Metabolism of Neighborhoods

Natalia Codoban[1] and Christopher A. Kennedy[2]

Abstract: Analysis of urban metabolism has been established as an appropriate approach for assessing the sustainability of cities. A desirable next step is to use the metabolism as a guide to *designing* more sustainable cities. This study provides an analysis of the metabolism of four representative Toronto neighborhoods. The annual energy consumption for buildings and transport is determined to be from 57 to 107 GJ/capita and from 0.5 to 9.2 GJ/capita, respectively. The annual consumption of food and water is found to be 1,100 and 92,300 kg/capita. The findings of the study have implications for the design of sustainable neighborhoods. This includes the construction of energy-efficient buildings, development of public transit, and encouragement of residents to replace inefficient water fixtures. More advanced methods might consist of growing the urban forest using nutrients from wastewater, and converting solar energy to building operational energy

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Introduction

With increasing global population and urbanization, it is evident that urban landscapes have changed nature in such dramatic fashion that the natural capital and stable climates upon which societies rely are seriously under threat. The metabolism of cities—the inflows of water, energy, and materials, and outflows of wastes—have increased dramatically in recent decades (Kennedy et al. 2007). With approximately half the world's population living in cities (United Nations 2003), redesigning and reconstructing urban habitat is central to addressing crucial global environmental issues.

The concept of an urban metabolism provides a rigorous and comprehensive basis by which to characterize the flows of resources and residuals associated with cities. Introduced by Wolman (1965), urban metabolism studies of real cities began in the early 1970s (Duvigneaud and Denayeyer-De Smet 1975; Hanya and Ambe 1976; Newcombe et al. 1978) and have been pursued with renewed interest since the late-1990s (Baccini 1997; Newman 1999; Hendriks et al. 2000; Warren-Rhodes and Koenig 2001; Gasson 2002; Sahely et al. 2003). A full description of an urban metabolism quantifies flow and stocks of water, energy, materials, and nutrients/biomass for an urban system, typically in annual terms (Baccini and Brunner 1991; Kennedy et al. 2007).

With the urban metabolism established as an appropriate tool for assessing the sustainability of cities, a desirable next step is to use the metabolism as a guide to *designing* more sustainable cities. Indeed such an approach has been proposed in the Netzstadt method of Oswald and Baccini (2003). In increasingly resource limited cities this would mean adopting technologies and reconstructing urban morphology so as to achieve a sustainable metabolism.

In many respects the unsustainable nature of contemporary cities is a consequence of poor planning at the micro or neighborhood level (Berg and Nycander 1997; Churchill and Baetz 1999). The development of a sustainable neighborhood requires strategies that promote: green buildings; integrated water systems; cycling, pedestrian, and transit friendly design; urban forestry; local energy production; and neighborhood waste management. Developing sustainable neighborhoods also helps to achieve sustainable urban form at the macro level (Kennedy et al. 2005). There are, however, many constraints to neighborhood design, including competition for space between different infrastructure elements. Thus, an integrated approach to neighborhood design is essential (Engel-Yan et al. 2005).

In order to design sustainable neighborhoods, it follows that we need to study the urban metabolism at the neighborhood scale. There have been some studies of Swiss household metabolism, which help towards this objective (Baccini and Brunner 1991; Brunner and Rechberger 2003). Otherwise, studies of neighborhood metabolism are seemingly absent.

As a first approximation, the neighborhood metabolism might be determined as a population weighted fraction of a whole urban metabolism. Yet, this might be quite inaccurate for construction materials; most cities are in a continual state of construction, but neighborhoods may not be. It is necessary to distinguish between the metabolism of neighborhoods as they are under construction and those that are already built. Moreover, the era of construction, proximity to city center, and other factors such as average income, will cause the metabolism of neighborhoods to be quite heterogeneous across a city.

The aim of this paper is to establish the metabolism of a typical Toronto neighborhood and where data are available determine how aspects of the metabolism vary between representative neighborhoods. In all cases, we are concerned with neighborhoods that are already built, so no construction materials are

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[1] Graduate Student, Dept. of Civil Engineering, University of Toronto, Toronto ON, Canada M5S 1A4. E-mail: natalia.codoban@utoronto.ca

[2] Associate Professor, Dept. of Civil Engineering, University of Toronto, 35 St. George St., Torontot ON, Canada M5S 1A4 (corresponding author). E-mail: christopher.kennedy@utoronto.ca

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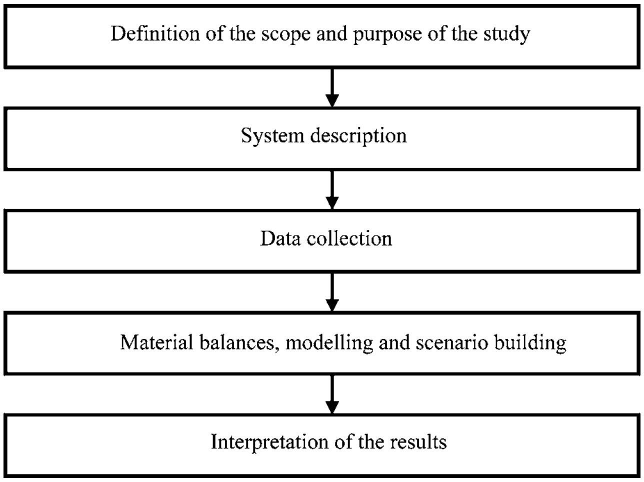

Fig. 1. Main methodological steps of material flow analysis

quantified. Reliable data on flows of goods such as furniture, electronic items, clothing, and textile products, etc. have not been determined. Thus the focus of the study is specifically on the flows of energy, water, and food in the neighborhood metabolism.

There are a few other limitations to the study. Year 2000 is chosen for the study due to the availability of data, but in some cases Toronto data, such as for building energy consumption and transportation, have been inferred from other years. For some fine details of the metabolism, such as retail food waste and cooking water consumption, Toronto specific data were not found, so estimates are taken from studies elsewhere. Finally, the water and food data are not sufficiently spatially disaggregated to show differences between Toronto neighborhoods and are only assessed on average.

The outline of the study is as follows. The methodology, based on material flow analysis, is followed by the results of food, water, and energy flows through Toronto neighborhoods. The discussion of the neighborhood metabolism and recommendations on how to design sustainable neighborhoods conclude the paper.

Methodology

Material flow analysis (MFA) is employed in the study to establish the metabolism of Toronto neighborhoods. MFA has been used to evaluate the metabolism of regions and households since the early 1990s (Baccini and Brunner 1991; Brunner and Rechberger 2003). In this study, MFA is used to explore the flows of energy, water, food, and wastes in Toronto neighborhoods. Balances of energy, water, and food are performed to determine the energy and materials consumed and wastes generated.

The use of MFA in this study follows a standard five step process (Fig. 1). The goals and the scope of the study are defined in the "Introduction." The study system and data collected are described in this section. Material balances are established in "Results," and interpretation of the MFA results is presented in "Discussion and Conclusions."

The MFA terminology is used throughout the study. A "system" denotes a set of material flows, stocks, and processes within a defined boundary. "Goods" represent entities of matter with a positive or negative economic value; and an "activity" denotes a set of flows, stocks, and processes of the materials that are necessary to carry out a particular human need. "Flow" and "flux" mean a mass flow rate and a flow per "cross section," respectively. The study system, data, and calculations performed are explained in more detail below.

System Description

The system "Neighborhood" is shown in Fig. 2. This diagram is a conceptual representation of processes studied for four representative Toronto neighborhood design types for the year 2000. Trinity-Bellwoods, Don Valley Village, Milliken, and Crescent Town neighborhoods are chosen to represent prewar and postwar suburban, contemporary urban, and suburban neighborhood design types, respectively. The postwar and contemporary suburban neighborhoods can be distinguished by their relatively low residential density, homogeneity, curvilinear wide streets, and separation of land uses. The contemporary suburbs have smaller parcel sizes and a slightly higher density compared to postwar suburban developments (Fletcher Marsden et al. 2000). Prewar suburban and contemporary urban neighborhoods have high residential density (Table 1), but due to a different development structure. Trinity-Bellwods lots are small and the buildings—duplexes, townhouses, multiunit low-rise buildings, and single detached houses—occupy a large percentage of the lot area (Wright 2000). Crescent Town is composed predominately of apartment buildings with five or more stories (City of Toronto 2004b). As a result of these specific design characteristics, the neighborhoods are expected to have different metabolism.

Three particular metabolic processes within neighborhoods are studied: operation of buildings; preparation and consumption of meals and beverages; and transportation (Fig. 2). Calculations are performed using "average" households and the estimates are normalized on a per capita basis. The inflows to neighborhoods include water, food, electrical, and fossil fuel energy; the outflows are solid waste and wastewater. The energy balance in the urban environment where the incoming net all-wave radiation equals the outgoing sensible, latent, and anthropogenic energy is recognized but not analyzed in the study. The energy dissipated from buildings and transport may have a contribution to the urban heat island (Oke 1987; Taha 1997).

Data Acquisition

The biggest challenge of this study was to find reliable data. Some of the current information on consumption of water, food, and energy at the neighborhood level is scarce and therefore the metabolism of neighborhoods is established with the data available. For the system defined above, data are collected from various sources. Efforts were made to use data from the same source for 2000, but because such data are not always available, some calculations are performed with 1990–2001 data.

Neighborhood data are obtained from the Neptis Foundation (Wright 2000), Maple Tree Publishing (1999), and City of Toronto (City of Toronto 1999; 2004b). Food calculations are performed with data from Statistics Canada (2004), SImetric (2006), and United States Department of Agriculture (2006). Food waste, water and wastewater data are taken from the City of Toronto reports (City of Toronto 2001a,b, 2004a, 2005c,d). Ontario residential waste data (Ministry of Environment 2004) are used to calculate Toronto residential food waste. The building energy data are obtained from the CREEDAC database (CREEDAC 2000) and from a study by Torrie Smith and Associates (1997). The transportation data are from Kennedy (2002) and the Transportation Tomorrow Survey (University of Toronto 2003).

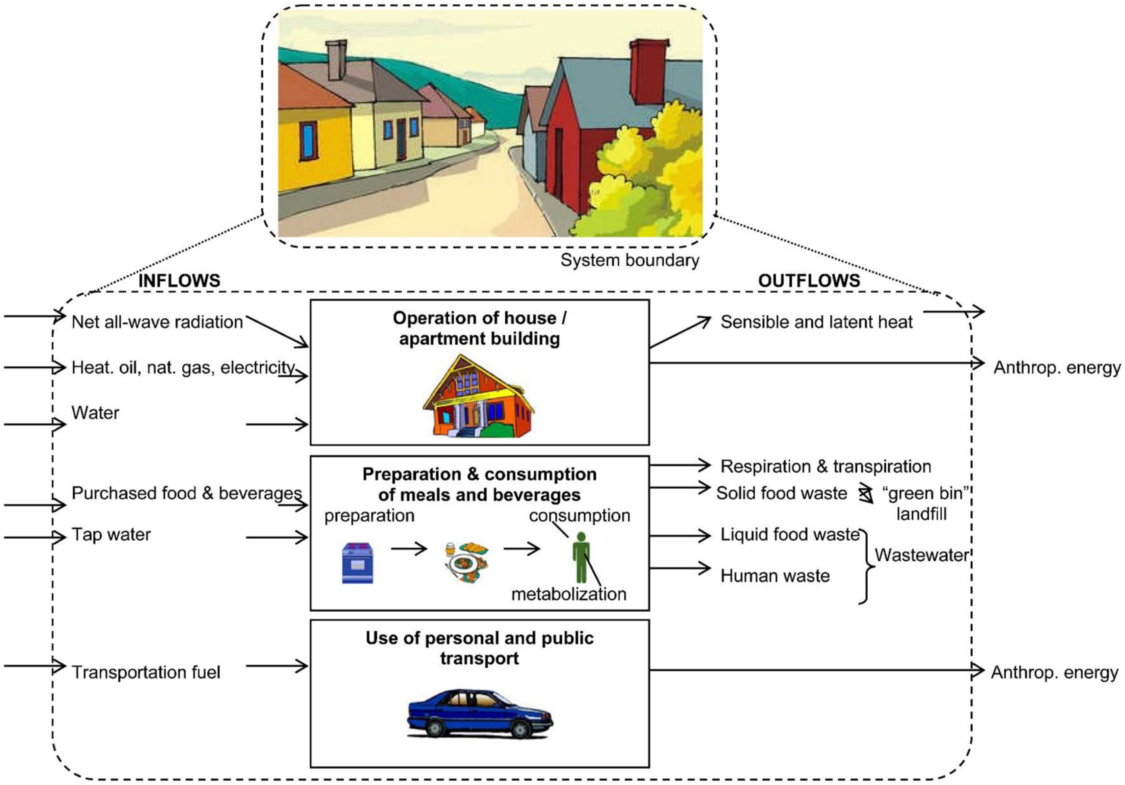

Fig. 2. Key metabolic processes of study system of Toronto neighborhoods

Where Canadian data were not available, data for other countries were referred to. Data on cooking water consumption and wastewater generation are adapted from Baccini and Brunner (1991) and Brunner and Rechberger (2003). Calculations of food energy consumption by the human body are performed with data from Baer et al. (1996), Schwartz (2003), Warwick and Baines (2000), and Warwick (2005). Toronto retail food waste is estimated with New York data (NYC WasteLe$$ 2006).

Material Balance

The mass conservation principle is applied to analyze processes in the study, according to which the mass of inputs in a process equals the mass of outputs plus a storage term

$$\sum_p \dot{m}_{\text{input}} = \sum_q \dot{m}_{\text{output}} + \dot{m}_{\text{storage}} \tag{1}$$

where m=mass; p and q represent summation over the inputs and output terms; and time derivatives are denoted by dots.

As no accumulation of energy, water, and biomass occurs in the system annually (i.e., $\dot{m}_{\text{storage}}=0$), the outflows of energy, water, and food are equal to the inflows (Fig. 2).

Results

Food

Two challenges in the analysis of food flows were to determine the amounts of food entering households (both consumed and wasted) and to understand how the energy in food passes through the human body. In the analysis, the term "food disappeared" means food entering grocery stores, where the weight is adjusted for processing and storage losses that occur before food appears in stores (Statistics Canada 2004).

Meals and Beverages Consumed

Two components of the food flow, beverages and meals, are analyzed separately in the study. It is estimated that about

Table 1. Characterization of Study Neighborhoods

Study neighborhood	Neighborhood design type	Land area (ha)	Density (dwelling/ha)[a]
Trinity-Bellwoods	Prewar "streetcar suburban"	172[b]	37
Don Valley Village	Postwar suburban	450[b]	21
Milliken	Contemporary suburban	280[c]	26
Crescent Town	Contemporary urban	25[c]	254

[a] Calculated with number of dwellings (City of Toronto 2004b) and land area (column 3).

[b] Wright (2000).

[c] Estimated with easy-to use *Toronto Region Map Guide* (2005).

Table 2. Food Consumed in Canada in 2000

Food group	Food description	Dry matter content of food purchased[a] (%)	Food disappeared[b] (kg/year/capita)	Food consumed[b] (kg/year/capita)	Food losses[c] (kg/year/capita) (% of food disappeared)
Cereals	Cereal products	88	88.6	65.3	23.3 (26)
Fruits	Fruits fresh and processed (fresh equiv.)	15	81.2	50.5	30.7 (38)
Vegetables	Vegetables fresh and processed (fresh equiv.)	15	183.4	112.0	71.4 (39)
	Pulses	86–94[h]	7.7	6.8	0.9 (12)
Meat	Red meat	35	64.0	28.3	35.7 (56)
	Poultry	30	35.3	13.2	22.1 (63)
Seafood	Fish	20	9.5	6.7	2.8 (30)
Dairy	Milk[d]	12	91.3	67.5	23.8 (26)
	Cheese	60	12.1	8.9	3.2 (26)
	Other dairy	12–60	24.1	5.1	19.0 (79)
	Eggs[e]	25	9.2	7.5	1.7 (19)
Other	Sugars and syrups	90–99	40.8	30.5	5.5 (25)
	Oils and fats	99	30.7	22.0	8.7 (28)
	Tree nuts	75–85[i]	1.5	1.3	0.2 (13)
	Alcoholic beverages[f]	10	102.2	99.5	2.7 (3)
	Nonalcoholic beverages (including bottled water)[g]	0.5 (water), 10 (beverages)	339.4 (26.7 is water)	302.7 (23.7 is water)	36.7 (11)
Total			**1120.9**	**827.8**	**288.4**

Note: Totals may not add up due to rounding.

[a] Baccini and Brunner (1991).

[b] Statistics Canada (2004).

[c] Calculated from columns 4 and 5.

[d] Calculated with the milk volume (Statistics Canada 2004) and the average milk density (SImetric database 2006).

[e] Calculated with the eggs' quantity (Statistics Canada 2004) and the weight of medium-sized egg (Burnbrae farms database 2006).

[f] Calculated with the volume of alcoholic beverages (Statistics Canada 2004), average alcohol content by volume, ethyl, and water density at temperatures equal to or higher than 4°C (SImetric 2006).

[g] Calculated with the volume of nonalcoholic beverages (coffee, tea, etc. from Statistics Canada 2004) and the water density at temperatures equal to or higher than 4°C (SImetric database 2006).

[h] United States Department of Agriculture (2006).

[i] Billings (1998).

865.2 kg/capita of water is consumed annually by the human body. This includes 302.7 kg/capita of beverages purchased (Statistics Canada 2004) and 244.8 kg/capita of water used to prepare additional beverages in households (Health Canada 2004; Baccini and Brunner 1991).

The results of the meal analysis are presented in Table 2. They demonstrate that the major portion of food entering grocery stores (1,120 kg/capita) is eventually ingested by the human body (830 kg/capita). This includes vegetables (120 kg/capita), dairy (90 kg/capita), cereal (65 kg/capita), fruits (50 kg/capita), meat (42 kg/capita), seafood (7 kg/capita), and other products (456 kg/capita). The results also suggest that only 55% (303 kg/capita) of water ingested by the human body comes from purchased beverages, the rest 45% (245 kg/capita) comes from beverages prepared inside households. As a result of the high-fat and high-fiber diet, Canadians consume about 4.3 GJ/year (Statistics Canada 2004). The food energy utilization in the human body is described in detail below.

Human Metabolism

The adult human body ingests food mainly to maintain the energy metabolism rather than to produce biomass, as shown in Fig. 3. The ingested food energy (Point 1) is partly lost in fecal energy (FE). Most of the absorbed energy is then available for the human consumption (Point 2), except for the urinary energy (UE), surface energy (SE), hair, skin, and other secretions. Point 3 is the traditional definition of the metabolizable energy—"old metabolizable energy" (OME). Several studies demonstrate that some of the energy that reaches the large intestine undergoes microbial fermentation, increasing the microbial mass. The energy of microbial mass is lost as fecal matter and is accounted for in FE losses (Warwick and Baines 2000). Point 4 reflects the metabolizable energy (ME), which is the energy available for total heat production and body gains (tissue or milk synthesis, energy stores) and includes the heat of fermentation. Heat produced during the processing of ingested nutrients contributes to thermogenesis, the energy expenditure that is stimulated by food, cold, drugs, and hormones, and that cannot be attributed to basal metabolism or physical activity.

The net metabolizable energy (NME) is available to the body (Point 5) after the heat produced during fermentation and obligatory thermogenesis from ME is deducted. Net energy (NE) on Point 6 is the energy that the body can use to support the basal metabolism and physical activity. NE is also spent on body tissue gains, any increases in energy stores, growth of the fetus during pregnancy, production of milk during lactation, and energy losses in synthesis/deposition processes of new tissues or milk (FAO

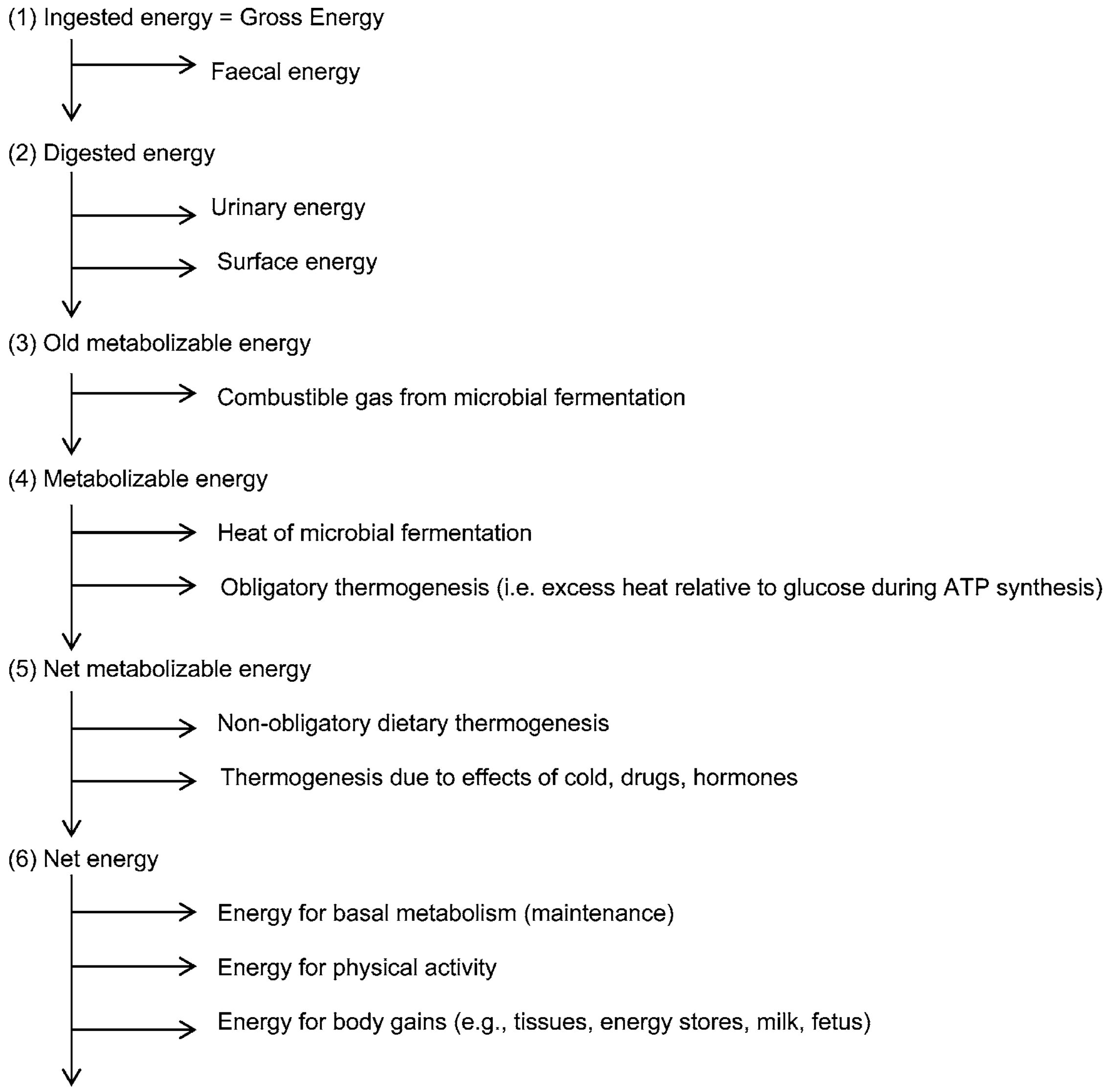

Fig. 3. Overview of food energy utilization (adapted from FASEB 1994 and Warwick and Baines 2000)

2003). In this paper, the ME rather than the NME energy is considered, as only the energy consumed and lost from the human body is essential for the goals of the study. Based on the United States data (Baer et al. 1996) it is estimated that Canadians excrete 0.3 and 0.2 GJ/year in feces and urine annually.

On a mass basis, air is the most important export path of human byproducts. About 51% (550 kg/capita) of byproducts are exhaled in transpiration and respiration gases, while 41% (440 kg/capita) and 8% (84 kg/capita) are excreted in urine and feces (ASPI Publications 1990; Baccini and Brunner 1991). On a dry mass basis, only 70 kg/capita/year of carbon is being exhaled from the body in the form of carbon dioxide. The mass of gaseous byproducts, which is determined here by subtracting urinal and fecal amounts from the amount of food ingested, is in the expected range of 440–2600 kg/capita (Baccini and Brunner 1991).

Food Waste

The mass of food wasted in retail stores was determined in order to calculate the mass of food and beverages purchased by households. Retail food waste mass of 14.3 kg/capita is estimated with Toronto population and nonresidential waste amount generated in 2000 (Statistics Canada 2005, City of Toronto 2001b), and average New York retail food waste amount (NYC WasteLe$$ 2006). This estimate is equivalent to 5% of nonresidential waste mass, which is reasonable, given that the organic part of Ontario nonresidential waste is 11%, and waste from restaurants and retail food establishments is higher than from other sources (Ministry of Environment 2004). Although the New York statistics are used here due to a lack of Toronto data, the estimate of food waste does not significantly affect the calculation of the mass and energy content of purchased food, since the amount of retail waste (14.3 kg/capita) is much smaller than the amount of food disappeared (1,120.9 kg/capita).

Residential food waste is estimated to be 87.5 kg/capita, based on the residential waste composition (Ministry of Environment 2004), Toronto population, and solid residential waste collected in 2000 (Statistics Canada 2005, City of Toronto 2001a). Of this amount, only 27.0 kg/capita was diverted to compost, the rest (59.5 kg/capita) was sent to landfills (City of Toronto 2001a, 2004a). (Organic composting in Toronto has subsequently increased.) The energy content of food waste diverted and landfilled are 0.1 and 0.3 GJ/capita; the dry masses are 8.1 and 17.9 kg/capita, respectively (Tchobanoglous et al. 1993). The food liquid

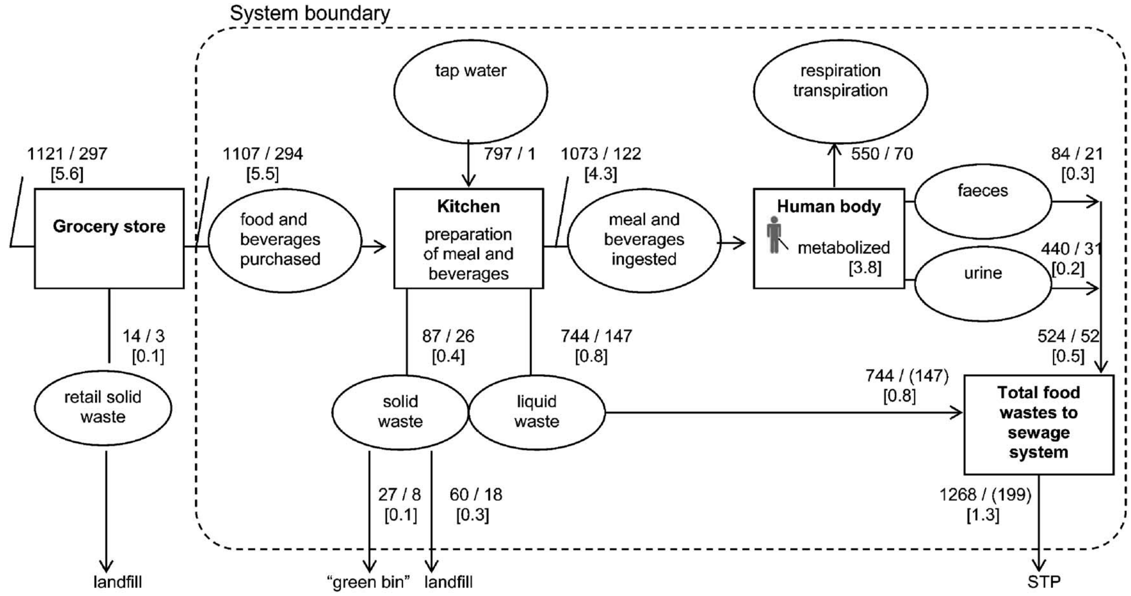

Fig. 4. Mass and energy flows of goods associated with activity *to nourish* in Toronto households in 2000. Figure on food input includes food consumed outside of home. Numbers indicate mass/dry matter (kg/capita/year); energy content is presented in square brackets (GJ/capita/year). STP denotes sewage treatment plant; GJ denotes Giga Joules, where 1 $GJ=10^9$ J. Note: Total amounts may not add up due to rounding.

waste of 743.8 kg/capita is estimated based on the mass balance of food and beverages purchased and tap water consumed for the body nourishment and also on resulting solid food and human waste. The results of food waste analysis show that the most significant food losses occur in the liquid waste (743.8 kg/capita, 0.8 GJ/capita).

Summary of Food Flow Analysis

The overall results demonstrate that the human body metabolizes 70% of energy in food and beverages that enter households (Fig. 4). Smaller amounts of food energy are transferred into liquid food waste (15%), solid food waste (9%), and human waste (7%). On a mass basis, about 44% of food does not nourish the human body, but leave the household as liquid (39%) and solid wastes (5%).

The findings of the food flow analysis are consistent with those of other studies. In particular, the solid food waste of 87 kg, which is 8% of purchased food and beverages, is in the expected range of 5–10% (Brunner and Rechberger 2003). The portion of liquid food waste that comes from purchased food and beverages (192 kg; 17%) is slightly below the expected 20–25%. Urine dry matter (31 kg) is higher than that of feces (21 kg), which is expected as the bulk of urine is made up of water-soluble salts, with high dry matter content; the fecal mass consists of organic substances (Baccini and Brunner 1991). The major portion of dry matter that enters a household (295 kg) is carried by the liquid waste flow (147 kg) rather than by the human byproducts (122 kg), which can be explained by the high dry matter content of cooking water, disposed through the kitchen sink.

Water

The results of the water flow analysis are presented in Fig. 5. The wastewater mass inside the households (i.e., excluding water used in gardens/yards) is estimated with masses of water and materials which enter the water stream during the processes: "Kitchen," "Toilet," "Personal care," "Laundry," and "Cleaning." Calculations are performed with data from Baccini and Brunner (1991), City of Toronto Works and Emergency Services (2002) and Environment Canada (2001). The dry matter of water is assumed to be 500 g/m^3, which is the maximum acceptable concentration of total suspended solids in Canadian drinking water (Tchobanoglous and Schroeder 1985). The results of the analysis show that on a wet basis the water mass incoming to households (92,300 kg/capita) is bigger than the wastewater mass (83,600 kg/capita). This is expected, as about 10% of incoming water mass is lost in leaks (City of Toronto 2005c). It is interesting to observe that 48,000 kg/capita of water is used to clean merely 7 kg/capita of skin waste and 8 kg/capita of waste from clothing, whereas 25,900 kg/capita of water remove 128 kg/capita of feces and urine in toilets!

The energy content of household wastewater is determined to be 1.3 GJ/capita, calculated with the energy amounts of wastewater from kitchens and bathrooms. The energy content of skin and dirt waste is not estimated in the study due to a lack of appropriate data, but this has a negligible impact on the overall wastewater energy estimate. The estimate of household wastewater of 1.3 GJ/capita agrees with the wastewater energy of the Don Valley treatment plant in Toronto (1.0 GJ/capita). To calculate the wastewater energy entering this plant, the energy content of municipal wastewater (Shizas and Bagley 2004), the flow rate and the number of residents served by the plant are used (City of Toronto Works and Emergency Services 2004).

Energy

The results of the energy flow through neighborhoods includes the energy consumption in buildings and transportation. The natural energy balance by which 1.8 $GJ/m^2/year$ (John Cuddihy, personal communication, July 2005) of incoming net all-wave radiation is dissipated along with anthropogenic waste heat is acknowledged but not studied.

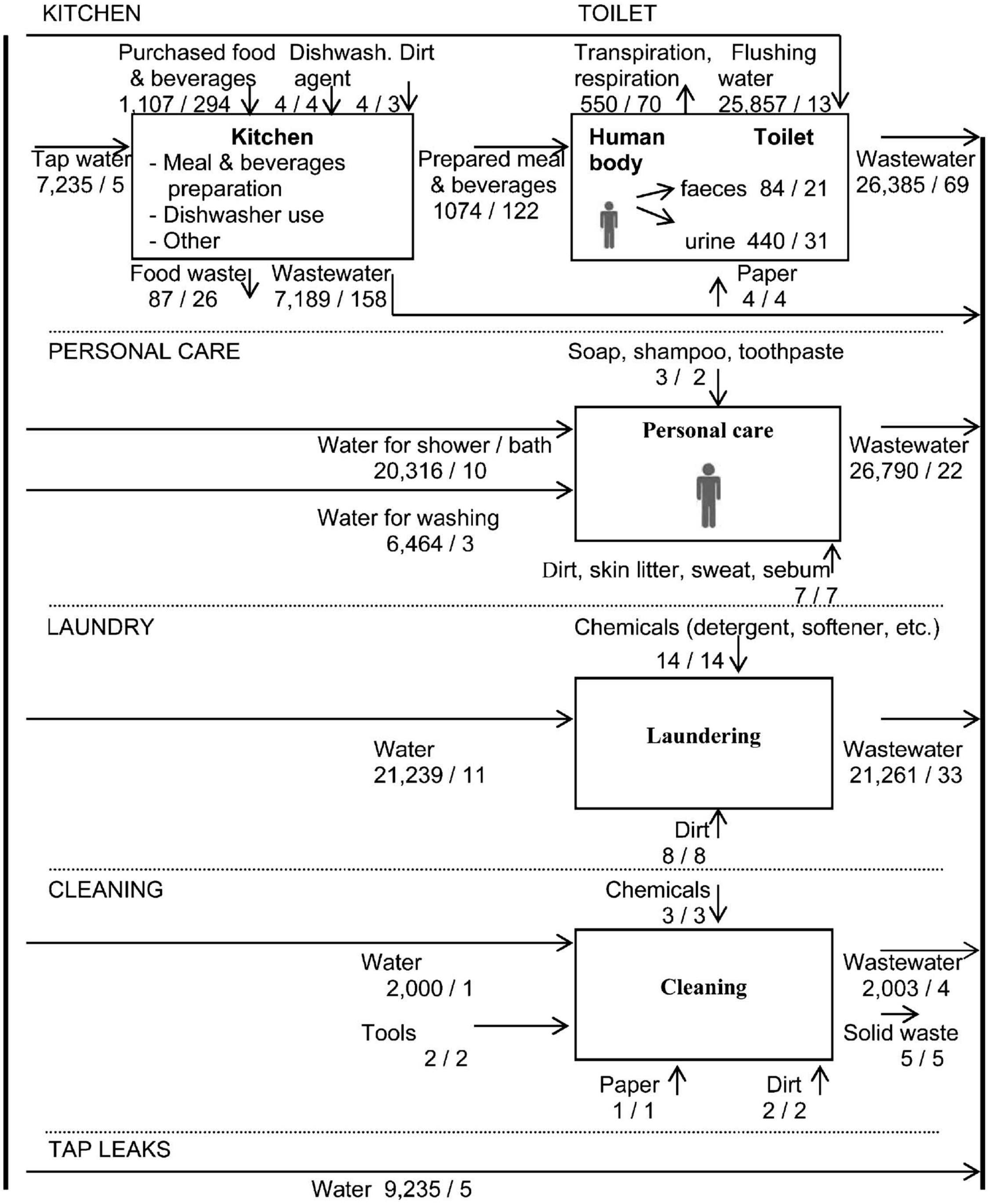

Fig. 5. Mass flows of water and materials of processes kitchen, toilet, personal care, laundry, and cleaning in Toronto neighborhoods, 2000. Numbers indicate mass/dry matter (kg/capita/year).

Building Energy

The energy consumption is estimated for representative City of Toronto buildings—single detached houses and apartment buildings. Here, "energy" denotes electrical energy and energy of fossil fuels (i.e., natural gas, oil, and wood) that are used primarily for space and water heating (Cuddihy et al. 2005).

The energy analysis for 812 single detached houses in Toronto is estimated with the Canadian Residential End-use Energy Data Analysis Center data (CREEDAC 2000). The energy analysis may have some bias because the CREEDAC study examines only houses that participated in the *EnerGuide for Houses* program, not necessarily a representative sample of the houses in the overall housing stock (Dong et al. 2002). Data are sorted by the house vintage, for the periods: pre-1946, 1946–1960, 1961–1970, 1971–1980, and 1981–1999, to analyze the energy consumption in different neighborhoods. For each grouping, the average per capita energy consumption is calculated based on the average Ontario house occupancy. The results show that the energy consumption in newer houses is lower than in older ones, despite increases in the average house size (Table 3).

The energy consumption in Toronto apartment buildings is 57.4 GJ/capita, based on the 1990 energy data (Torrie Smith and Associates 1997) and the average Canadian apartment occupancy (Statistics Canada 1999). We expect that the differences in energy

Table 3. Average Annual Residential Energy Consumption and Net-All Wave Radiation Flux Incoming to Toronto Single Detached Houses

Years of house construction	Average residential energy consumption (GJ/house/capita)[a]	Average house footprint (m^2)[a]	Average net-all wave radiation energy to rooftops (GJ/house/capita)[b]
Before 1946	107.1	79.6	47.7
1946–1960	79.5	99.0	59.4
1961–1970	80.7	111.9	67.2
1971–1980	77.6	118.5	71.2
1981–1999	74.7	115.5	69.3

[a] Estimated with CREEDAC data (2000).

[b] Calculated with annual net all-wave radiation flux of $57\ \mathrm{W/m^2}$ in Toronto (Cuddihy, personal communication, 2005), converted to $1.8\ \mathrm{GJ/m^2}$, and the average Ontario house occupancy of three people (Statistics Canada 1999).

consumption between 1990 and 2000 are small. A more detailed analysis would show differences in the energy consumption by the building type (low-rise, high-rise, duplexes), building characteristics (i.e., vintage, construction materials, apartment size), and perhaps by microclimate conditions.

Transportation Energy

Transportation energy use in the neighborhoods is analyzed with the transportation data of the regions where they are located—Toronto Core, East York, and North York. The exception is Milliken neighborhood, where energy consumption is analyzed with the data for the Town of Markham, located next to Milliken. For each neighborhood, the number of trips/capita/day is estimated with the number of trips in the region, transport mode, and region population (Table 4). For each transit mode, the per capita annual energy use is quantified by multiplying energy use of a particular mode (in MJ/capita km) by the number of trips (trips/person/day), median trip length (km/trip), and modal split. The same calculations are performed for light-duty vehicles, where the average energy use for a car kilometer is estimated with the gasoline combustion energy, fuel efficiency, and average light-duty vehicle occupancy (Table 5).

The results of the transportation energy analysis show that downtown residents prefer using public over private transport (Table 5). In neighborhoods located farther from the downtown, people tend to choose private transport over public transit due to shorter automobile routes, less developed transit infrastructure, and other factors not examined in the study (e.g., time traveled, passenger comfort). This finding agrees well with results of other

Table 4. Median Trip Length by Transport Mode in Study Neighborhoods

Transport usage/neighborhood case	Trinity-Bellwoods	Crescent Town	Don Valley Village	Milliken
Light-duty vehicle[a] (trips/person/day)	0.59	1.00	1.10	1.45
Light-duty vehicle median trip length[b] (km)	4.6	4.5	5.0	5.6
Transit[a] (trips/capita/day)	0.62	0.52	0.39	0.15
Transit modal split[c]/Median trip length[b] (km)				
Bus	20%/2.5	45%/5.3	50%/7.0	85%/16.0
Streetcar	50%/2.5	10%/5.3	—	—
Subway	30%/2.5	45%/5.3	50%/7.0	—
Train	—	—	—	15%/24.5

[a] Estimated with amount of trips made by residents in the characterization region and their population in 1996 (University of Toronto 2003).

[b] University of Toronto (2003).

[c] Modal splits are estimated based on transit routes close to neighborhoods (Transit Toronto 2005; Toronto Transit Commission 2003).

Table 5. Per Capita Transportation Energy Consumption in Toronto Neighborhoods, 1996

		Annual energy use (MJ/capita)			
Transport mode	Energy use (MJ/capita km)	Trinity-Bellwoods	Crescent Town	Don Valley Village	Milliken
Car	3.12[a]	**3091**[c]	**5125**[c]	**6263**[c]	**9247**[c]
Bus	1.66[b]	188[c]	751[c]	827[c]	1,236[c]
Streetcar	0.77[b]	218[c]	77[c]	0	0
Subway	0.42[b]	71[c]	190[c]	209[c]	0
Train	0.35[b]	0	0	0	70
Total public transport	—	**477**	**1,019**	**1,036**	**1,306**

[a] Estimated with combustion energy of gasoline of 35.4 MJ/L (MacLean and Lave 1998), fuel efficiency of 10.32 L/100 km for 1990–1999 fleet (Norman et al. 2006) and average vehicle occupancy of 1.17 person/vehicle (City of Toronto 1999).

[b] Kennedy (2002).

[c] Estimated with energy use (Column 2), median trip length, number of trips/person/day, and modal split (Table 4).

Table 6. Summary of Metabolism Flows in Toronto Neighborhoods in 2000

Neighborhood	Trinity-Bellwoods	Crescent Town	Don Valley Village	Milliken
Location	Toronto	East York	North York	Scarborough
Predominant building type	Houses	Apartment buildings	Houses	Houses
Years of building construction	Before 1880	1970–1980	1960–1970	1970–1980
(a) Inflows				
Net all wave radiation $\{GJ/m^2/year\}$	← {1.8} →			
Energy (GJ/capita):				
- Electricity, Natural gas, Heating oil to buildings	107	57	79	75
- Fuel to public transit	0.5	1.0	1.0	1.3
- Fuel to private transport	3.1	5.1	6.2	9.2
Water (kg/capita)	← (9.2×10^4) →			
Food (GJ/capita) (kg/capita)	← 5.5 (1.1×10^3) →			
Total energy (GJ/capita)	116	69	92	91
(b) Outflows				
Latent and sensible heat $\{GJ/m^2/year\}$	← {1.8} →			
Anthropogenic energy (GJ/capita)	?			
Wastewater (GJ/capita) (kg/capita)	← 1.3 (8.4×10^4) →			
Solid food waste (GJ/capita) (kg/capita)	← 0.4 (8.7×10^1) →			

studies. For example, the NRTEE (2000) study shows that transportation use increases up to 26 vehicle km/capita/day in the outer suburbs, compared to 6 vehicle km/capita/day in the city core. This leads to the energy consumption up to 27,500 MJ/capita/year by light-duty vehicles (Norman et al. 2006).

Summary of Neighborhood Metabolism

The findings for each of the four neighborhoods, shown in Table 6, can be summarized as follows. On a per capita basis the apartment buildings are more energy efficient than any houses. The newer houses consume less energy than older ones. The energy consumption of both private and public transport is distance related: the farther the neighborhood is from the downtown, the higher the transportation energy consumption is. About 90% of water inside households is returned to the cycle and water becomes enriched with the energy of materials disposed into it. The major portion of food nourishes the human body and only a small portion (on a mass and energy basis) becomes solid and liquid food waste.

Discussion and Conclusions

Before discussing the implications of this study for the design of sustainable neighborhoods, it is useful to comment on the applicability of the results. The metabolism flows for the Toronto neighborhoods are summarized in Table 6. While there are notable differences between neighborhoods, particularly in terms of energy inputs, this metabolism provides suitable numbers to begin assessing strategies and technologies for reducing inputs and closing metabolic loops. Moreover, although further study would be desirable, it is likely that the neighborhood metabolism shown in Table 6 is quite representative of inner city neighborhoods in older cities on the north-east of the continent. Cities with similar climates, urban form, and levels of public transportation, such as Montréal, Boston, and New York, probably have similar neighborhood metabolism.

The findings of the study show that reducing energy use for buildings and transportation must be the first step towards sustainable neighborhood design. In the case of older neighborhoods, the focus should be on buildings—the biggest consumers of energy in the residential sector. The construction of energy-efficient apartments and houses (e.g., to R2000 standard in Canada) can reduce the energy consumption in neighborhoods considerably. A tough question is whether to retrofit the existing building stock, or rebuild with energy efficient designs. If energy use were the only concern, then the better option is to rebuild (Dong et al. 2005). Transportation energy consumption in distant neighborhoods can be improved by developing new public transit routes, which would encourage people to use more energy-efficient public transit rather than private transport. The attractiveness and economic viability of transit systems does depend to some extent on neighborhood design (Kennedy et al. 2005); guidelines for the design of transit friendly neighborhoods have been produced (Institute of Transportation Engineers 1997; Morris 1997).

Water use in neighborhoods can be reduced using relatively straightforward demand management techniques, such as installing more efficient toilets, washing machines, showers, and faucets. Currently, Torontonians are encouraged to replace their toilets and washing machines with newer, efficient models, saving not only on their water and energy bills, but also receiving cash back through rebate programs (City of Toronto 2005b). Additional water reduction can be achieved by encouraging residents to replace shower heads with new models which limit the water flow rate. In Ontario, the efficient shower heads and toilets have already been installed in buildings constructed in 1996 or later (City of Toronto Works and Emergency Services 2002). Water meters in residential units also encourage people to reduce their consumption. Where legislation permits, further reductions in water demand can be met through grey water recycling or rainwater harvesting.

More advanced methods bearing long-term sustainability objectives can also be applied in neighborhoods. The negative impacts associated with waste disposal can be avoided by closing the metabolism flows. This approach has already been adopted in 2000, when Toronto set a course to achieve 100% diversion of solid waste from landfills by 2010 through recycling and "green bin" programs. In addition to reduced transportation energy and landfilled waste, the city has benefitted from the program by applying the compost from "green bins" on agricultural lands (City of Toronto 2001a), and paying lower garbage fees. In the near future, the "green bin" program is planned to be implemented in multiresidential units (City of Toronto 2005a).

Another possible way for the city to close the metabolism flows might be to grow urban forestry using nutrients from wastewater. The urban forest not only pleases the human eye but also provides homes with heating and cooling benefits. For example, a single large tree in a postwar and contemporary neighborhood leads to a reduction of annual energy consumption of up to 950 and 1200 kW·h, respectively, which translates into savings of $37 and $44 Canadian (Engel-Yan 2005). Handled carefully, because of the odor problems, residential wastewater might be used to fertilize the urban forest due to the presence of nitrogen and phosphorus. Back in the 19th century, American farmers applied manure from human waste in order to return these key nutrients back into the soil (Wines 1985). Later, this practice was dropped due to a wide application of more effective guano and of industrial fertilizers. In modern conditions, when human waste contains traces of antibiotics, the application of wastewater in agriculture is questionable. However, use of wastewater for the urban forest might be a feasible alternative.

Using the incoming solar energy to rooftops for building operations is a further advanced method that potentially can be applied. In this study, the solar energy incoming to rooftops of single detached houses is about 45–93% (Table 3) of the energy required to operate the houses. If passive solar and natural cooling techniques are followed, however, close to 100% of heating and cooling requirements of low rise buildings might be met, even in cold climates. Energy recovery through solar water heaters, photovoltaic cells, and heat pumps can also be used to exploit the natural energy in the neighborhood metabolism.

Notation

The following symbols are used in this paper:

$\dot{m}_{\text{input}}$ = mass flow rate of inputs;
$\dot{m}_{\text{output}}$ = mass flow rate of outputs;
$\dot{m}_{\text{storage}}$ = rate of storage change; and
p, q = indices of summation.

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