]	—	—	—	—

[a]Source unless otherwise noted, Reference 72.
[b]Source, Reference 54.
[c]Source, References 77, 275–283.
[d]Source, Reference 284.
[e]Source, Reference 285.
[f]Source, Reference 78.
[g]City proper only: less than half the metro population. Source, Reference 35.
[h]Source, Reference 33.
[j]Source, Reference 174.
[k]City proper only: less than half the metro population. Source, Reference 286.
[m]Source, Reference 175.
[n]Source, Reference 287.
[p]Source, Reference 37.
[q]Source, Reference 288.

oxidation alters planetary-scale photochemistry (41). Landfills can thus be considered a major urban biogeochemical reservoir.

Although cities also refine, process, and assemble raw materials into goods for export, the materials predominantly come from outside the city. Agricultural production within metropolitan areas is a notable exception, as in Mexico City (42) and Shanghai (43), but the practice is becoming rare as land is being transformed to residential, commercial, and industrial uses (16, 44). It is estimated that less than 10% of material inputs are exported as goods (45–47). Thus, cities are net sinks for most materials.

3.2 Transformed Inputs: Food, Fuel, and Water

Three consumables—water, food, and fuel—are perhaps the most important materials imported into urban systems. The transfer of food through cities impacts ecosystem nitrogen cycles much the way fuel use and transformation impacts carbon cycles (48). The two elements carbon and nitrogen provide mass and/or energy needed by humans or their tools to function, and they must be supplied constantly. Each requires substantial energy input to be produced (or extracted), processed, and transported, and each is transformed into waste products that have significant effects on downwind and downstream ecosystems. Anthropogenic mobilization of carbon and nitrogen is so vast and so intrinsically tied to the production and consumption of food and fuel that food and fuel must be included in systems models in order to fully understand local, regional, and global carbon and nitrogen cycles (2, 49–51).

3.2.1 Food Inputs Estimating food import into megacities is difficult because the production and delivery system is extremely diffuse. There are virtually no published reports of megacity food production or consumption. An exception is an estimate that New York City consumes 20,000 tons of food per day (52). Half of this is eaten; the rest is solid waste, often rotting before it gets sold. Food production data summarized at the country level suggest that wealthier nations produce more food per capita (3). National level data, however, may underestimate urban food consumption. Some evidence exists that suggests urban residents eat more and are better nourished (53). If this is the case, urban food consumption may be higher than national averages, and a consequently larger portion may terminate in landfills.

3.2.2 Fuel Inputs No major international organization currently collects statistics on energy consumption at the city level (World Energy Institute, personal communication). Published data on fuel use in megacities are scarce, and fuel is categorized in a variety of ways. However, predominant fuel types in most megacities are known. Oil-intensive urban areas include Jakarta and Manila. Natural gas–dominated cities include Bangkok, Bombay, London, Mexico City, and Moscow. Coal is the main fuel source in Beijing, Shanghai, Calcutta, and Seoul.

TABLE 4 Shares of energy consumption in Bangalore, India[a]

	Consumption by sector (%)					
Energy Carrier	**Residential**	**Industrial**	**Commercial**	**Transportation**	**Other**	**Total**
Firewood	13.9	1.6	1.4	0	0.4	17.4
Charcoal	1.6	0.3	0.4	0	0.4	2.7
Liquified petroleum gas	2.3	0.2	0.5	0	0.1	3.1
Electricity	8.9	8.5	0.7	0	0.5	18.5
Petroleum	12.6	15.5	0.4	25.3	0.5	54.4
Coal	0	2.2	0	1.7	0	4.0
Total	39.2	28.3	3.4	27.1	2.0	100.0

[a]Total consumption in one year (1989–1990) equaled 45,240 terajoules. Petroleum includes gasoline, diesel, and light diesel oil (55).

Hydroelectric energy is the largest source in São Paulo and Los Angeles (1). Importantly, these estimates do not include transport fuels, which can comprise over 50% of urban fuel use. In Bangkok, transport sector fuel use has risen from 43% to 56% between 1973 and 1986 (54). Nor do they include biomass fuels that predominate in the urban fringe of developing cities. As an example, Table 4 shows energy consumption by sector and fuel type in Bangalore, India, a city of approximately 5.2 million (55).

Domestic coal dominates China's fuel supply (56, 57). Beijing alone consumes 21 megatons (Mt) of coal per year, meeting 70% of the city's energy needs (1); Shanghai consumes 38.08 Mt per year (58). Proposed expansion of the urban vehicle fleet in China will increase oil imports for auto fuel. Pressure to decrease urban air pollution will force cities to use cleaner energy sources such as natural gas (59, 60). We can assume that development in other countries will similarly drive megacities up the "energy ladder" to cleaner fuels, more transport fuels, and more electricity generation (61, 62).

São Paulo is an example of this trajectory. Ninety-five percent of electric power generation is hydroelectric. Clean fuels are a large proportion of inputs, and 30% of autos run on alcohol fuels (1). Estimates of fuel use in the metropolitan area for 1988 are 5700 kilotons (kt of sugar cane pulp, 1700 kt of diesel oil, 1700 kt of hydrated ethanol, 1600 kt of fuel oil, 1500 kt of gasoline, 1100 kt of wood, 1000 kt of natural gas, 850 kt of coke, 680 kt of anhydrous ethanol, 600 kt of liquefied petroleum gas (LPG), 600 kt of coal, and 500 kt of kerosene. Total fuel use is 17,500 kt per year.

Estimates of total annual urban fuel consumption and the partitioning of sources are scarce. In developing countries, wood and charcoal are more accessible to lower income groups than natural gas and electricity. A high proportion of biofuel use is

TABLE 5 Shares of energy consumption in Mexico City[a]

Energy carrier	Qty.[b] (kt)	Consumption by sector (%) Electric	Industrial	Commercial	Transportation	Other	Total
Gasoline	3990	0	0	0	36.0	0	36.0
Diesel	1230	0	5.2	0.4	8.1	0	13.7
Fuel oil	960	8.1	1.6	0.3	0	0	10.0
LPG	1540	0	0	0.8	0	9.1	9.9
Natural gas	1770	5.6	13.9	0	0	0.5	20.0
Electricity			4.8	1.7	0.5	3.4	10.4
Total		13.7	25.5	3.2	44.6	13.0	100.0

[a]Total consumption in 1986 equaled 512 petajoules. LPG, liquid petroleum gas (1).
[b]Qty, quantity consumed in 1989 in kilotons. Does not include 630 kt of kerosene or biofuels (71).

common, making accurate estimation of fuel use more difficult. In Jakarta, biofuels comprise over 25% of fuel inputs (63). Annually, Jakarta also consumes 6700 kt of gasoline and diesel, 2200 kt of oil, and 2100 kt of LPG (1). In Karachi, 1360 kt of coal, 613 kt of gasoline and diesel, 610 kt of oil, and 650 Mm^3 of natural gas (equivalent to 585 kt oil) are consumed annually (64). No estimates of biofuel use exist. In Delhi, annual fuel consumption includes 658 kt of gasoline and diesel, 391 kt of biofuels, 143 kt of kerosene, 127 kt of oil, 121 kt of coal, 110 kt of LPG, and 109 kt of soft coke (65).

Mexico City is perceived as the archetypal settlement of the next century (33, 66–70). Table 5 shows that the transportation sector is the largest consumer of energy in the city, totaling 50% of fossil fuels (1, 71). Total fuel consumption is 10,120 kt per year in the metropolitan area. However, there are no estimates of biofuel use, which predominates in the urban periphery.

Fuel use is tied to the size of a city's automobile fleet. Table 6 shows demographic data and vehicle fleet sizes for the world's megacities. The number of automobiles in megacities varies from 4 per 1,000 residents in Lagos (about 40,000 vehicles) (72) to 645 per 1,000 in Los Angeles, or about 8 million autos (1). Vehicle fleets are themselves dependent on transportation infrastructure (73). However, the automobile tends to infiltrate new cultures before roads can be built to accommodate them (61, 74, 75). For example, over the past 30 years, motor vehicles in Shanghai increased 13-fold—and nonmotor vehicles increased ninefold—whereas road space only increased by 50% (76).

3.2.3 Water Inputs Along with food and fuel, the third major consumable is water. Although water also enters cities passively (see below), active input from aquifers and distant watersheds often provides the bulk of the human water supply. Water is essential to all biological and most mechanical functions. It is the ultimate

TABLE 6 Demographic and transportation indicators of world's megacities[a]

City	1995 Pop.[b] (10^6)	Area[c] (km^2)	Density (km^{-2})	2000 Pop.[b] (10^6)	Growth Rate[b] ($year^{-1}$)	Total Autos[c] (10^3)	Vehicles per 1,000[c]
Tokyo	26.8	2,162	12,396	27.9	0.8	4,400	164.2
São Paulo	16.4	8,000	2,050	17.8	1.6	4,000	243.9
New York	16.3	3,585	4,547	16.6	0.4	1,780	109.2
Mexico City	15.6	2,500	6,240	16.4	0.9	2,500	160.3
Bombay	15.1	603	25,041	18.1	3.7	588	38.9
Shanghai	15.1	6,300	2,397	17.2	2.6	148	9.8
Beijing	12.4	16,800	738	14.2	2.8	308	24.8
Los Angeles	12.4	16,600	747	13.1	1.2	8,000	645.2
Calcutta	11.7	1,295	9,035	12.7	1.6	500	42.7
Seoul	11.6	1,650	7,030	12.3	1.1	2,660	229.3
Jakarta	11.5	5,500[d]	12,490[d]	14.1	4.1	1,380	120.0
Buenos Aires	11.0	7,000	1,571	11.4	0.7	1,000	90.9
Tianjin	10.7	11,305[e]	—	12.4	2.9	283	26.5
Osaka	10.6	—	—	10.6	0.0	727	68.6
Lagos	10.3	—	19,400[f]	13.5	5.4	—	4.0[f]
Delhi	9.9	591	16,751	11.7	3.3	1,660	167.7
Karachi	9.9	3,530	2,805	12.1	4.1	650	65.7
Rio de Janeiro	9.9	6,500	1,523	10.2	0.7	—	177.0[f]
Cairo	9.7	214	45,327	10.7	2.1	939	96.8
Manila	9.3	636	14,623	10.8	3.0	510	54.8
Moscow	9.2	994	9,256	9.3	0.1	665	72.3
Dhaka	7.8	—	—	10.2	5.3	—	7.0[f]
London	7.3	1,579	4,623	7.3	0.0	2,700	369.9
Tehran	6.8	>600[g]	—	7.3	1.5	—	66.0[f]
Bangkok	6.6	1,565	4,217	7.3	2.2	1,760	266.7

[a]All values are uncertain.
[b]2000 population is estimated. Source, Reference 26.
[c]Area is UN Metropolitan Area. Source, Reference 1.
[d]Source, Reference 285.
[e]Source, Reference 287.
[f]Source, Reference 72.
[g]Source, Reference 289.

solvent, transporting waste products out of biotic, mechanical, and ultimately, urban systems. Unlike fuel and food, water can be purified and reused repeatedly before it is exported from the urban system, though this will only happen in wealthy cities that can afford large treatment facilities. The damaging components in water are not from water consumption itself but are residuals from food, fuel, and material consumption.

Unfortunately, like fuel imports, water fluxes through megacities are poorly documented. Table 3 shows estimates of urban water use and percent of homes with piped water. For many megacities, water flux assessment is difficult because not all residents receive municipal water or sewage services in their homes. Estimates of water use in Dhaka, for example, vary from 25% to 80%. It is clear, however, that access to piped water generally decreases towards the city periphery. In Mexico City, for example, piped water service declines from 45% in the urban core to 27% in the perimeter, dropping close to zero in squatter settlements (33, 72, 77).

The absence of comprehensive water service in rapidly growing cities results in a lack of water to meet basic municipal and residential needs, most importantly sanitation. Karachi suffers from a water shortfall estimated at 1410 kt per day (78). Compounding the problem, leakage in water supply systems from supply networks into surface and groundwater channels is significant in many megacities, with rates of 33% in Bombay, 37% in Seoul, 49% in Bangkok, 50% in Cairo, and 51% in Manila (79).

From the figures in Table 3, it is clear that water is the single largest material flux in urban ecosystems. Cities are consuming around 1,000 kt of water daily, on average. This dwarfs the 10,124 kt of fuel consumed annually in Mexico City or the 17,530 kt per year in São Paulo by factors of 36 and 21, respectively. For reference, mean discharge from the Thames is 5,800 kt per day, and mean discharge from the Ganges is between 260,000 and 4,750,000 kt per day (for dry and wet seasons) (80).

3.3 Passive Inputs: Air, Water and Heat

3.3.1 Air Inputs Passive chemical inputs to the urban atmosphere are dominated by gas phase elemental nitrogen and oxygen, N_2 and O_2 (21). Oxygen is a requirement for both human and urban metabolism. Nowhere in earth's troposphere, however, is it significantly depleted relative to its rough average mole fraction 21% (81, 82).

Build-up of gas phase carbon dioxide (CO_2) threatens to drive a significant global greenhouse effect (20). The CO_2 results from combustion of fossil fuels and thus represents a sink for the bulk O_2 (hydrocarbon reacts with molecular oxygen to give CO_2 and water as products). The average concentration of CO_2 added to the atmosphere by man's activities over the last century is on the order of 100 ppm by moles. Global coal reserves are about 10^4 gigatons (Gt) carbon (3, 83) and the atmospheric CO_2 content of 400 parts per million translates to

10^3 Gt carbon. However, oxygen is unlikely to be severely depleted by the human economy even under extreme circumstances.

Other molecules present at the parts per million level or above include water vapor and methane. Both have significant climate impacts and cycle through the many material reservoirs of the urban environment. The global hydrological cycle determines when and where water is available for human use (20). The methane content of air is augmented in cities by leakage of natural gas and by generation in anaerobic chemical environments, primarily landfills and sewers (84). Methane absorbs in several narrow bands in the infrared portion of the electromagnetic spectrum and is considered a major greenhouse gas (84, 85).

Key trace species generated in the remote troposphere define the background over which local air chemistry is superimposed (86–88). Hydrocarbons enter the air column at the surface from natural terrestrial and marine ecosystems (89–91). The N_2 molecule is fixed by lightning and fires to form a suite of nitrogen oxide molecules (NO_x) of varying thermodynamic and kinetic stability (21). They are short lived as a group so that concentrations vary at the mesoscale (92). NO_x acts catalytically during hydrocarbon breakdown to form ozone (93), which in the troposphere is an oxidant and greenhouse gas [contrast this with its protective role as the absorber of ultraviolet radiation in the stratosphere (94)]. A background aerosol is also present, supported by the degradation of natural reduced sulfur gases and consisting of a sulfuric acid/water mixture (95, 96). Where ammonia is available from natural sources (97, 98), the acid is neutralized in whole or part (99, 100).

For geographically isolated cities, these will be crucial inputs to the atmospheric system and will define the natural states from which pollution episodes evolve. Many of the world's megacities, however, are embedded in megalopolitan zones and must themselves accept urban-processed air as inputs (1). A classic example is the Washington-Boston corridor of the eastern United States (101, 102). It encompasses New York City, Philadelphia, Boston, and Washington, DC, and has a total population exceeding 50 million. Even Mexico City suffers from inputs of polluted air. Neighboring basins contain urban complexes that are large in their own right (Puebla, Toluca, Cuernevaca) and input materials into the Valley of Mexico (103). The Chinese megacities are located on a coastal flood plain so densely populated that visibility is universally affected by an anthropogenic aerosol haze (104–107). Furthermore, this region lies climatologically upwind of the Japanese megalopolis, leading to potential political conflict (59, 104, 108).

Los Angeles offers a study in contrasts. It is situated almost alone on a strip of temperate, Mediterranean ecosystem but is surrounded by the sparsely populated Sonoran and Chihuahuan Deserts. It is interesting to note, however, that the arid U.S. Southwest is quite scenic and supports an important tourist industry. Long-range transport from Los Angeles has been implicated in visibility degradation within the Grand Canyon (102). Also, it is now known that Asian air pollution can cross the entire Pacific (109).

Mass flow of the sum total of these gases and particles (dominated by N_2 and O_2) differs from city to city with local topography and meteorology. Relatively complete estimates of total atmospheric throughputs are available for Mexico City (68, 69, 110). Located at 20° north latitude, the Valley of Mexico experiences westerly wind systems in winter and returns to the trades in summer. The major flow is blocked by a U-shaped ring of ridges opening to the north and rising from the basin floor at 2200 m to about 3000 m altitude. The ring is punctuated by the 5500 m volcanic peaks of Popocatépetl and Iztaccíhuatl. (Popocatépetl has in fact displayed moderate activity in the last few years. Its plume may be contributing on occasion to the local air chemistry.) The ridge is extended from the meteorological point of view by a mountaintop chimney effect, to roughly 2000 meters above the valley floor. Below this level, daytime heating of the surface drives vertical turbulence, and some rising air parcels interchange with the general circulation. Within the volume defined by the chimney effect, total air mass directly influenced by the city is almost 5 Gt and throughput is around 6 Gt per day (68, 70). Budgeting for carbon monoxide and ozone indicates a total turnover (reciprocal residence time) of 1.33 per day in the winter. Within the valley, micrometeorological processing of the input air is complex due to the rich topography of mountains and high-rises. Interchange from the global general circulation into the basin is analogous to transfer from the bulk urban atmosphere into street canyons; the vertical scale differences are similar (111). The chemical and microphysical implications of air transformations at the canopy level (that of the rooftops and sides of large buildings) are understudied.

Other basin and river cities also exist in complex flow regimes. Chongqing, China, lies 1500 km up the Yangtze River and is approaching megacity status. The Szechuan Basin in which it resides is so densely populated that the metropolitan area is difficult to distinguish. Population contours appear to closely follow tributaries of the major Yangtze River system (112). For urban areas in flat terrain, throughput is simpler to compute. It consists of general flow across the urban area. A metropolis possesses a well-defined target (cross-sectional) length and downwind plume. The distribution of pollutant emissions across the Midwestern United States has these characteristics (113, 114). Coastal megacities experience sea-breeze effects. Transverse mountain ranges may block circulation and contribute to serious local pollution problems. Automobile-dominated (ozone) air pollution was discovered and first studied in Los Angeles because it lies in a coastal basin. The volume of the city is only enclosed on one side and its boundaries are difficult to pinpoint because the confining mountain systems are rugged and broken up. Residence time of air in the Los Angeles urban area has been estimated at half a day (115).

3.3.2 Water Inputs Passive input of water into cities consists of precipitation and surface flow. The urban infrastructure has a profound effect on the water cycle. Owing to the heat island effect (see below) and increases in surface water from human outdoor water use, the built environment can increase urban evaporation and precipitation (27). Pavement and construction leave the urban surface virtually impermeable. This drastically decreases infiltration (penetration of water into soils), soil moisture, and groundwater recharge and flow. Large storm water runoff events consequently become common. Downstream, these larger floods result in greater erosion of stream channels (53). In Tokyo, 82% of the surface is covered by buildings, concrete, or asphalt (52). Decreases in groundwater recharge also contribute to subsidence in some megacities (15). The center of Mexico City has subsided 9 meters since 1910, mostly due to active draining of the aquifer, though reduction of recharge is also a factor (16). Parts of Bangkok sank 1.6 m between 1960 and 1988, averaging 5.7 cm per year (54).

Passive inputs of water are treated both as assets and nuisances. A city's perspective depends on both how reliant it is on a centralized water supply, and how scarce fresh water is relative to demand. In developing cities, rooftop catchment is common on the urban periphery, where service even by water trucks may be unreliable. At the other end of the development spectrum, Tokyo has initiated rooftop catchment on 579 city buildings, including the sumo wrestling stadium (52). Most of this gray water is used on location with minimal treatment.

In most developed cities with centralized water supplies, however, urban rainwater is conceived as a nuisance, and rainwater is shunted through drain systems out of the city (116). In temperate and tropical cities, this can be a considerable amount of water. New York City receives approximately 10,000 kt of rainwater per day, exceeding their estimated use of 7,610 kt per day by 36% (53). Harvesting and treating rainwater on a large scale requires substantial and costly changes in municipal and/or residential infrastructure; it is unclear exactly when these changes become cost-effective.

3.3.3 Heat Inputs The heat budgets of cities are influenced by solar radiation, anthropogenic sources, and structural design. The combination of an increase in heat-absorbing surfaces (such as asphalt), increased surface area (due to building construction), and increased heat production (due to industry, transportation, and heating of water and space) results in an urban heat island. Mean surface and air temperatures increase by several degrees Celsius (58, 117–120). In Mexico City, buildings and surfaces store so much heat during the day that the city maintains an upward heat flux throughout most nights (120).

The suite of urban pollutants includes heat trapping (greenhouse) gases that further enhance the heat island effect (121). Increased atmospheric temperatures can modify the rates of atmospheric chemical reactions; usually they rise. Ozone production, for example, is strongly dependent on temperature above 27°C (122, 123). The aerosol haze scatters incoming solar radiation both in the multiple (back and forth) sense and upward out of the urban system. This process alters photolysis rates for trace species such as nitrogen dioxide (NO_2) (124). Photolysis is a key mechanism through which reactive gases are produced in the urban air chemistry system. Effects of air pollutants on the radiation field within cities are only beginning to be quantified and modeled (125).

Increased temperatures also affect rainfall patterns, often resulting in increased precipitation in the city versus the surroundings (27). In Shanghai, temperature increases in the urban core of up to 5°C contribute to precipitation increases on the order of 100 mm per year (58).

4. OUTPUTS

4.1 Atmospheric Outputs

Emissions into the local city atmosphere and chemical transformations occurring there are some of the most heavily investigated aspects of the urban environment. We use the available data as a springboard for a general review of atmospheric output. The volume of the air quality literature is large, in part because research tends to be conducted independently within and by individual large cities (1). Cross-cutting references have been sought here, but they are rare. Most constitute simple comparisons of pollution levels (1, 126, 127). Because infrastructure and economic factors vary widely, the nature of air chemistry does as well. From the multiple-city perspective, however, the data are poorly organized, and the potential to analyze them statistically is not being fully explored.

Development of an air chemistry culture began in the pollution centers of first world countries in the 1950s (128–130). Their monitoring and regulation systems have been used as models worldwide. For example, U.S. environmental scientists advised in the setup of an air quality network in Mexico City in the 1960s and 1970s (131). Today the Mexican system is among the most extensive in the world (132). Proper operation of the many chemical samplers involved is expensive, and maintenance can be sporadic in developing countries.

The economic driving forces of the global air quality monitoring culture are concern for human health and visibility (133). Particles containing sulfur acids caused many deaths in London before coal content and use were controlled (134). In China, aerosol outbreaks are now having similar effects (135, 136). The health impacts on urban residents and ecosystems are well appreciated, but concern is now broadening to include nonurban neighboring ecosystems and the global atmosphere. Greenhouse gases and their precursors emanate from areas of intense human activity (20). Nitrogen outputs from the megacities can act as fertilizer for natural areas downwind, both terrestrial (137) and marine (138). Outputs of iron from China will increase micronutrient levels in part for some remote North Pacific waters (59, 139–141). Oxidants are known to reduce crop yields in the agricultural areas of densely populated East Asia (10, 142). The anthropogenic aerosol may also reduce photosynthetically available radiation (106).

Material flow associated with the air exiting metropolitan areas can be usefully conceived of as a superposition on the background tropospheric input; cities

TABLE 7 Selected substances within the Valley of Mexico atmosphere[a]

Variable	**CH_4**	**CO**	**C_3H_8**	**NMHC**	**NH_3**	**SO_2**	**NO_x**	**NO_y**	**Soot**	**Dust**
Remote c	1800	100	0.2	30	0.01	<1	<1	<1	0.1	0.1
Urban c	1950	3000	25	700	20	50	75	100	5	5
Chemistry t	Long	>10	1	0.4	10	1	0.1	Long	Long	Long
Scale height	Large	>10	3	2	10	3	1	Large	Large	Large
2 km c	1850	1000	8	250	7	16	—	35	1.5	1.5
% Covered	100	100	100	100	100	100	50	100	100	100
Transport t	0.75	0.75	0.75	0.75	0.75	0.75	0.75	0.75	0.75	0.75
Average t	0.75	0.75	0.55	0.39	0.75	0.55	0.16	0.75	0.75	0.75
% Vented	100	100	73	51	100	73	20	100	100	100
Burden	270	10000	120	1000	40	350	90	175	15	15
Emissions[b]	750	11000	130	1500	—	300	300	230	—	—
Emissions[c]	360	13000	220	2500	50	650	600	230	20	20
Venting[b]	750	11000	100	750	—	220	60	230	—	—
Venting[c]	360	13000	160	1250	50	475	120	230	20	20

[a]Concentrations (c, ppb for individual gases and ppbC for NMHC, micrograms m^{-3} for fine particles), removal time constants (t, days), scale or e-folding height (km), areal coverages (%), ventilation or valley exiting fractions (%), burdens (tons for individual gases and for particles in the fine mode, tons C for NMHC, tons NO for NO_x, tons N for NO_y) and fluxes (tons per day). The methane burden is effective over background. Hydroxyl radical concentrations were estimated for city air as in Reference 86. Rate constants were taken from standard atmospheric chemical kinetics tabulations (86, 96, 202).

[b]Bottom up.

[c]Top down.

generate plumes of chemically altered fluid. The typical urban area injects most of the background tropospheric species and adds to the concentration distribution as well. Some pollutants enter city air directly, whereas others are produced photochemically. Substances in these two categories are often referred to as primary and secondary pollutants (86, 96). The interrelationships are best demonstrated by example. Results of a simple budgeting exercise are offered in Table 7, which shows properties of selected substances in the Valley of Mexico atmosphere (68, 103). The computations were undertaken peripherally to recent intensive investigations of the local air pollution (69, 110, 143). However, they adopt a megacity inflow-outflow theme.

Mexico City raises the methane concentration above the global background by about 150 ppb. Although levels of gas phase oxidants such as hydroxyl are high, the added methane is stable and leaves the metropolitan area unoxidized because reaction times are much longer than basin residence times. Sampling near major sources indicates that incineration, automobile exhaust, natural gas distribution systems, landfills, and sewers all emit vapors rich in CH_4 (144–146). Combustion of waste and gasoline constitutes transformation of material inputs under the rubric established here. However, efficient burning yields pure CO_2 (147, 148). Methane can thus be viewed as a leaked byproduct. Ideally, natural gas distribution would be perfectly efficient. However, significant losses often occur upstream of the user (149). Methane is produced anaerobically by bacteria in the landfills and sewers (21, 85). It actually represents terminal electron acceptance by more oxidized carbon compounds. The material transformation undergone is electrochemical reduction of carbon atoms.

The other simple one-carbon compound in Table 7 is carbon monoxide (CO). It is much shorter lived than methane in the bulk atmosphere (about 1 month versus 10 years for CH_4), but emissions are much larger locally (21). Consequently, the urban concentration is on average 30 times the tropospheric background. CO is produced almost exclusively by automobiles in gasoline combustion. Because it is partially oxidized (toward CO_2), CO can be conceived as either a leakage or carbon transformation. Although CO is more reactive than methane, its lifetime is nevertheless much longer than the residence time of air in the basin. Thus, it is also efficiently ventilated. Tailpipe CO concentrations have been measured at a distance via laser spectroscopy and coupled to vehicle registration through license plate photography (150). In intercity comparisons, vehicle maintenance emerges as a primary factor in CO emissions, across cultures as diverse as Scandinavia, Eastern Europe, Latin America, and Southeast Asia (151).

A particularly strong source of propane (C_3H_8) can be deduced through a method known as Chemical Mass Balance (CMB) (152, 153). Combinations of mass distributions from well-understood sources can be sought that reproduce concentrations of urban scale input data. In local Mexico City air, the ratios of ethane, propane, and the butane (C_4H_{10}) compounds strongly resemble the profile found in liquefied petroleum gas (LPG), fossil fuel consisting primarily of the C_3 and C_4 alkanes (154). Therefore, LPG is probably the major source of propane.

Multivariate techniques such as factor analysis also provide information about the probable sources of chemical species released into city air. Factor analysis represents the interrelationships among large sets of variables by constructing a smaller number of dimensions based on correlations in the data. These orthogonal (uncorrelated) dimensions help distinguish the common underlying factors. A typical computation is provided in Table 8 (70). Hydrocarbon samples obtained during a week-long study of Mexico City pollution (154) were grouped into morning and afternoon bins. They were then subjected to a principal components analysis (155). Factor loadings represent a correlation between a variable and the underlying factor. In the morning samples, for instance, LPG is implicated as factor 1, as loadings are high for substances most concentrated in LPG. The first two factors explain most of the variance in the data, suggesting LPG and auto exhaust are the major inputs. Afternoon loadings suggest cars and a variety of methane sources. The afternoon factors may also refer collectively to the more photochemically active compounds (Table 8).

The application of composition profiles along with mass balance or multivariate statistics can be powerful but is not a panacea. For example, in Mexico City air, it

TABLE 8 Factor structure matrices for hydrocarban concentrations within Mexico City[a]

Hydrocarbon	**Morning (0300–1200 h) N = 26**				**Afternoon (1200–2100 h) N = 34**	
	Factor 1	**Factor 2**	**Factor 3**	**Factor 4**	**Factor 1**	**Factor 2**
Potential Source[b]	**LPG**	**FC**	**Mixed**	**PM**	**AE, PE**	**LPG, NG, PM**
c-2-Butene	**0.980**	−0.006	0.049	0.016	**0.936**	0.142
t-2-Butene	**0.979**	−0.097	−0.029	0.106	**0.965**	0.086
1-Butene	**0.909**	0.316	0.205	0.149	**0.964**	0.232
Propane	**0.892**	0.163	0.159	0.245	−0.027	**0.971**
i-Butane	**0.888**	0.223	0.198	0.199	0.192	**0.949**
n-Butane	**0.888**	0.237	0.223	0.179	0.336	**0.906**
i-Butene	**0.854**	0.438	0.180	0.117	**0.979**	0.137
1,3-Butadiene	**0.764**	0.485	0.113	0.224	**0.978**	0.125
1-Hexene	**0.721**	0.431	0.375	−0.034	**0.904**	0.073
Methylcyclopentane	**0.683**	0.423	0.535	0.018	**0.933**	0.160
1-Pentene	**0.579**	0.303	0.512	−0.120	**0.691**	−0.004
Ethene	0.254	**0.908**	0.268	0.090	**0.946**	0.286
Ethyne	0.106	**0.853**	0.494	0.041	**0.911**	0.374
Propyne	0.198	**0.843**	0.475	0.023	**0.936**	0.280

Benzene	0.232	**0.728**	0.511	0.244	**0.913**	0.374
Propene	0.619	**0.690**	0.266	0.192	**0.970**	0.194
n-Heptone	0.162	**0.660**	0.573	0.340	0.549	0.514
Ethane	0.225	**0.659**	0.169	−0.234	0.402	**0.820**
n-Hexane	0.220	**0.615**	0.519	−0.029	**0.774**	0.576
Toluene	−0.031	0.164	**0.953**	0.047	**0.713**	0.644
3-Me-Pentane	0.121	0.368	**0.904**	−0.006	**0.744**	0.478
2-Me-Pentane	0.195	0.414	**0.872**	0.489	**0.847**	0.425
Cyclopentane	0.316	0.581	**0.741**	−0.024	**0.889**	0.396
n-Pentane	0.408	0.560	**0.695**	−0.070	**0.888**	0.329
i-Pentane	0.494	0.554	**0.624**	−0.087	**0.904**	0.348
Methane	0.324	−0.060	−0.002	**0.884**	−0.127	**0.887**
Isoprene	0.619	0.116	−0.022	**0.715**	**0.970**	0.059
Eigenvalue	17.711	5.187	1.289	1.236	21.015	4.048
% of variance	63.3	18.5	4.6	4.4	75.1	14.5
Cumulative explained variance	**63.3**	**81.8**	**86.4**	**90.8**	**75.1**	**89.6**

[a]Factor analysis using principal components was conducted on morning and afternoon concentrations separately. A VARIMAX rotation was performed to ensure that factors were orthogonal. For the morning samples, four factors explained a substantial amount of the variance (eigenvalues >1.0). Two factors were identified from the afternoon samples. Factor loadings are analogous to standardized partial regression coefficients (e.g. methane $= 0.324F1 - 0.060F2 - 0.002F3 + 0.884F4$) and can be used to identify common emission sources. The largest loading is in bold for each hydrocarbon. Communalities can be calculated by summing the squares of the factor loadings for individual species. Source, Reference 70.

[b]Potential sources: LPG, liquefied petroleum gas; FC, fuel combustion; PM, "pure" methane; AE, automobile exhaust; PE, photochemical effects; NG, natural gas.

is difficult to quantify the source distribution for methane. The propane emission into the valley suggests a leak rate of about 5% for urban LPG (103, 154). Leakage of 5% methane may not be inconsistent with the available data. If extrapolated to other natural gas–intensive cities, it would translate to a significant addition to the global methane inventory (85).

The nonmethane hydrocarbons (NMHC) include the alkanoic constituents of LPG, unsaturated species (those with multiple carbon-carbon bonds), oxygenates, and others. NMHC are produced via leakage and transformation from the carbon-based fuels as they are consumed. The hydrocarbons also emanate from solid and liquid waste repositories. Their production chemistry is analogous to that of CH_4 and CO but is more complex (91). The list of species in Table 8 is representative. The chemical lifetime in Table 7 is merely a composite.

Ammonia (NH_3) and sulfur dioxide (SO_2) are chief sources of basicity and acidity to the urban atmosphere. In Mexico City, bases happen to be present in excess, titrating the major acids, sulfuric and nitric. The salts formed are involatile and reside in the aerosol phase (96). NH_3 and SO_2 remaining in the gas phase are removed photochemically only on time scales of one day or longer. Unlike aerosol particles, they undergo Brownian transport to solid surfaces very rapidly (96). They are thus unprotected against deposition. The major source of ammonia to the Mexico City atmosphere appears to be the excrement of urban animals such as rats, dogs, and cats (156). Ammonia volatilized from animal waste is a primary source of mass and material cross section in aqueous particles and results in decreased visibility (103, 156–159). Transformation of NH_3 constitutes an oxidation of food nitrogen mobilized through pets and feral mammals. Sulfur in the acid is a trace constituent of fossil fuels (21, 132). Present in the high +4 oxidation state in SO_2, it is best termed a transformed fuel component.

Combustion processes occurring in the world's cities are a major source of fixed nitrogen to global ecosystems (50, 160, 161). Molecular nitrogen entering car engines or power plants is oxidized in part. The simple NO exits the tailpipe or smokestack in trace quantities (96). It reacts rapidly with ozone to yield NO_2. The two species then enter into a rapid photolysis/ozone reaction equilibrium. Together they are often referred to as the NO_x species (small quantities of NO_3, N_2O_2, and other pure nitroxides are included) (86). Reaction of NO_2 with the OH (hydroxyl) radical produces nitric acid, HNO_3. The time constant for the transformation is on the order of hours, so that little NO_x escapes Mexico City directly.

Nitric and sulfuric acids can be titrated by ammonia into nondepositing droplets (158, 159). In general, suspended urban particles are mixtures of the inorganic ammonium compounds, a variety of high-molecular-weight hydrocarbons, and solids (96, 162). The aerosol is sufficiently chemically heterogeneous that it is well suited to Chemical Mass Balance or principal components analysis approaches. In fact, the methods were developed to discriminate particle sources (152).

Soot and dust are dominant components of many megacity atmospheres. Soot is a complex mixture of involatile hydrocarbons and graphite (pure two-dimensional polymers of carbon)(86). Like methane and the NMHC, it is produced as a partial combustion product when carbon fuels are burned (147). Thus, incineration and diesel fuel are likely sources. The dust referred to in Table 7 is really crustal material—aluminosilicate matrices with trace elements embedded. Iron is present at around 5%, and from the earth system standpoint, it is the most important constituent. In polluted urban plumes, acidic aerosol photoreduces the metal to the +2 oxidation state and renders it bioavailable (163). Because large tracts of the open ocean are thought to be iron limited (164), deposition of bioavailable iron can act as a large-scale marine fertilizer.

Downwind (100 to 1000 km), the urban plume is supplemented by those of neighboring cities and dilutes into the tropospheric background, which was initially the passive input. Mass fluxes for trace substances leaving the Valley of Mexico as pollutants are given to culminate as venting values in metric tons per day (Table 7). The calculations were conducted both from a bottom-up perspective (using government emissions data) and, as a check, from the top down as well (based on overall removal rates from valley air). As the effluent disperses, short-lived hydrocarbons oxidize with the catalyst NO_x species present and generate ozone. The Mexico Basin may yield plumes visible to satellite ozone instruments (165). Ozone from the megalopolis of coastal East Asia can also be detected from space (166). Soot is a strong downwind absorber in the visible portion of the spectrum, where the ammonium salt aerosol scatters solar radiation effectively. Several megacities generate hazes that are obvious to the naked eye for hundreds of kilometers.

The air chemistry of large industrial cities can be quite complex. Internal transformations are now understood for several developed urban areas. On the global scale, however, key population centers and relationships between them remain understudied. Because urban infrastructure details vary widely, so then do the components of material flows and their interactions.

The megacities under discussion here can be compared and contrasted on several levels to demonstrate this concept. Mexico City has been our point of departure. It relies to a large extent on LPG as an energy source in residential areas because natural gas pipelines were deemed unsafe in the earthquake-prone Central Plateau (132, 167). In a city with high natural gas use, such as Buenos Aires (168) or London (169), leakage of residential fuel would have a direct greenhouse consequence.

Emissions of the automotive pollutants CO, NMHC, and NO_x stand to rise substantially as the world urbanizes. Vehicle fleets are growing faster than population in most megacities. In developed settlements (e.g. Los Angeles), vehicle ownership can exceed 0.5 per capita (Table 6) while reasonable traffic flow is maintained (1). However, the road and highway network may not keep pace with rising vehicle densities in developing zones. Congestion is increasing globally, and average vehicle speeds are dropping drastically in many of our sample cities. Peak hour speed on main roads is 20 kilometers per hour (kph) in Tehran, 18 kph in Seoul (75), 13 kph in London (170), 12 kph in Manila (61), and 4.8 kph in Bangkok (54). Such reduced speeds produce over 60% higher emissions than standard highway velocities due to decreased fuel efficiency and increased travel time (171). In developing areas, vehicles also tend to be poorly maintained.

If first world vehicle ownership rates are achieved worldwide, Mexican pollution levels will easily be exceeded. For example, China currently supports the lowest total area of paved road of any major country (172). As vehicle use and road construction increase in arid areas of Central Asia, atmospheric dust loadings will rise (59). In Mexico City, an excess of ammonia effectively titrates nitric acid into the aqueous aerosol. Developed urban areas will not have the strong source from domestic animal waste so that HNO_3 vapor can move to surfaces in the Brownian sense and deposit. Because the Valley of Mexico is heavily hydrologically engineered, the megacity sits astride the dry remnant of the lake of the Aztecs (16). Suspension of sodium chloride particles may impart a component of chlorine oxide radical (ClOx) chemistry to the gas phase. This is normally only observed on the sea coast. Studies of particle composition are highly resolved chemically and have become quite portable. Aerosol composition data for the megacities of North and South America have been compared, but primarily as a reflection of relative pollutant levels (1, 126, 127, 173).

Computations such as the ones in Table 7 could be completed from many of the available urban air chemistry data bases. However, they are rarely performed even for the developed megacities. This is largely attributable to the economics of urban air chemistry research. The driving force is to understand the temporal and spatial evolution of pollutant fields within the city. Residents and the industries serving them focus by necessity on local health issues and visibility. From the planetary point of view, however, what will be required is a synthesis of outputs across the distribution of global settlements.

4.2 Aquatic and Marine Outputs

As with solid waste, it is difficult to estimate piped sewage service (sewerage), sewage production, and destination in developing megacities. When available, estimates can vary widely even for the same city. For example, the estimates of percent of households with sewerage in Mexico City vary from 32% (33) to 80% (77). In many megacities sewerage is extremely limited (Table 3). Furthermore, sewerage is not necessarily treated; often raw sewage flows directly into local waterways. Estimated daily sewage generation is 1.0 Mm^3 in Karachi (78), 1.98 Mm^3 in Los Angeles County (35), 2.9 Mm^3 in Moscow (174), and 5.4 cubic megmeters (Mm^3) in Shanghai (175). Although water treatment clearly improves with increasing wealth and development, wastewater generation generally increases as well.

4.3 Earth System Linkages

For the three transformed groups of substances (food, fuel, and water), complex feedback loops exist between the environment and the megacity. Recent research in Asia provides several examples. In China, gas phase air pollution may be reducing crop yields in agricultural areas through the interaction of oxidants with leaf surfaces (10, 142). The key species involved are ozone and sulfur dioxide, which are derived from fossil fuels. Further, over the last decade, anthropogenic particles consisting in part of ammonium nitrate have rendered the atmosphere of China so turbid that additional crop damage may ultimately result from losses of photosynthetically available radiation (106). In Asia, radiative transfer is more than just an aesthetic issue. The challenge of feeding the world's most populous nation (176) may lead to air quality controls that would otherwise be politically impossible. The chemical content and availability of fossil fuel supplies, for example, may be regulated to protect energy and nutrition sources for the population. Controls on ammonia emissions from animal waste may also be required. Thus, feedbacks between urban carbon and nitrogen cycles in China have profound effects on the environment.

Complex links between East Asia motorization, North Pacific ecosystems, and global climate offer a second example. Modernization of the highway network linking Chinese urban centers is currently a major engineering project (76, 172). Suspension of large quantities of iron-bearing dust may occur before an updated road system can be built (140, 177). Acidity attributable to coal burning provides a reducing environment, which promotes conversion of iron to bioavailable forms (141, 163). Because much of the North Pacific is iron limited (178, 179), fertilization of delicate marine ecosystems is a distinct possibility (59, 161, 180). Potential ecosystem effects are unknown.

Mobilization from Asian urban areas also increases bioavailable nitrogen concentrations in the geostrophic westerly winds. Nitrogen fertilization of the open ocean will lead to drawdown of CO_2 from the atmosphere owing to photosynthetic activity (181). Changes in primary production will alter the ventilation of dimethyl sulfide. Sea-to-air flux of dimethyl sulfide is the primary source of reduced sulfur to the remote marine troposphere, and therefore of sulfate and cloud condensation nuclei (95). The cloud condensation nuclei in turn dictate cloud particle sizes and the planetary albedo over the open ocean. Changes in the albedo over the North Pacific have the potential to alter global temperatures (164). Climate change is likely to have significant yet poorly defined impacts on regional winds and hydrological cycles. Thus, it is possible that evolution of the Chinese urban infrastructure will induce large-scale climate and biogeochemical effects with serious repercussions for human activities in Asia.

Flows of material and energy through megacities likely form other teleconnections with remote ecosystems. Diversion of water for urban use, production of food for urban consumption, and burning of fuels in megacities are all global-level activities whose local impacts are slowly becoming identified (2). The effects on distant ecological processes are likely complex but have received little attention.

5. MODELS

A variety of numerical simulations have been developed to examine many aspects of the urban environment. For the most part, however, they have been limited to models of single cities in developed countries, not only because they are more tractable, but because funding for such efforts is easier to procure from local jurisdictions. The most sophisticated models of traffic flow, for example, have been developed for Dallas, Texas (182, 183), and are being applied to Portland, Oregon. Little cohesive effort has gone into cross-cutting comparisons of the development or growth of megacities. Developing megacities constitute crucial ecosystems from the biogeochemical perspective but are among the last to be studied quantitatively. The research base, although high in quality, is haphazard. The future megalopolises of India and China, for instance, remain virtually unsimulated.

Models of the carbon, fuel, and economic cycles have been constructed at the national level resolving states/provinces (57) and at the global level discriminating countries (184). Urban centers are only treated implicitly, and intercity linkages are nonexistent.

Urban biogeochemical fluxes are only rarely modeled. One exception is residuals-environmental quality management (REQM), an approach that was developed in the 1970s to address the specific problems of regional pollution and waste management (185). REQM quantifies and models the generation and flow of waste outputs from anthropic processes (i.e. residuals). Residuals' impacts on ambient environmental quality are then determined (186). One REQM study occurred in the lower Delaware Valley of the Eastern United States. The region extends 12,200 km^2 and had a population of 5.5 million in 1970, most of whom lived in Philadelphia (187). Models were developed to explore biogeochemical and economic linkages among solid, gaseous, liquid, and energy residuals. A second study was conducted in the Ljubljana area of Slovenia, a region of 930 km^2 and 257,000 people (188). Both studies measured ambient environmental quality indicators such as wastewater quality, solid waste mass and content, and emissions of SO_2, CO, and NO_x. Integral to REQM analysis is the development of models to predict residuals' production, and to estimate costs of reducing residuals to desired levels. Although no REQM studies have occurred recently, the conceptual approach is carried on in environmental resource management models. It is attractive because it focuses specifically on measuring and managing pollutants and water quality (189).

A model linking element and nutrient cycling was developed in 1991. METALAND considers the total material flux of human systems (190). The model classifies objects as materials (treated by physics) and goods (treated by economics). The processes are transport, transformation, and storage. METALAND was applied to the Lower Bünz Valley in Switzerland, a 66-km^2 region with 26,000 residents (46). Results suggest that water was the dominant material flux (69% by mass), followed by air (15%), construction materials (8%), and fuel (1%). Goods accounted for 8% by mass of the region's export. Interestingly, household consumption was the chief process of regional material transformation.

An advanced biogeochemical/ecological modeling technique is general systems theory (GST), developed in 1971 (191). In GST, relationships among energy, matter, economics, and society are analyzed using the theoretical frameworks of physics and ecology. All materials, fuels, and processes are converted to the basic currency of energy (in joules or calories). Power (energy flow per unit time) is postulated to be the fundamental organizing principle. Conversion of all materials to energy equivalents and all processes to power equivalents permits the inclusion of factors with no market cost that are omitted in most economic analyses, i.e. externalities. GST is typically used to study the energy flux of biotic systems. Whereas GST has enormous potential for interdisciplinary integration and thorough analysis, it has been utilized infrequently. A notable recent application is the simulation of Taipei, which examined the energy flows associated with urban development (192).

Modeling of urban demographics has a longer history. Such efforts extend back nearly a century in the fields of geography, sociology, and economics. Consideration of the material and energy basis of demographic activity, however, is relatively recent. Most demographic models still consider socioeconomic factors exclusively, and ecology is only incorporated if it is economically valued (e.g. open space, clean rivers). In the last decade, several demographic models have been developed that are dynamic, spatially explicit, and computer intensive (193–195). Nonetheless, these models lack thorough incorporation of biogeochemistry. Full integration of environmental and human components is the aim of the Urban-Ecological Model, part of a larger multidisciplinary simulation effort of the Puget Sound system (196). This model, which is still under development, aims to represent links among environmental, social, and economic components (197–199).

Arguably the most advanced suite of simulations regarding the global city deals with air quality. Emissions, meteorology, photochemistry, and aerosol microphysics can now be computed in a coupled fashion. Again, the driving force for development has been the economics of health and visibility. Programming skills are generally applied to wealthy cities first, and primarily to intraurban processes. As an example of one trajectory for model development, we offer a brief history of air quality simulations. The sequence of events closely parallels general developments in urban atmospheric chemistry studies, as described above in the outputs section.

Air chemists in the major first world pollution centers (e.g. Los Angeles, London) first deduced the mechanisms of ozone and haze aerosol generation through laboratory experiments and hand calculations in the precomputer era. Ozone production and chemistry can actually be approximated through a few simple kinetic equations (200). The initial, crucial discoveries were made in the 1950s and 1960s. By the late 1970s, several air quality and pollution engineering groups were developing models inclusive of the dozens of photochemical reactions that must be considered in complete treatments (201, 202). Most were doing so, however, in low physical dimensionality. The chemistry was placed in a nondimensional “box” initially, or in a traveling column of such boxes (158, 159, 203, 204).

Several key photochemical issues proved numerically and computationally challenging (96). In the box configuration, gas phase transformations and aerosol microphysics can be represented as a system of coupled nonlinear ordinary differential equations. The dependent variables are concentrations for gas phase species or mass/number densities for particles. The distribution of chemical species must be considered across a wide range of aerosol sizes. The system is quite "stiff" numerically (205). Roughly, this means time constants for the evolution of individual concentrations are linked and span many orders of magnitude. Implicit integration methods of varying sophistication were experimented with (206). Chemically intuitive groupings such as "families" were found to shorten computation times (207). The NO_x species constitute an example. Meanwhile, the number of individual chemical and microphysical processes that had to be tracked rose from dozens to hundreds (208, 209).

As vector and massively parallel supercomputers became commonplace, numericists were able to place the complex chemical system into a physically realistic three-dimensional context. Initially, gridding of the geographical space was coarse and simple (210, 211). Rectilinear coordinates were adopted, with cells several kilometers on a side and many hundreds of meters deep or high. The general circulation of an urban zone was taken as off-line input; observed wind fields were interpolated into the model mesh and used to drive advection (212). Careful attention had to be paid to subgrid scale (turbulent) transport processes and their relation to deposition of surface-reactive substances (213).

Most recently, it has become possible to drive the air quality models with wind fields computed from basic meteorological (fluid dynamical) principles (214). Mesoscale (1000-km domain) models of atmospheric flow use boundary conditions determined by global general circulation models. Radiative transfer, heating, and cooling are computed internal to the large-scale grid. Water phase transitions and latent heat release are tracked as well. A nested subgrid represents the vicinity of the city, and therein the full photochemistry and aerosol microphysics computations are conducted (69). Comparisons can be performed between results obtained with wind fields derived from first principles and those measured in the field.

Although urban air chemistry models simulate distributions of several forms of bioavailable nitrogen (213), connections to the biogeochemistry of nearby wild ecosystems are only made peripherally. The outflow of nitric acid from the Los Angeles basin is often computed implicitly because model domains extend beyond the San Bernardino Mountains. Air chemists sometimes quantify nitrogen deposition and mention the possible effects on soils (137, 159). Recent intensive studies of Mexico City air quality enabled informal estimates of nutrient mobilization and flux to other Central American ecosystems, and to those of the Caribbean and Gulf of Mexico (103). The results suggest that nitrogen inputs contribute significantly to soil budgets quantified elsewhere (215–217), and to the nutrient supply of surface waters. Full chemistry transport modeling of the Central Mexican atmosphere has been conducted (68, 69), but downwind nitrogen deposition rates have not been analyzed by ecologists. The U.S. Southern Oxidants Study (218, 219) was regional in its scale, covering many of the southeastern states. The Southern Oxidants Study focused its modeling component on the interpretation of ozone distributions. Biogeochemistry was not an emphasis.

Simulations supported under the recent Chinese Metro-Agro-Plexes study have strongly coupled air quality computations with atmospheric chemistry/physics and with biogeochemistry models (106). This study may act as a prototype for next-generation earth system–level research. The modeling array utilized includes mesoscale meteorology, photochemistry, aerosol, and radiative transfer codes (106, 142, 220) deployed alongside crop-yield simulations (221). An unexpected result of the radiative transfer computations indicated that surface fluxes of photosynthetically available radiation are reduced dramatically by the Asian aerosol loading (106, 222, 223).

Global chemistry/transport simulations will soon be coupled to atmospheric general circulation models to yield interactive portraits of chemistry and climate evolution. Offline global chemistry codes are already at hand (87, 88). Subgrid scale parameterization of city plumes may well be required for accurate dissemination/processing of the anthropogenic outflow. This will become more true as the world urbanization level approaches 100%. North American urban plumes have been parameterized on-line in continental scale air chemistry simulations (114). The latest megacity studies are incorporating research into subgrid representation of the urban atmosphere throughput (224).

The urban air chemistry model has improved over the decades, in its resolution of grid cell internal processes (aerosol microphysics and photochemistry), in its treatment of topography, and in its ability to track feedbacks. Areas requiring further development are described below. Common threads in this assessment of city modeling include spatial resolution, process level detail, feedback loops, and global synthesis. These themes also apply to the collection of empirical data, and the two approaches will likely develop in concert.

6. SYNTHESIS

Information regarding urban inputs, outputs, and transformations of materials and energy is abundant but diffuse. Conceptual frameworks are needed to organize our comprehension of urban systems. Preferably, these will yield insight into the underlying structures and processes. Although socioeconomic perspectives are commonly used to analyze urban dynamics, biogeochemical approaches may also be useful, in particular by advancing our understanding of cities as ecosystems.

At the level of an individual organism, biogeochemistry comprises the metabolic processes: the conversion of water and food into biomass and waste. The parallels to urban systems are obvious and compelling (13). Cities transform raw materials, fuel, and water into the urban built environment, human biomass, and waste. Conceiving urban energy and material flows as an urban metabolism accentuates the fundamental physical processes that govern city growth and functioning. The concepts are not new, and we adapt them as an organizational tool and attempt to expand them. A potentially powerful contribution will be the parallel between urban evolution and succession.

Biogeochemical analysis of wild ecosystems is known as ecosystem ecology. Properties studied in this framework include net system productivity, net system respiration, biomass accumulation, nutrient cycling, energy transfer efficiency, and system resilience (225–227). The ecosystem analogy draws attention to the differences between urban and wild ecosystems. Further, it raises the question of whether city systems undergo succession in any form, and provides a framework for addressing urban change. After describing urban metabolism and urban succession concepts, open areas of research are suggested.

6.1 Urban Metabolism

The metabolic approach to studying city systems has been proposed several times under different names, but it has not been pursued rigorously beyond a few small groups. The name was first coined in 1965 to address water supplies and water and air pollution in cities (13). Using country-level data for the United States, rates of water, food, and fuel use and sewage, refuse, and air pollutant production were calculated for urban residents. These rates were then used to estimate the metabolism of a hypothetical American city of one million people (Figure 2). The estimates have been updated recently, with a substantial change only in the amount of pollutants emitted—down to 520 tons per day (228).

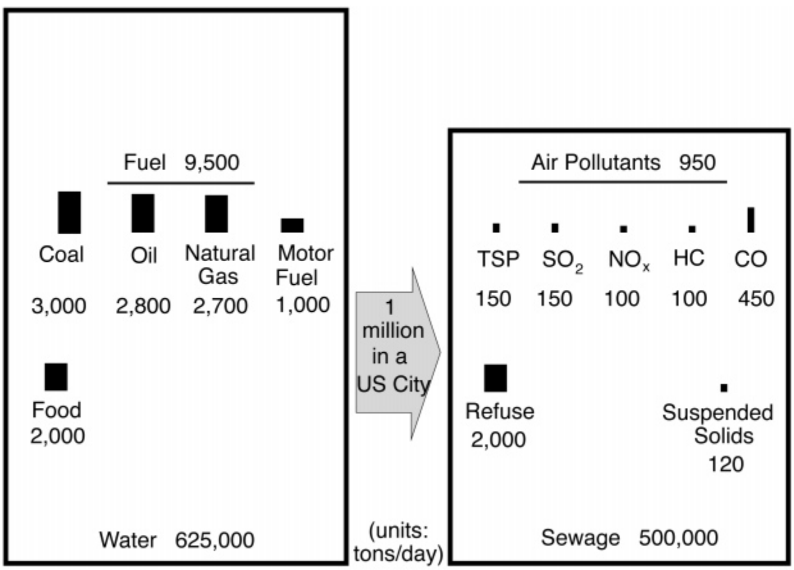

Figure 2 Material budget (tons per day) for a hypothetical U.S. city of 1 million residents in 1965. Rectangle area is proportional to rate for each substance. Suspended solids are in sewage water. Adapted from Reference 13.

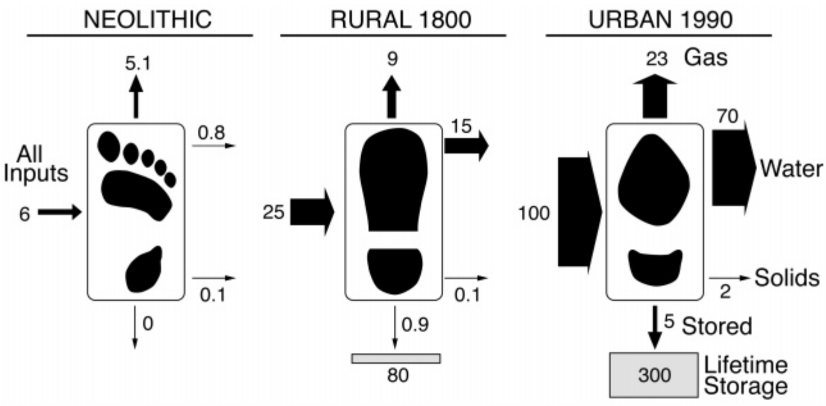

Figure 3 Material budget (tons per year) for an individual human from the Neolithic to present. Lifetime storage includes built structures and artifacts. Adapted from References 46 and 233.

General systems theory (GST) is arguably the first research program in which urban metabolism was studied (191). It is also perhaps the most theoretically rich, as it fully addresses the physics, biogeochemistry, and ecology of human systems (229). Ecological concepts are used as guides for sound human system design and functioning (230). Industrial metabolism (231), industrial ecology (232), and regional metabolism (233) are other names given to the energy and material accounting of human activities. Mass budgets are developed for toxic materials (234, 235), nutrients such as nitrogen and phosphorus (46, 236), and water (237) for entities ranging in size from households to countries. Urban metabolism studies illuminate basic trends in human energy and material fluxes. Figure 3 shows an estimate of the change in total per capita energy flux through human activity since the Neolithic; the increase is 16-fold (46, 233). Modern industrial humans metabolize up to 40 times the amount of energy that extant hunter-gatherers do (45).

Metabolic budgets for cities are still rare. A notable exception is the thorough analysis of Hong Kong's metabolism, conducted as part of UNESCO's Programme on Man and the Biosphere in 1971 (238, 239). The population of 5.5 million metabolized approximately as much as Wolman's hypothetical U.S. city of one million, resulting in much lower per capita levels of consumption and emissions (Figure 4). This is likely due to a substantial difference in the standard of living between the United States and Hong Kong. Figure 5 shows a similar mass budget for Sydney in 1990 (population 3,656,500). The drastic increase in CO_2 production compared with Hong Kong and Wolman's estimate is in part due to auto emissions being much higher in Sydney (240).

Urban material storage is addressed in only some of these analyses. In the Lower Bünz Valley REQM study, it was estimated that approximately 20 tons of

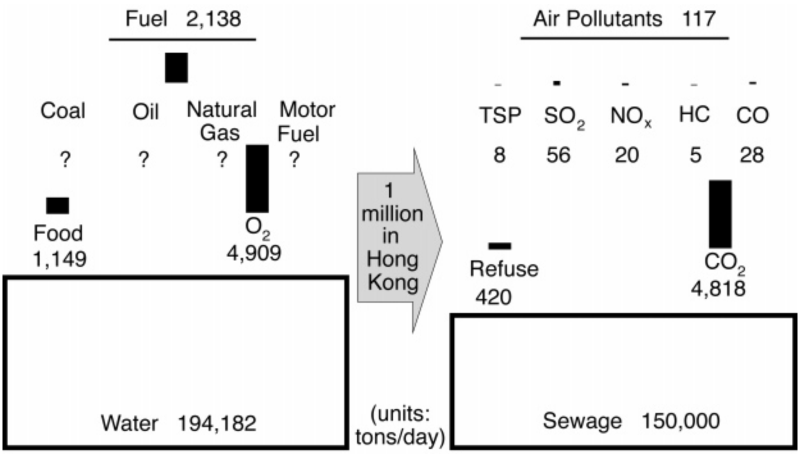

Figure 4 Material budget (tons per day) for Hong Kong in 1971, shown per million residents. Adapted from Reference 239.

material per capita, or 8.3%, remain in the region each year (46). Lead accumulation is nearly 18%, and phosphorus accumulation is 26.6%. Accounting of municipal phosphorus fluxes in Gavle, Sweden, estimated that of the 330 tons of phosphorus per year (3.7 kg per capita) entering the urban system, only 35% (116 tons) leaves the system, half of it in exported goods and half expelled into the Baltic Sea (47). The remaining 65% is stored in the city, mainly as sewage sludge in landfills. Further, leaching of phosphorus in some areas suggests that the city may be both

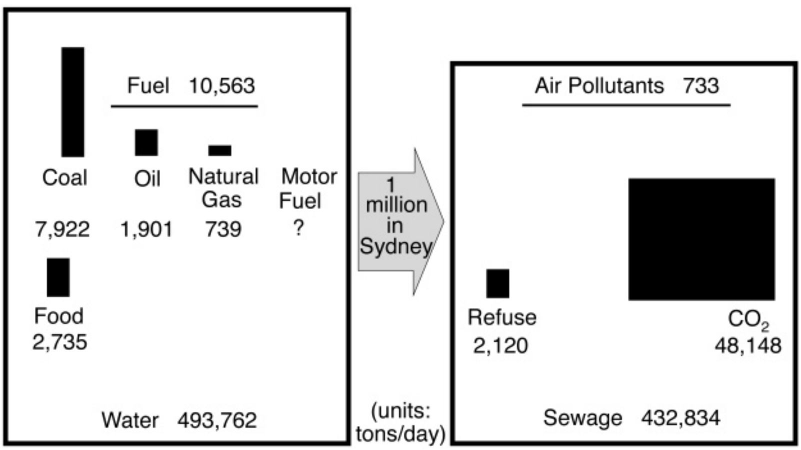

Figure 5 Material budget (tons per day) for Sydney in 1990, shown per million residents. Adapted from Reference 6.

a phosphorus sink on a regional scale and a phosphorus source locally. Other studies of phosphorus budgets show similar evidence of large storage levels and sink-source shifts (241).

Of the energy assimilated by living organisms, by far the largest proportion is dissipated as heat and not available for useful work. Likewise, energy inefficiency in cities can be quite high due to losses and waste during water use, construction, fuel combustion, or food spoilage. Most energy losses go unaccounted for because initial supplies are rarely quantified in energetic terms. However, some estimates of inefficiency have been made for fuel systems because they are inherently energetic and they are economically valued. Energy loss in Hong Kong, for example, was 27.6% prior to reaching end-users (238). In metropolitan Toronto, only 49.3% of the 150,940 GWh that entered the city was actually available to end-users owing to processing and distribution losses (242, 243). These estimates do not include end-use inefficiencies, which also can be extremely high. For example, end-use device inefficiency in Bangalore, India, is 51% (55).

Finally, urban metabolism can be measured spatially. The concept of the ecological footprint expresses the amount of land a city, region, or country requires to meet its metabolic needs (244, 245). Regions in the developed nations are running "ecological deficits" and depend on a large quantity of land beyond their boundaries to provide resources and absorb waste. Industrialized cities are the most obvious example. The 29 largest cities in the Baltic Sea drainage basin cover a total of 2,216 km^2 yet require an amount of open land 200 times larger to supply necessary renewable resources (246). More importantly, the amount of open land required to assimilate the nitrogen, phosphorus, and CO_2 generated as waste products in cities is 400 to 1,000 times the size of the cities themselves (Figure 6; see color insert). These estimates may be quite low compared to the total metabolism of these cities, as many substances are not included in the analysis (most notably fresh water). Although the ecological footprint concept does not usually account for spatial discontinuity (teleconnection) between a region and its footprint, it does draw attention to the services that wild and managed ecosystems provide to human settlements (247, 248). Ecosystem services include air filtering, climate regulation, and sewage treatment, though most of these have no economic value until they must be replaced by energy-intensive anthropogenic substitutes.

6.2 Succession in the Urban Ecosystem

Succession in wild ecosystems involves the colonization of bare ground, bare soil, or open water by flora and fauna and the successive replacement of colonizers by other species, often leading to a predictable climax community that is relatively stable (249). At the ecosystem level, growth from primary production at first exceeds energy consumption for maintenance (respiration), and biomass accumulates (250). When the system reaches climax, respiration approximately equals production, biomass stabilizes, and the system is in steady state (Figure 7). This "strategy of ecosystem development" results in increased community stability,

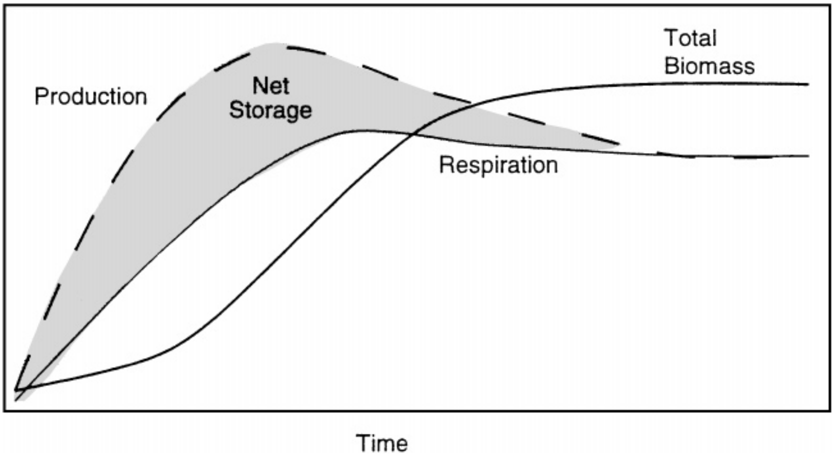

Figure 7 Total standing biomass and rates of production, respiration, and storage during succession in wild ecosystems. Adapted from Reference 14.

structural complexity, material storage, biogeochemical cycling, and energy efficiency (14).

Do urban ecosystems undergo a similar succession from highly productive regimes to steady states? If so, do they follow the strategy of ecosystem development? Industrialization is certainly a process of infrastructure and capital accumulation that results in greater structural complexity (12, 45). There is some evidence that economies of scale result in lower per capita energy flux in larger cities (6, 73). However, cities do not follow all the strategies of ecosystem development (191, 230). Biogeochemical paths become fairly straight relative to wild ecosystems, with very reduced recycling, resulting in large flows of waste and low total energy efficiencies. By contrast, in wild ecosystems, one population's wastes are another population's resources, and succession results in efficient exploitation of available resources. However, even modernized cities may still be in the earliest stages of a succession that may take centuries or millennia to complete.

Closing material cycles in urban ecosystems is rare, due predominantly to the lack of processes to reuse and recycle waste. In contrast, the detritus food web dominates wild terrestrial ecosystems. In many megacities such as Cairo, Calcutta, and Tokyo, informal waste handling by "rag pickers" recycles substantial resources from the otherwise linear solid waste streams (39, 40). In New York City, citizens are urging adoption of a full recycling program because the majority of solid wastes are recyclable (38). The government opposes recycling owing to handling costs and has proposed a waste-to-energy incineration project. Incineration is opposed by the citizens, who are concerned about toxic pollutants. Urban water cycles are similarly straightened for both storm and sanitary water. "State-of-practice" urban storm water management in industrialized cities treats runoff as a nuisance rather than an asset (116). Likewise, municipal wastewater reuse and recycling is still a novel proposal for most industrialized cities (228). Los Angeles is unique in its plan to reuse 40%, 70%, and 80% of sewage water by the years 2010, 2050, and 2090, respectively (251). Yet due to the energy intensity and therefore the cost of water treatment facilities, large-scale water reuse is currently unrealistic for most cities in developing countries (252). Clearly, megacities are not increasing biogeochemical cycling or efficiency with increasing development.

Whereas wild ecosystems achieve steady-state material fluxes through succession, urban energy and material flows continue to increase with development (253). This is because humans can supplement locally available energy and material sources from afar. Low-energy, dirty biofuels are replaced with higher-energy, cleaner fossil fuels as income increases; the situation is known as the energy ladder (62). Replacement happens on both the national (254) and household levels (55, 255). The growth of megacities also depends on large increases in motorized transportation, which increases with per capita energy use (61).

Interestingly, premodern cities may have approximated a climax state. Energy and food sources were strictly renewable, and transport time on foot limited the extent of a town's hinterland from which it could draw food, water, and fuel and recycle its waste (12). A town was built up until these local resources were maximally utilized. In analogy to wild ecosystems, urban infrastructure accumulated until maintenance costs equaled maximum local energy input. Modern cities have circumvented limits to local energy availability through teleconnection with remote sources of food, water, fuel, and materials. If modern urban systems are undergoing some form of succession, it is now at the earth system level. The climax will occur when global energy sources are maximally utilized, energy flux is at steady state, and infrastructure growth has ceased.

6.3 Open Areas of Research

The urban metabolism model suggests several important lines of inquiry. Data on energy and material fluxes at the city level are extremely scarce. Due to its dominance in mass budgets and importance to humans, the urban flux of water should be a prime focus for researchers. Virtually nothing is known about flows of food and construction materials through megacities, despite their significance to human sustenance and urban infrastructure. Energy budgets should include measures of system and end-use inefficiency. Mechanisms of system regulation, information flow, and feedback loops should also be investigated, both for understanding how urban systems function and for informing policy and management decisions. The recent establishment of urban long-term ecological research stations in Phoenix, Arizona (256), and Baltimore, Maryland (257), offers hope that this critical research will begin.

The urban ecosystem model offers a framework for studying other properties. Conversion of material flux into estimates of carbon, nitrogen, phosphorus, or sulfur flux is necessary for placing cities in the context of global biogeochemical cycles. For example, human nitrogen inputs to food production are some of the greatest fluxes in any ecosystem, often dwarfing wild nitrogen fluxes (10, 50, 161, 258). The role of cities in the global nitrogen cycle is still not well understood. The study of urban succession must be revived, as very little has been done since the pioneering and still advanced work using general systems theory (229, 230). Some recent interdisciplinary models are examples of much-needed research programs (192, 196).

A recurrent theme in our discussion has been that studies of aspects of the global city tend to focus tightly on individual urban areas. The typical intensive air quality study yields measurements for most of the species listed in Table 7 many times per day over several weeks. We have noted that Los Angeles and Mexico City receive close scrutiny of their air pollution inventories every few years in the form of field campaigns (69, 110, 159). Meanwhile, regional biogeochemical intensives remain sporadic. Geographic integration will be necessary if an earth system view is to be developed. Large, analytically unified data sets must be generated. Repetition of a standard protocol over a well-chosen subset of the megacities would facilitate pattern recognition.

An example from some of our own experience (DRB, FSR) demonstrates the potential of the approach. Students and staff from the atmospheric hydrocarbon measurement facility at the University of California at Irvine periodically descend upon large cities with quantities of evacuated canisters. The sample containers are opened at key locations such as known sources of pollution (roadways or landfills), or near representative demographic zones (downtown, residential areas, outskirts). Gas chromatography performed later separates and quantifies dozens of hydrocarbons (see Table 8). The various species are injected into the urban atmosphere by individual mechanisms with "fingerprints" that can be quantified based on chemical constituency and ratios. The measurements can serve as the basis for multivariate analyses. For instance, a one-week study of the Mexico City hydrocarbon distribution revealed the dominance of LPG leakage as a source for the C_3-C_4 alkanes and a selection of unsaturated (multiply carbon bonded) species (154). In Santiago, Chile, hundreds of canisters were filled at regular intervals over several days, for 25 sites situated evenly throughout a 5-km^2 grid. We are applying factor decomposition and chemical mass balance computations to deconvolve the methane source distribution for several of the megacities. LPG leak rates of 1%–10% computed for Mexico City (103) suggest that commercial gas systems will be difficult to maintain in developing areas. Preliminary data from a recent study in Karachi (a natural gas–driven city) (DR Blake & FS Rowland, unpublished) indicate very high urban additions to the free tropospheric CH_4 inflow. Leakage of natural gas has severe earth system implications because methane is a strong, direct greenhouse species (85).

Our urban data for methane have been interpreted from the global standpoint. A preliminary computation is presented in Table 9 (84). The manmade halocarbon CCl_3F is introduced to the troposphere almost exclusively from cities, and thus constitutes a reference tracer. It is among the chlorofluorocarbon compounds that were revealed as a threat to the stratospheric ozone layer in the mid-1970s (260). Usage is decreasing in the face of international regulation, but chlorofluorocarbon is still widely used as a refrigerant. Leakage from automobile air conditioners and landfills is a major fate. The global source strength of CCl_3F is not only dominantly urban, but is well documented because the compound is widely monitored and regularly inventoried (20). The ratio of methane to fluorocarbon added to the global city throughput thus provides a relative source strength. Urban areas add 30 to 60 megatons of methane per year worldwide. The total methane emission from human activity is on the order of 350 megatons per year (85, 261), with considerable uncertainty (262). Moreover, source distributions are poorly understood (263). More precise quantification of methane emissions from landfills (264) and urban vehicles (265) is occurring.

How do the urban methane emissions vary among megacities? Multivariate statistics and Chemical Mass Balance of the collective hydrocarbon data set will reveal differing source groupings for the variety of cities studied. We hope to quantitatively correlate the emissions structure with demographic, economic, and social factors to generate a global portrait of source distributions along urban growth trajectories. It should be possible to express global urban hydrocarbon emissions for the major source types as a function of state variables related to city population and infrastructure.

Satellite data on atmospheric composition are geographically integrative by their very nature (266, 267). Resolutions are increasing such that ozone and CO can be detected over many urban areas simultaneously. However, the satellite species set will be restricted to a few compounds. Ground-based field research will always be complimentary and required. Regional aircraft studies of tropospheric chemistry provide an example of the integrated approach necessary. The NASA Pacific Exploratory Mission series has continually shifted emphasis to new, ecosystem-scale portions of the atmosphere over the oceans (222, 223, 268, 269). Unlike most studies, interpretation of the results has been cumulative and integrative.

Future developments in air quality modeling have been anticipated by many authors. The geographical domain must be extended to encompass multiple urban areas because they often lie upwind of one another and thus interact. Regional atmospheric composition models have usually been uniform in their gridding and represent city plumes parametrically (113, 114). Several nested urban grids may be inserted into the mesoscale mesh. This method has been envisioned for the Boston-Washington corridor on the U.S. eastern sea board (101). In global change biogeochemistry simulations, it will be important for individual urban areas to evolve demographically and economically. One physical location (i.e. a city in some number of grid cells) may move through several stages of economic growth. Feedbacks from the photochemical and aerosol system into the meteorology are only beginning to be included (125). It has been possible to ignore these effects in the small, clean cities of the developed world, but they will be prominent in the developing megacity regions where oxidants, absorbing gas phase species (NO_2), and the multiply scattering aerosol haze are pervasive.

TABLE 9 Urban tropospheric concentrations of CH_4 and CCl_3F[a]

		Concentrations[b]					Urban Excesses Fractional			
		CH_4		CCl_3F						
Location	**Date**	**U**	**R**	**U**	**R**	**RAI**	**CH_4**	**CCl_3F**	**RFI**	**CR**
Santiago, Chile	1/20/80	1.59	1.51	204	165	2100	0.053	0.24	0.22	0.15
Rio de Jan., Brazil	1/26/80	1.72	1.51	236	165	3000	0.14	0.43	0.32	0.22
Paramaribo, Surinam	2/01/80	2.44	1.61	474	165	2700	0.52	1.87	0.28	0.18
Cracow, Poland	5/08/80	3.42	1.65	599	180	4200	1.07	2.33	0.46	0.31
Warsaw, Poland	5/09/80	1.96	1.65	422	180	1300	0.19	1.34	0.14	0.09
London, England	7/25/80	2.02	1.62	564	184	1200	0.25	2.07	0.12	0.08
London, England	7/25/80	2.03	1.62	509	184	1300	0.25	1.77	0.14	0.09
Copenhagen, Denmark	8/01/80	1.68	1.60	455	182	300	0.05	1.50	0.03x	0.02
Copenhagen, Denmark	8/01/80	1.69	1.60	470	182	200	0.06	2.13	0.03	0.02
São Paulo, Brazil	8/13/80	1.66	1.52	226	175	2700	0.09	0.29	0.32	0.22
Santiago, Chile	8/21/80	1.69	1.52	251	175	2200	0.11	0.43	0.26	0.17
Beijing, China	9/16/80	1.65	1.62	197	182	2000	0.02	0.08	0.25	0.16
Dalian, China	9/22/80	1.67	1.62	209	182	1900	0.03	0.15	0.02	0.13

Ketchikan, AL, USA	11/22/80	1.92	1.63	329	189	2100	0.17	0.68	0.25	0.17
New York City, USA	2/20/81	1.91	1.64	590	193	700	0.17	2.06	0.08	0.03
Rio de Jan., Brazil	6/14/81	1.62	1.53	192	175	5000	0.06	0.10	0.60	0.40
Hamburg, Germany	8/22/83	1.83	1.67	353	210	1100	0.10	0.68	0.14	0.10
Hamburg, Germany	8/24/83	1.82	1.67	317	210	1400	0.09	0.51	0.18	0.12
London, England	9/09/83	1.75	1.67	318	210	700	0.05	0.51	0.09	0.06
Brussels, Belgium	9/16/83	1.70	1.67	378	210	200	0.03	0.80	0.04	0.03
Rome, Italy	11/09/83	2.16	1.67	894	210	700	0.29	3.26	0.09	0.06
Rome, Italy	11/10/83	1.93	1.67	837	210	400	0.16	2.99	0.05	0.03

[a]Abbreviations: U, urban location; R, remote location; RAI, Ratio of absolute increase in CH_4 to absolute increase in CCl_3F; RFI, Ratio of fractional increase in CH_4 to fractional increase in CCl_3F; CR, Ratio of fractional increase corrected for total atmospheric burden by yearly release in 1980: $CH_4 = 10$, $CCl_3F = 15$.

[b]Concentrations of CH_4 in ppmv (10^{-6}) and of CCl_3F in pptv (10^{-12}).

Modeling the feedbacks between social forces and emissions is also imperative. Links are evident in Los Angeles and London, where significant progress in reducing particulate levels has been achieved. Behavioral models of the process by which health and visibility degradation influence urban evolution are currently unsophisticated. However, studies of this connection will be central to earth system simulations of urbanization. Some cities reach their pollution prime and begin to solve local air quality problems before they reach megacity status. Tokyo and Los Angeles have followed this sort of trajectory (1). Often, however, megacities continue to grow without addressing pollution issues. It may be possible to quantify demographic and economic factors distinguishing the many trajectories for urban growth. Synthetic databases and analyses thereof would be needed. The effects of politics and war will long remain unquantifiable. For example, urban environments of Moscow and other large cities of the former Soviet Union continue to degrade, despite or because of the transition to capitalism (270).

Linkage of realistic atmospheric, social, economic, and biogeochemical models lies on the horizon. Global integration looms as well. Biogeochemical and ecological simulations of cities are rare and generally do not correspond with the locales of greatest global import. We envision that integrated models of the several urban subsystems—metabolic, demographic, atmospheric, and economic—will evolve rapidly in the next century.

In summary, there is a need for integration of both measurements and models at the city level, and for connecting city level processes to the earth system level. Our review suggests that all major aspects of the urban system deserve synthetic, cross-cutting examination. Synthesis will require that scientific resources be allocated to the construction of well-organized and accessible databases. Much of the required information must be generated afresh, through observation and simulation. Furthermore, resources must be made available for interdisciplinary interpretation. Although complete investigations of megacity metabolism will be difficult to design and implement, we submit that much progress can be made in the near term through data scavenging. For example, we can attest that air quality, water quality, and demographic data are present in excess; they accumulate faster than they can be integrated. Here several data synthesis centers provide guidance. In the past decade, the U.S. National Science Foundation formed National Centers for Geographic Information and Analysis (NCGIA) and Ecological Analysis and Synthesis (NCEAS). They excel in fostering collaborative research, synthesis of existing data, and production of large public domain datasets. Both NCGIA (271) and NCEAS (272) manage a wide range of projects across multiple subfields and at many scales. They have quickly become international hubs of exciting research and synthesis.

These research agendas will provide much-needed information on the structure, function, and dynamics of urban ecosystems. Attention to megacities is imperative for analyzing the logical conclusion of present trends of global urbanization: a world of megacities. Data and models on urban metabolism will be crucial for comparisons of wild and urban ecosystems. Such research should provide insight into ways that urban ecosystems can become more sustainable, as wild systems are inherently more stable and sustainable than their human-built counterparts (273).

7. CONCLUSIONS

With nearly half of the world's six billion people living in cities, understanding the energy and material processes of urban systems is imperative for facing the social, environmental, and energy challenges of the next century. The impact of megacities on global biogeochemical cycling and ecological processes remains grossly understudied.

We have attempted to review the available data and models on energy and material flows through the world's megacities. Aside from the fact that they tend to be ports along coastlines, climatic and socioeconomic generalizations are not apparent. Modern technology and teleconnection is helping humans overcome ecological constraints on building massive cities in a variety of locales with a broad range of ecological, historical, economic, and political conditions.

The flux of water stands out as the dominant material flux across megacities, comprising up to 90% of all material entering the system. Increasing urban water demand will require passive inputs of water to be treated as a resource, necessitating changes in water management infrastructure. Little is known about gross food consumption in any individual global city, yet the flow of food is likely to have a great impact on the nitrogen cycle and on solid waste accumulation. Comparison of fuel flows among megacities shows large variation in both quantity and breakdown by fuel type. Nonetheless, there is a strong trend of movement up the energy ladder towards cleaner fuels and increasing automotive fuel use. It is clear, however, that the earth system is being severely degraded as cities climb up the ladder using current technologies and vast quantities of fossil fuels.

Atmospheric pathways surface as the most important for understanding impacts of megacities on neighboring ecosystems and at the earth system level. Since most megacities lie in temperate regions of the northern hemisphere, their plumes are geostrophic (westerly). In developed cities, fuel use in automobiles has the largest impact on atmospheric fluxes of nitrogen and carbon. Emissions from urban systems are defined by pollution chemistry but depend critically on infrastructure factors—fuel distributions, agricultural inputs, construction, and the treatment of animal excrement. Most studies of urban air focus on individual cities. Cross-cutting field research and integrative data analysis are urgently needed.

The analogies of urban metabolism and succession suggest that modern urban systems will only reach a climax state at the earth system level. Currently, succession in the urban ecosystem is a process of growth, industrialization, and increased energy use. Whereas preindustrial towns achieved a steady state with local renewable resources, modern megacities will only begin to climax when global fossil fuel reserves are exhausted and global water and food resources are maximally utilized. Analysis of urban metabolism and succession will provide critical information about energy efficiency, material cycling, waste management, and infrastructure architecture in urban systems.

To conclude, we propose a comprehensive research agenda for the urban ecosystem. It begins with correlating input and output variables from tables such as those presented here. Results can be used to predict material and energy fluxes for arbitrary cities in a biogeochemically useful way. A gridded, regional, time-dependent model of material flows through cities should then be developed. It should demonstrate urban growth and evolution and include stored, transformed, and passive inputs. This model can then be used to determine a set of state variables and construct a biogeochemical theory of city composition and structure. Finally, models and data should be used to quantitatively consider the earth system level climax state we appear to be approaching. If such a state is reached, insight from the structure and function of wild ecosystems will be essential for insuring the stability and persistence of urban ecosystems.

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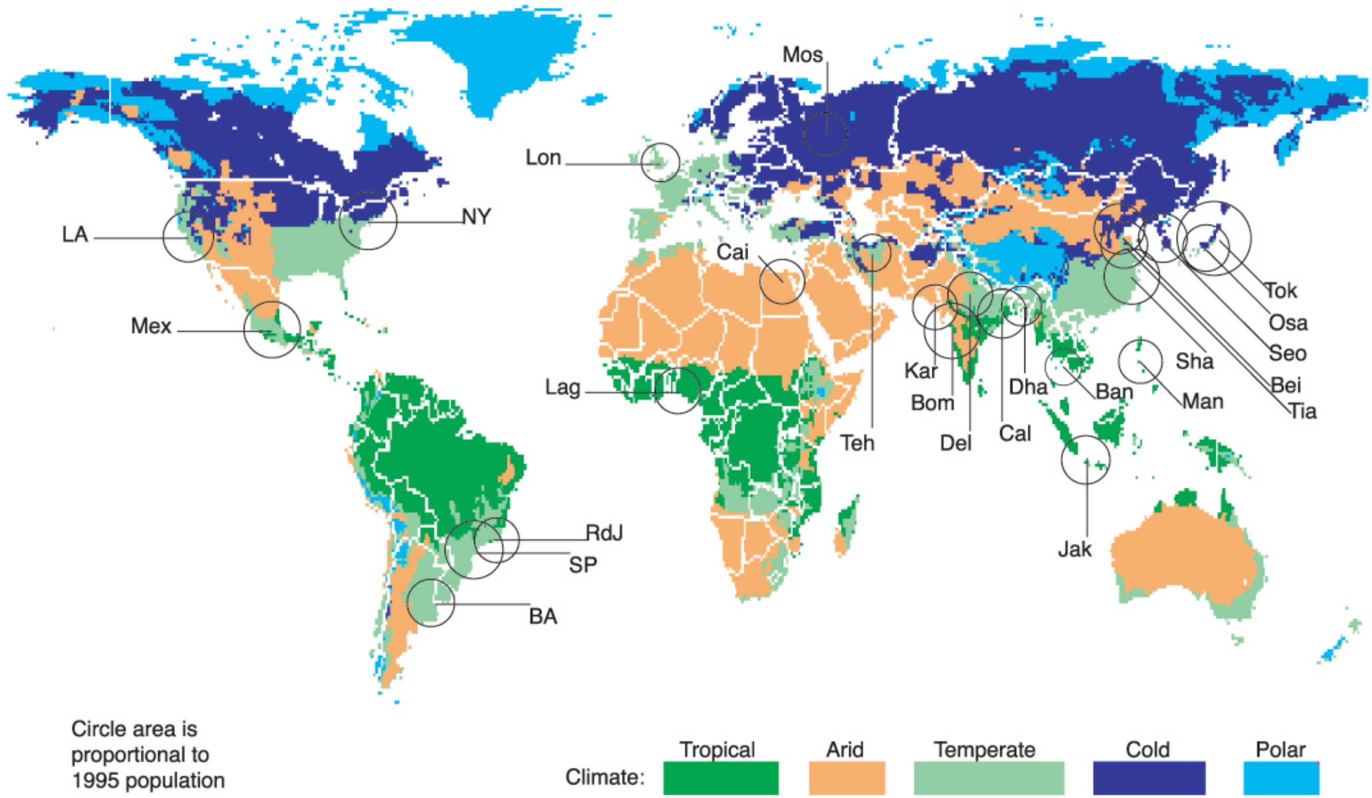

Figure 1 Location and relative size of the world's 25 largest cities.

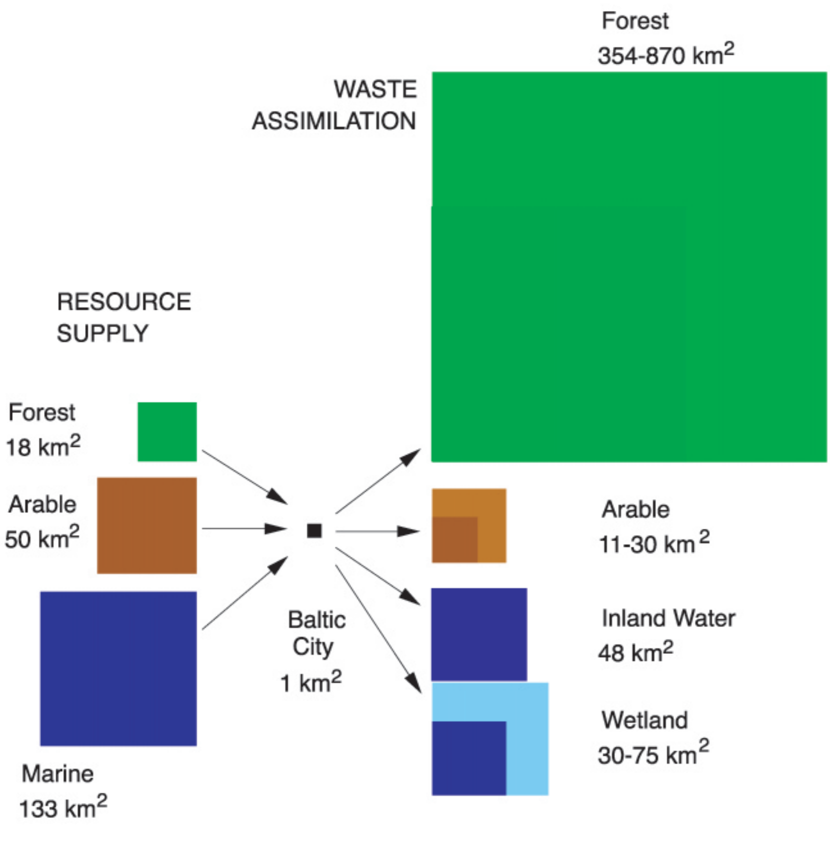

Figure 6 Ecological footprint (in km^2) for the 29 largest cities of Baltic Europe, shown per km^2 of city. Resource supply footprint is calculated as the area needed to provide selected renewable resources: wood, paper, fibers, and food, including seafood. Fresh water is not included. Waste assimilation footprint is calculated as the area needed to absorb the nitrogen, phosphorus, and carbon dioxide emissions from cities. Adapted from Reference 246.

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