

Carbon, nitrogen, and phosphorus fluxes in household ecosystems in the Minneapolis-Saint Paul, Minnesota, urban region

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Abstract. Rapid worldwide urbanization calls for a better understanding of the biogeochemical cycling of those macroelements that have large environmental impacts in cities. This study, part of the Twin Cities Household Ecosystem Project, quantified fluxes of carbon (C), nitrogen (N), and phosphorus (P) at the scale of individual households in the Minneapolis-Saint Paul metropolitan area in Minnesota, USA. We estimated input and output fluxes associated with several components of household activities including air and motor vehicle travel, food consumption, home energy use, landscape, pets, and paper and plastic use for 360 owner-occupied, stand-alone households. A few component fluxes dominated total input fluxes of elements. For instance, air and motor vehicle transportation, together with home energy use, accounted for 85% of total C consumption and emissions. All total and component fluxes were skewed to varying degrees, suggesting that policies targeting disproportionately high fluxes could be an effective and efficient way to reduce pollution. For example, 20% of households contributed 75% of air travel emissions and 40% of motor vehicle emissions. Home energy use was more nearly normally distributed. Nitrogen fluxes were dominated by human diet and lawn fertilizer applications, which together accounted for ~65% of total household N inputs. The majority of P inputs were associated with human diet, use of detergents, and pet food. A large portion of the variation among household fluxes of C, N, and P was related to a few biophysical variables. A better understanding of the biophysical, demographic, and behavioral drivers of household activities that contribute to C, N, and P fluxes is pivotal for developing accurate urban biogeochemical models and for informing policies aimed at reducing sources of pollution in urban ecosystems.

Key words: carbon; element budgets; households; macroelement fluxes; Minneapolis-Saint Paul, Minnesota (USA); nitrogen; phosphorus; Twin Cities Household Ecosystem Project; urban ecosystems.

INTRODUCTION

The interaction between human beings and the biophysical environment is most evident in urban ecosystems, home to one-half of the world's population (FAO 2001). As more and more people live in urban areas, there is a compelling need to gain a better understanding of how activities in urban areas affect the fluxes of major elements such as carbon (C), nitrogen (N), and phosphorus (P) (Kaye et al. 2005, Grimm et al. 2008, Baker 2009), building on earlier work on urban metabolism (e.g., Wolman 1965). Concentrated cycling of these elements in urban ecosystems results from intensification of combustion associated with air and vehicular traffic and power production, food consumption, landscape fertilization, and waste flows to landfills

and aquatic ecosystems. Biogeochemical cycling is intensified outside cities, to support production of food, materials, and energy used within cities. This intensification and concentration of biogeochemical cycling due to urban activities has overwhelmed the effectiveness of “end of the pipe” strategies to reduce environmental pollution that focus solely on treatment of pollution rather than on source reduction (Baker and Brezonik 2007, Gu et al. 2009).

The study of urban ecology and the view of cities as both ecological and social entities dates back to the pioneering work of Park et al. (1925) who were among the first to discuss changing land use and available resources with the expansion of cities. Similarly, three decades later, Form (1954) and Foley (1954) addressed the need to include sociological factors in the study of urban ecology. Specifically, Foley identified possible changing patterns in daily human activities (such as commuting) in relation to the concentric expansion of cities. Despite the growing body of work in urban

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ecology (reviewed by McIntyre et al. 2000), it is only lately that the articulation of cities as unique ecosystems (in which nutrient and water cycles are substantially altered by direct human activities and land use change) has been explored more closely (McDonnell and Pickett 1990, Arnold and Gibbons 1996), continuing the foundational work of a few early scholars (McHarg 1964, 1969, Leopold 1968). However, until recently the integration of human activities and biophysical processes in urban ecosystem studies has been under-theorized and often proposed based on limited evidence, and therefore, insufficient to understand the dynamic nature of this interaction (Alberti et al. 2003). In addition, some have suggested that the household is an appropriate scale to capture the complexity of such a dynamic system (Chakravarty et al. 2009), yet very few studies of urban metabolism to date have focused at the household scale.

Nevertheless, in postindustrial urban ecosystems, a large proportion of the human activities that influence element cycling occurs within the conceptual boundaries of households (*sensu* Baker et al. 2007). For example, home energy use and personal travel contribute to ~41% of total carbon dioxide (CO₂) emissions in the United States (Bin and Dowlatabadi 2005), and it has been estimated that interventions at the individual household level could lead to a 7.4% reduction in national CO₂ emissions (Dietz et al. 2009). Yet, despite their importance, understanding of the fluxes of macroelements through households remains incomplete because it is generally segmented into studies of single behaviors or sectors, such as transportation (e.g., Nicolas and David 2009), or of a limited number of households (e.g., Carlson-Kanyama et al. 2005).

Several studies of total household consumption have been conducted outside the United States, all focusing on fossil fuel use. A socioeconomic sector analysis of seven representative groups of households in the United Kingdom showed that energy consumption and associated emissions were related to type of dwelling and geographic location, with households in the city center having lower emissions than suburban households (Druckman and Jackson 2008). However, information on total household emissions for individual households (in contrast to "sector" studies) is critical to inform the complex interaction of human activities with biogeochemical cycling in urban ecosystems, and this type of information is scarce, particularly in the United States (Chakravarty et al. 2009).

A challenge in characterizing biogeochemical cycling of elements at the household level for large urban areas arises from the high degree of variability of component fluxes that contribute to total element cycles through households. Such variability reflects inter-household differences in lifestyle and consumption patterns (Bin and Dowlatabadi 2005, Baker et al. 2007, Druckman and Jackson 2009). In a voluntary, nonrandomized survey of 103 Irish households, variability in CO₂, CH₄,

and N₂O emissions from transportation and energy consumption was related mainly to number of household members, lifestyle, and property size, with the average emissions being strongly influenced by a few outliers (Kenny and Gray 2009). A more extensive study of 655 households in Melbourne, Australia similarly indicated high flux variability among households when emissions from cars, air travel, and home energy use were considered (Stokes et al. 1994). It is important to use caution when drawing generalizations from the available literature, and one has to take into account spatial diversity of urban areas across geographic regions, differences in boundary definitions of "households," and the differences in individual lifestyle and consumption choices. Despite these complexities, work conducted in specific urban regions, such as that reported here, provides the key data required to understand patterns and trends in consumption and emissions that may be general across cities.

The work we present here is part of the Twin Cities Household Ecosystem Project, an extensive coupled human–biophysical analysis of household-level biogeochemical cycling for the Minneapolis–Saint Paul, Minnesota, USA (henceforth Twin Cities) urban region. The study is unique in that: (1) it quantifies both total and component fluxes of three major macroelements (C, N, and P) through each household; (2) it is large enough (3100 households of which 360 households are the focus of the present in-depth work) to be representative of the sample population and to allow analysis of disproportionality (*sensu* Nowak et al. 2006) among households; (3) it employs a broad definition of "household" that includes landscape vegetation and off-property activities; and (4) it encompasses a large gradient of housing density, from urban to exurban.

We conducted our work in Ramsey and Anoka counties, from near the center of the Twin Cities urban region to the exurban fringe. We used a hybrid approach that combined a household mail survey with direct landscape measurements, home energy records, public geographic information system (GIS) data, and published coefficients, integrated into a computational tool that we developed (household flux calculator, HFC) to estimate C, N, and P fluxes associated with the following activities: air and motor vehicle travel, landscape management, human and pet diet, home energy use (heating, cooling, appliances), paper and plastics, and detergents. In our study, we define a household unit to include consumption and emissions that take place within the physical parcel boundaries as well as fluxes related to food consumption and travel by household members occurring off the property. Our work strictly quantifies direct consumption fluxes; we recognize that indirect fluxes associated with manufacture or production of materials entering the household system may be large, but quantifying them (i.e., through life cycle assessment) was beyond the scope of the present study.

The present paper specifically focuses on the quantification of C, N, and P fluxes through the household and analyzes the potential disproportionality (Nowak et al. 2006) of the distributions of fluxes among households to address the following hypotheses:

1) Total fluxes of C, N, and P show great variability and a skewed distribution among households, indicating that activities by a small number of households contribute disproportionately to overall biogeochemical cycling.

2) Component fluxes (i.e., transportation, home energy consumption) similarly show great disproportionality among households, and the degree of variation and skewness varies among component fluxes.

3) A few component fluxes, such as those associated with transportation and energy consumption, dominate the total (household) fluxes of elements, with other components representing a minor proportion of total fluxes.

In this study we also investigate the influence of biophysical variables, such as number of household members, house size, and distance from the city center, as potential drivers of element fluxes, both total and component fluxes.

METHODS

Our study took place in the Twin Cities metropolitan area, Minnesota, in Ramsey and Anoka counties, along a 55-km urban-to-exurban gradient (Fig. 1) with varying housing density from the city of Saint Paul to the northernmost part of Anoka County (Hammer et al. 2004). Our population frame was single-family, detached, owner-occupied households, a common dwelling type in the Twin Cities that houses ~64% of the population. The randomly selected houses spanned a wide range of age and size (as house finished floor area and landscape area). We obtained information on household biophysical variables from mailed surveys (e.g., number of household members) and from the 2008 Metropolitan Council parcel database (e.g., house finished floor area).

Our approach for estimating element fluxes through the household included a combination of mailed surveys, energy records, landscape measurements, literature values, and computational tools described in the following sections.

Mailed survey and population frame

We developed a 40-question survey on household characteristics and choices (Nelson et al. 2008). Through this survey we gathered information on household physical characteristics (e.g., number of household members), household members' diets and levels of physical activity, number and masses of cats and dogs, food waste disposal and recycling habits, air and motor vehicle travel activities, and landscape management practices (fertilization, irrigation, grass clipping and leaf litter management). The survey, which took individuals

~40 minutes to answer, was completed between May and August of 2008. We asked household members to report activities for the previous year. We also gathered information concerning the respondents' attitudes, norms, and perceived control related to specific behaviors (driving, diet, lawn fertilization, energy use) as well as household demographics (age, gender, ethnicity, education, income). Socio-demographic variables, attitudes, norms, and perceived control results will be the focus of future publications. In addition, we requested permission to obtain household energy billing records from electricity and natural gas companies for the period May 2007 to April 2008. This information allowed us to estimate household yearly energy consumption. During this period, the total number of heating and cooling days (i.e., the number of days above or below the base temperature of 18°C, respectively) combined were 9% higher than the 10-year average. The cost of residential energy in Minnesota was ~10% higher in 2007–2008 than during the period 2000–2006 (in 2008 U.S. dollars) (EIA 2008). For a subsample of the households (those reported here), we obtained permission to visit the property to make vegetation measurements.

We developed a provisional sample frame using GIS to select areas that met the following criteria: (1) >0% impervious surface cover, (2) "upland" hydrologic type, and (3) "single-family detached" residential land use type. All areas in Ramsey and Anoka counties that satisfied all three criteria were overlaid on census blocks (U.S. Census Bureau 2000). Those census blocks in which >50% of the area satisfied our selection criteria were included in the provisional sample frame. This provisional sample frame was provided to Survey Sampling International (Shelton, Connecticut, USA), which identified homes that were owner-occupied and had telephones, to yield a final sample frame of households. We then mailed a total of 15 000 surveys to a random sample of houses within our sample frame. The number of addressees selected from each census block was proportional to the block's housing density (based on Hammer et al. 2004), such that higher density census blocks received more surveys (per unit area) than lower density census blocks.

The survey mailing followed a modified Dillman (2000) method and included: (1) an initial mailing to the selected sample of 15 000 homes with an introductory letter in May 2008, (2) a reminder postcard sent to all addresses 10–14 days after the initial survey was received, and (3) a second mailing sent approximately one month after the initial mailing to any addresses in the original sample that did not respond to either the first mailing or the postcard reminder. This method has been shown to reach the largest number of respondents and to encourage response from some segments of the population that may not have responded to the initial mailing alone. Due to the extensive nature of our survey, we anticipated a low response rate; therefore, we

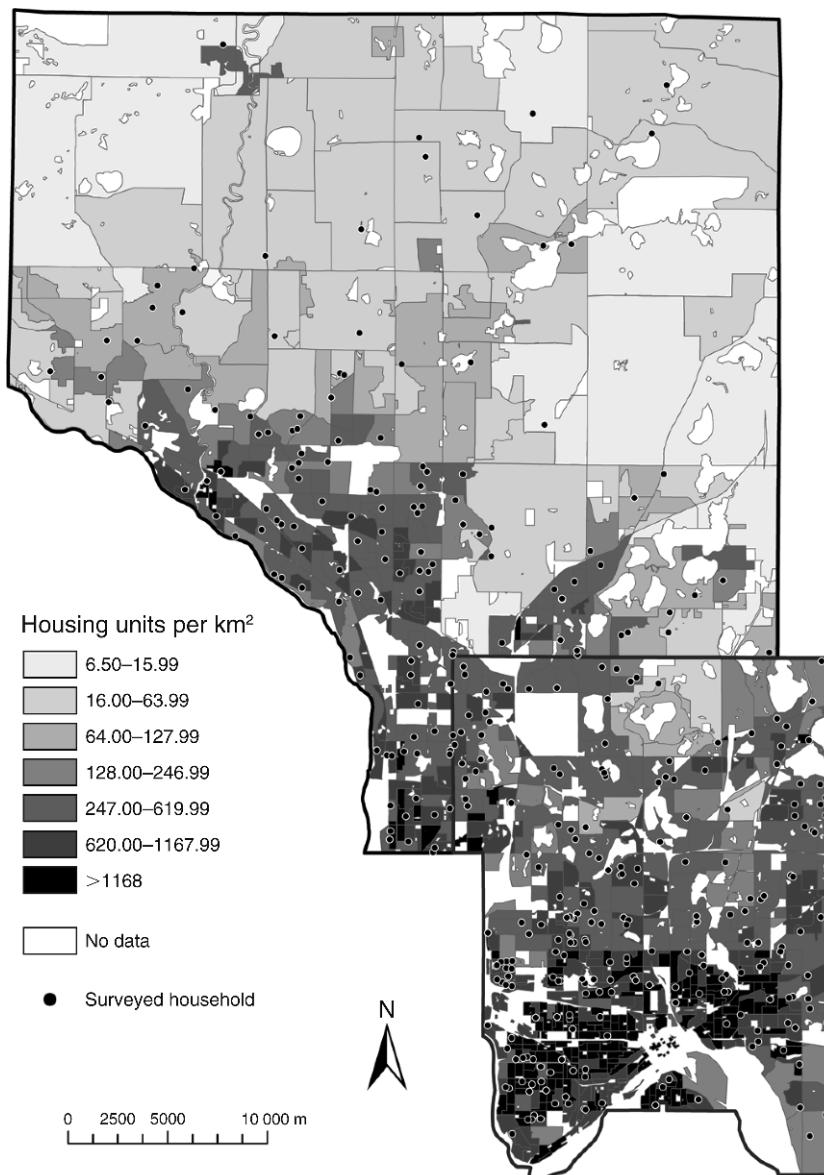


FIG. 1. Locations of the 360 surveyed households along the gradient in housing density in Anoka and Ramsey counties in Minnesota, USA. Dots indicate individual households, lines indicate census block boundaries, and shading indicates the housing density of each block. Household locations have been randomly shifted to protect the anonymity of survey respondents.

oversampled to obtain a completed sample that was sufficiently large to minimize sampling error. The total response rate was 21%, corresponding to 3100 households, a robust sample for statistical analysis of interactions. We catalogued the incoming surveys and contacted utility providers to obtain energy records. Survey responses were coded, entered into spreadsheets, and consistency checked for all entries.

Of the respondents who returned the survey, 1517 granted us permission to obtain their utility billing records and allowed us to make vegetation measurements on their property. We then randomly selected 360 of those households for which we obtained all required

information (completed survey, energy billing records, permission to make landscape measurements), distributed in proportion to housing density within the study area. For these households, the focus of this paper, we conducted field measurements of vegetation and developed complete household C, N, and P balances.

Landscape assessment

We conducted vegetation measurements of these 360 households during the summer of 2008 to estimate C, N, and P fluxes and storage in vegetation on each property. We identified each tree within the property limit and measured all parameters required by the Urban Forest

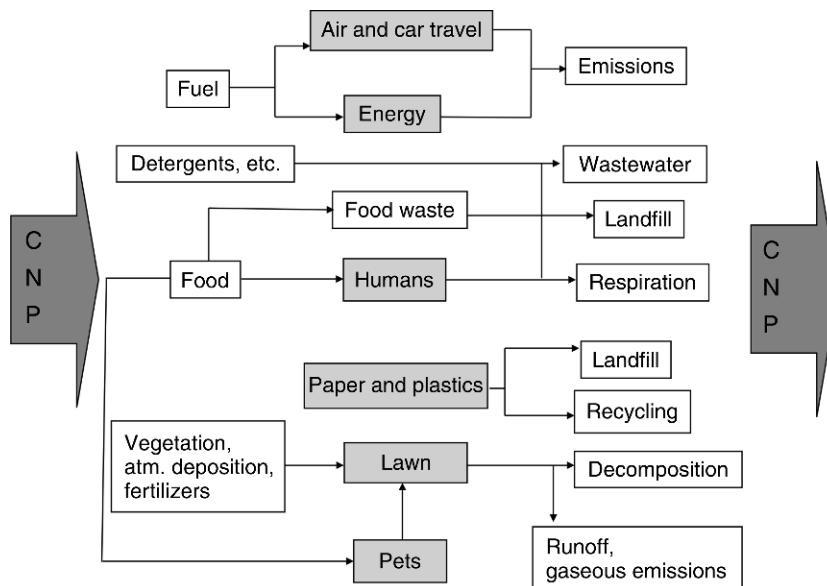


FIG. 2. Schematic representation of sources of input and output fluxes of elements (C, carbon; N, nitrogen; P, phosphorus) through the household showing components (shaded rectangles) and subcomponent fluxes considered in the household flux calculator. "Atm." stands for atmospheric.

Effects (UFORE) model to estimate tree C uptake (Nowak et al. 2008), including tree diameter at breast height, total height, height of first branching, canopy light exposure, percent of canopy missing, and dieback (as percent of dead branches). Additional measurements included percent of property area covered by tree canopy and distance and direction of trees from buildings for trees that were at least 7 m tall and located <20 m from the building. Vegetation measurements were conducted for the entire parcel for the majority of properties. For a limited number of properties that were >0.1 ha and included large wooded areas (48 households or 13% of total), we used a modified approach that consisted of sampling five random, 8 m radius, nonoverlapping subplots per hectare and then scaling the vegetation measurement to the total parcel area (excluding buildings and driveways).

Data from field vegetation assessments were recorded in a relational database and analyzed by the USDA Forest Service using the UFORE model (Nowak et al. 2008). The model uses field-measured data to estimate tree-specific attributes, such as leaf biomass C, net primary productivity (NPP) of wood and foliage, and C storage in wood, that were used in this study to calculate tree NPP and C, N, and P sequestration rates in wood at the household level (see *Household flux calculator: Landscape*).

Household flux calculator (HFC)

We developed a computational tool (hereafter called the household flux calculator, HFC) to convert all relevant information (from the returned surveys, energy records, parcel data, and landscape assessment) into

annual fluxes of C, N, and P (expressed as kilograms of element per household per year; see also Appendix A). The current version of the HFC was modified from Baker et al. (2007) to better adapt to the sampling and survey approach (mail survey vs. in-home survey) and to improve certain algorithms and/or update coefficients based on more recent literature.

The HFC is organized into seven main components (motor vehicle transportation, air travel, household energy consumption, human diet, pet diet, landscaping, and paper and plastic consumption) and two subcomponents (food waste and wastewater) (Fig. 2) such that fluxes of macroelements through each one of these components can be analyzed independently. Every component of the HFC receives inputs of C, N, and P in different forms (i.e., food for human and pet nutrition, fuel for transportation) that then leave the household as outputs (i.e., CO₂ from human and pet respiration; CO₂ and nitrogen oxides (NO_x) from fuel combustion). We developed the HFC to convert the diverse sources of inputs and forms of outputs into common units by using a series of algorithms and conversions and by relying on available literature. For specifics see Appendix A accompanying this paper. The sum of the component fluxes represents the total flux of elements at the household level.

Motor vehicle transportation.—Through the survey, household members provided information about number of motor vehicles owned; make, model, and number of cylinders for each vehicle; year of purchase; and odometer reading at the time of purchase and at the time the survey was completed. Based on that information, we estimated number of miles (1 mile = 1.6 km) driven

annually and vehicle fuel efficiency (EPA 2007) for each vehicle by averaging highway and city mileage. Then we divided annual miles driven by fuel mileage economy to estimate annual fuel consumption. We calculated C emissions due to gasoline combustion assuming a C content of 640 g C/L (nominally 2421 g C/gallon) of gasoline (EPA 2007). We used average NO_x emissions from EPA (2007), assuming that all NO_x is emitted as NO₂. If respondents did not provide information concerning motor vehicle odometer readings, we assumed a value of 20 117 km/yr (nominally 12 500 miles/yr) (EIA 2008).

Air travel.—For each household we obtained information on the origin and destination of each flight as well as the number of flights taken and by how many family members during the period 1 May 2007 through 30 April 2008. We calculated the total amount of fuel combusted based on the assumption that each trip was round-trip and nonstop along the geodesic distance between origin and destination. The HFC assumes different constant emissions for domestic and international flights (see Appendix A). Our approach may overestimate emissions for long flights and underestimate emissions for short flights because emissions vary during different flight phases and as a function of type of aircraft (Jamin et al. 2004); however, we did not have the detailed information that would be necessary to refine the approach. We treated nonresponses as indication of no travel.

Household energy consumption.—Household energy in the Twin Cities metropolitan area is provided mainly as electricity and natural gas, with few households using propane, oil, or wood. For those households granting permission, we gathered information on electricity and natural gas consumption from regional providers. Values for CO₂, methane (CH₄), and NO_x emissions associated with electricity and natural gas usage were obtained from EIA (2002). In the case of propane and fuel oil use, we relied on estimated average cost per gallon (1 gallon = 3.8 L; EIA 2009) and estimated volume used based on respondents' reported yearly expenses for these fuels.

Human diet.—Through the mailed survey we collected demographic information for each household member (gender, age, height, mass, daily minutes of moderate and high activity, and diet type divided into meat-based, lacto-ovo vegetarian, or vegan) that was used to compute total energy requirements for each household member (Otten et al. 2006). The amount of fat, carbohydrate, and protein (as percentage of total calories) was based on diet type following Messina and Messina (1996) who also provide a range of fiber intake (expressed as grams per day) associated with diet types. Food intakes were then converted to C and N inputs using literature values. Based on P intakes from Ervin et al. (2004), P input was calculated to be 0.3% of food mass.

In addition to the C, N, and P in food actually consumed by household members for nutrition, we accounted for additional food that was brought into the household and then wasted (e.g., fruit peels), exiting the household via garbage (to a landfill or incinerator), via garbage disposal (to the sewer), or composted in situ or off-site. This food waste term also included industrial, commercial, and institutional wastes (ICI), to account for waste production due to household members' consumption of food prepared outside the home and is described in *Household flux calculator: Food waste*.

Macroelements contained in food leave the household as respiration (all food C minus C in fiber) and through wastewater, compost, and landfill or incinerator (all C in fiber, all N and P in food used for human nutrition, plus a portion of C, N, P that is food waste, see *Household flux calculator: Food waste*). We did not take into account accumulation of elements in human biomass that occurs through growth of children. We estimated that including growth in children and teenagers (age 1–18, corresponding to 119 individuals or 13% of the household members) would have minimally affected element storage and output, corresponding to a reduction in output fluxes of C, N, and P in the households of 0.2%, 0.1%, and 0.1%, respectively.

A number of surveys were returned with incomplete information concerning household members' age, height, or mass. In the case of missing age (41 members or 11% of total) we assumed the mean age for all respondents by gender; for missing height (36 members or 10% of total) and missing mass (62 members or 17% of total) we assumed the average of respondents with similar gender and age. In only two cases were we missing age, height, and mass information, and for these we assumed energy requirements based on the average of all respondents of that gender.

Food waste.—The food waste subcomponent (residential and ICI) in the HFC includes a per capita amount of food that is disposed to landfill or incinerator, composted in situ, or discarded through wastewater (i.e., garbage disposal). Element inputs through this subcomponent are accounted for in the diet component of the HFC according to the view that broadly it belongs to the overall amount of food that enters the household boundary. Because of its complexity and input sources that are independent from those for food used for human nutrition, food waste is treated independently here and in the HFC, as a subcomponent. The ICI component of food waste is generated outside the physical boundary of the household (e.g., workplace, restaurants), and we assumed it is entirely discarded to landfill or incinerator. We computed per capita food waste entering local landfills using data from Beck (1999), and per capita garbage disposal rates using data from Siegrist et al. (1976). Presence or absence of a garbage disposal in the household (from the survey) determined the proportion of residential food waste that is discarded to landfill/incinerator or to waste water. We

assumed that if a respondent answered that food waste is composted in situ, no food waste was sent to a landfill or incinerator or to garbage disposal, as it would have been impossible to accurately determine the proportion of food that was actually composted vs. thrown away.

Wastewater.—Wastewater represents an output pathway for other HFC components rather than being strictly a subcomponent, but because of its importance and links with several other components, it is treated separately in the HFC. Outputs to the wastewater subcomponent of the HFC (Fig. 2) include human excretion, the proportion of food waste going through garbage disposals, other sources of gray water (e.g., detergents), and C from toilet paper. We assumed that all C from food fiber and all N and P in human food were excreted, becoming wastewater. The remaining terms were calculated on a per capita basis, and, therefore, do not capture household-to-household variability, except that caused by variation in number of household members.

Plastic and paper.—Plastic inputs to households could not be assessed directly through the survey; hence, we relied on available landfill and recycling data (Beck 1999; Eureka Recycling, Minneapolis, Minnesota, USA, *personal communication*). Total plastic input to the household was calculated as the sum of annual per capita plastic going to the landfill (33 kg per capita per year; Beck 1999) and recycled (3.1 kg per capita per year; Eureka Recycling, *personal communication*). We estimated C flux as plastic by assuming 60% C content (Tchobanoglous et al. 1993).

Inputs of paper to households occur mainly in the form of magazines, newspapers, mail, and packaging. Through the survey, respondents provided information concerning the household's number of weekly and monthly magazine and newspaper subscriptions. We assumed that all the paper from newspapers and magazines leaves the household within the year, either to landfill/incinerator or to recycling. The amount of magazines and newspaper being recycled was calculated from the proportion of total paper each respondent reported to recycle. The HFC calculates total C flux by assuming a C concentration of 43% (averaged from Tchobanoglous et al. 1993, Rowen et al. 2001, Hobbie 2005).

The amount of mail (excluding magazines and newspapers) and packaging entering the household could not be assessed directly from the survey; hence, we relied on per capita landfill and recycling data (Beck 1999; Eureka Recycling, *personal communication*), and used the homeowner-reported values for proportion of paper recycled (0%, 25%, 50%, 75%, or 100%) to partition outputs between landfill and recycling (see also Appendix A).

Household pets.—The HFC calculates dog and cat food inputs of C, N, and P to the household based on type, number, and mass of dogs and cats. Calculations of annual dog food intake are based on metabolic

equations (NRC 1985). The HFC uses this value along with the average nutrient content of commercial dog food (Baker et al. 2007). We assumed that all C contained in proteins, fats, and carbohydrates is respired, but that fiber C is excreted in feces. We assumed that 60% of dog owners pick up feces after their dog (Swann 1999). Therefore, we assumed that all N and P in dogs' urine and 40% of C, N, and P in feces enters the household's landscape, representing an input to the landscape element budget (see Appendix A).

The HFC uses information on cat mass to determine cat daily energy requirements (McDonald et al. 1984) and cat food and nutrient intake based on data provided by a commercial brand for dry food (*available online*).⁷ We assumed that all C, N, and P from cat food leaves the household to go to the landfill or incinerator without transitioning through other components or subcomponents of the HFC (i.e., the landscape). Energy requirements and food intake were assumed to be for adult pets. In two instances (0.5% of total) respondents did not provide masses of their cats, so we assumed an average mass from all respondents who did report cat masses.

Landscape.—We used a combination of models, published data, and survey information to assess element fluxes through the household landscape (i.e., total parcel area minus impervious surface area). The HFC accounts for inputs of C, N, and P to the landscape from net primary production (NPP) of tree leaves, tree wood, and turfgrass, atmospheric deposition (N and P), fertilizer application (N only, as the Twin Cities fall under a state law restricting P fertilizer use on lawns), dog excreta (C, N, and P), and gasoline to fuel lawn mowers (C). Fluxes leaving the household landscape include leaf litter and soil organic matter decomposition (C), grass clipping and leaf litter removal (C, N, and P), dog feces decomposition (C), dog feces disposal (C, N, and P), and gasoline combustion in lawn mowers (C). Differences between fluxes to and from the landscape represent element accumulation and export (as runoff, volatilization, nitrification, denitrification). We were unable to partition exports among potential loss pathways and combined them into a single term.

We calculated leaf NPP ($\text{kg}\cdot\text{m}^{-2}\cdot\text{yr}^{-1}$) from UFORE's (Nowak et al. 2008) leaf biomass output by assuming that annual litterfall = leaf NPP = leaf biomass ($\text{kg}\cdot\text{m}^{-2}\cdot\text{yr}^{-1}$). For deciduous trees, leaf life span was assumed equal to one year. For evergreen trees, species-specific leaf life span was estimated from the GlopNet database (Wright et al. 2004), which contains extensive trait data for some of the more common species across different ecosystems (see Appendix A). For species not in the database, we used the average leaf longevity at the genus level. To determine litterfall N and P fluxes, we estimated leaf litter N and P concentrations based on

⁷ (www.iams.com)

species-specific leaf data in the GlopNet database (Wright et al. 2004). We accounted for nutrient resorption using the equations of Kobe et al. (2005) and multiplied litter nutrient concentrations by litterfall to determine litterfall N and P fluxes. For leaf litter remaining on site, we assumed that litterfall was in equilibrium with litter decomposition such that all litterfall C was respired each year and all litter N and P entered the soil. Leaf litter removal by the household caused all elements (C, N, P) to leave the household system; hence, they did not contribute N and P to soil. UFORE model output includes leaf biomass and “gross C sequestration in wood” (equal to net wood C production), so we did not estimate leaf or wood gross primary production and respiration as explicit C fluxes. We obtained wood NPP (kg C/yr) from UFORE output, which was based on tree metrics obtained from the landscape survey for each tree on the property, and we calculated the N and P in wood production based on average wood C:N and C:P stoichiometry (Rodin and Bazilevich 1967). Because of lack of necessary information, we ignored C, N, and P fluxes associated with tree root NPP, removal of woody yard waste, and decomposition of dead wood (e.g., fallen branches). As a result, these fluxes may be underestimated in the landscape component of the HFC, causing us to underestimate tree nutrient uptake and therefore overestimate losses of N and P from leaching and denitrification, among others, and to underestimate losses of C from wood removal and decomposition.

We estimated turfgrass (lawn) NPP, heterotrophic respiration, and clipping fluxes based on a published turfgrass model and survey information concerning irrigation, fertilization, and clipping management practices (see Appendix A). Specifically, we obtained lawn NPP, heterotrophic respiration (R_H), and clipping removal C fluxes from the Biome-BGC ecosystem process model for turfgrass in Minneapolis, Minnesota (Milesi et al. 2005; C. Milesi, *personal communication*). Milesi et al. (2005) estimated NPP, R_H , and clippings production for unmanaged lawns (no irrigation or fertilizer inputs) and well-watered lawns that received moderate or heavy fertilization (73 kg N·ha⁻¹·yr⁻¹ or 146 kg N·ha⁻¹·yr⁻¹, respectively) under conditions where clippings were either removed or left in place. We used their model output to generate response surfaces for fluxes as a function of fertilization rate (separately for clippings removed or left in place) and assumed that fertilizer was applied to the entire impervious landscape. However, because Milesi et al. (2005) did not model different irrigation practices for fertilized lawns, we adjusted their NPP, R_H , and clippings fluxes for fertilized lawns downward based on Ahlgren (1938) when households reported in the survey that they “rarely/never” or “occasionally” watered. We estimated turfgrass C, N, and P concentrations from published and unpublished values (Jiang et al. 2000, Kopp and Guillard, 2002, Kussow 2004; J.

Oleksyn and P. B. Reich, *unpublished data*). If lawn clippings were reported to be removed in the survey, we divided annual clippings C production by turfgrass C:N or C:P ratios to estimate clippings N and P removal fluxes, respectively.

Nutrient inputs to the landscapes in the HFC come from atmospheric deposition, lawn fertilizer, and pets (see Appendix A). The HFC uses survey information on the number of fertilizer application events per year to calculate annual kilograms of N applied, assuming each application occurs at the rate of 48.9 kg N·ha⁻¹·yr⁻¹ (nominally 1 pound N per 1000 square feet, as recommended on retail fertilizer packages) and that fertilizer is applied to the entire landscape area. Dog excreta contribute to the landscape nutrient budget as described in *Household flux calculator: Household pets*; we assume all un-scooped feces are deposited on the dog owner's landscape. All fiber C from dog feces is assumed to decompose within one year and leaves the system as CO₂, while all N and P in un-scooped dog feces contribute to total nutrient inputs to the landscape.

The HFC calculates net landscape accumulation or loss of elements as the difference between element inputs to and outputs from the landscape. Landscape C accumulation rates equal the soil C accumulation rate, estimated as the difference between grass NPP and the sum of heterotrophic respiration and grass clippings removal rates (if clippings were removed, as reported in the survey), plus the wood C sequestration rate from UFORE. Nitrogen and P accumulation or loss was driven by C accumulation, assuming fixed C:N and C:P ratios of soil (Elliott 1986, Horgan et al. 2002) and wood (Rodin and Bazilevich 1967). If N and P inputs exceeded nutrient uptake by vegetation and soils plus exports as tree leaves or lawn clippings, we assumed that excess nutrients were lost, likely through runoff, leaching, and denitrification (N only). Our model did not allow us to specify the loss pathways. If, on the other hand, N and P inputs were insufficient to meet ecosystem uptake requirements, we assumed that all inputs of nutrients (minus any removed in tree leaves or lawn clippings) were retained in the landscape, and any tree uptake likely came from nutrients stored in soil. Note that nutrients could be lost from the landscape through human removal of leaf litter and lawn clippings, even when inputs were less than nutrients required for plant uptake and soil accumulation.

Statistical analysis

We fitted two continuous distributions, the Gaussian (normal) and the gamma distribution, and we calculated the skewness for the total and component fluxes of elements through the sampled households. The gamma distribution provides a flexible representation of a wide range of shapes for a continuous random variable that is always positive and has a skewed distribution (Johnson et al. 1994, Wilks 2006). It has a shape parameter, α , that is dimensionless and a scale parameter, σ , that takes

the same physical units as the random variable. When $\alpha = 1$, the distribution is equivalent to the special case of the exponential distribution. Larger values of α result in progressively less skewness until, for very large α , the gamma distribution converges to the normal distribution. We tested goodness of fit using the Shapiro-Wilk test for the normal distribution and Cramér-von Mises W^2 for the gamma distribution. The null hypothesis that the samples were drawn from the given distribution was rejected when $P < 0.05$. Distributions were considered significantly skewed if skewness (as absolute value) was greater than twice the standard error of the skewness. We used simple linear regression to investigate how biophysical variables such as number of household members, distance from city center, housing density, house finished floor area, lawn size, and house age were related to total and component element fluxes. Additionally, we used stepwise backward regression analysis to obtain models of biophysical drivers for total C fluxes and for some of the component C fluxes. For our analyses we used JMP-SAS version 7 (SAS Institute, Cary, North Carolina, USA), and in all cases significance was assessed with $\alpha = 0.05$.

RESULTS

Our selected households were located between <1 and 48 km from the Saint Paul city center along a gradient of housing density from 6 to >1168 housing units/km². Among the biophysical factors we studied (Table 1), the geographical housing distribution showed that the landscaped area increased with decreasing dwelling age and that newer dwellings were located farther from the city center, in areas of decreasing housing density.

Total element fluxes

Across our sample of households, total C, N, and P input fluxes showed large variability (Table 2), were significantly skewed, and departed significantly from the normal distribution (Fig. 3, Table 3), supporting our first hypothesis that total fluxes exhibit disproportionality. Total C and N input fluxes were consistent with the gamma distribution (Table 3; Appendix B). Total P input flux departed from the gamma distribution, likely because the largest contributors to this flux depend on the number of household members (human diet, fixed per capita amount of detergents and the like to wastewater), which caused this flux to have a tendency toward bimodality unlike the other fluxes (Fig. 3). Due to the positive skewness of the element fluxes in our sample, ~30% of the sampled households were responsible for 50% of total input fluxes summed across all households (Fig. 4). Further, we observed significant pairwise correlations among all three aggregate fluxes ($P < 0.001$).

Among the biophysical drivers of total fluxes, number of household members was significantly related to total C, N, and P fluxes in bivariate and multiple regressions

TABLE 1. Main biophysical characteristics of the 360 households selected for this study of carbon, nitrogen, and phosphorus fluxes in household ecosystems in Minneapolis-Saint Paul, Minnesota, USA.

Characteristic	Mean	SD	Min.	Max.
Number of household members	2.6	1.2	1	8
Finished floor area (m ²)	138	49	45	348
Lawn area (m ²)	1457	3118	162	37556
Age of house (yr)	49	27	5	124
Distance from Saint Paul city center (km)	15	10	0.4	48

(C, see Tables 4 and 5; N, $P < 0.001$, $R^2 = 0.22$; P, $P < 0.001$, $R^2 = 0.87$). Increasing distance from the city center and increasing property size (both house finished floor area and landscape area) corresponded to an increase in C input fluxes (Table 4). Increasing house age resulted in a decrease in total C and an increase in total N input fluxes (C, Table 4; N, $P < 0.0001$, $R^2 = 0.11$). The nonintuitive negative relationship between total C flux and house age was significant in bivariate regression (Table 4) but not in multiple regression (Table 5), likely because of significant correlations between house age and finished floor area, distance to the city center, and housing density ($r = -0.18, -0.59$, and 0.63 , respectively, $P < 0.001$ in all cases); older homes tended to be smaller and located in higher density neighborhoods, factors that were associated with lower total C flux.

Component fluxes of elements through the household

Total fluxes of elements through the household described previously are derived from the sum of the multiple component fluxes (Fig. 2, Table 2). A small number of different household activities constituted a large fraction of each element budget, as shown in Fig. 5 and described in the following sections.

Carbon.—As hypothesized, a few household activities dominated C fluxes. Specifically, transportation (motor vehicle and air) and home energy consumption (Fig. 5, Table 2) together accounted for an average of 85% of total household C inputs. There was high variability in the contribution of each component to the total C flux, and every component C input flux departed significantly from the normal distribution (Appendix B). Some of the component fluxes were significantly skewed (both motor vehicle and air transportation), whereas others tended more toward a normal distribution (e.g., home energy use) as evidenced by larger values of the parameter α of the fitted gamma distribution (Appendix B). For example, 20% of households contributed >75% of air travel C emissions (Fig. 6), whereas 42% of the respondents reported no flights in the previous calendar year and 28% and 14% of households reported one or two flights per year, respectively. Motor vehicle transportation varied among households between 2% and

TABLE 2. Summary of (a) input and (b) output fluxes of C, N, and P relative to the main components analyzed in the HFC, and percentage contribution of each component to the total flux.

Component	Carbon (kg C-household ⁻¹ .yr ⁻¹)				Nitrogen (kg N-household ⁻¹ .yr ⁻¹)				Phosphorus (kg P-household ⁻¹ .yr ⁻¹)			
	Mean	SD	Range	% of total	Mean	SD	Range	% of total	Mean	SD	Range	% of total
a) Input fluxes												
Motor vehicles	3012.7	1942.5	84–14 200	37	11.4†	7.1	0.3–52	21				
Air travel	624.2	1166.5	0–13 328	8	2.9†	6.7	0–81	5				
Home energy	3260.5	1073.8	88–10 046	40	1.3†	0.5	0–3	2				
Human diet	306.0	153.9	66–986	4	21.7	10.8	5–69	40	2.1	1.0	0.5–6.6	51
Pets												
Dogs	16.8	34.6	0–273	0	1.5	3.1	0–25	3	0.3	0.7	0–5.3	8
Cats	2.0	3.5	0–19	0	0.2	0.4	0–2	0	0	0.1	0–0.4	1
Landscape‡	723.2	1521.1	40–13 771	9	13.6	23.0	0.2–322	26	0	0.1	0–3.7	1
Plastic	55.4	27.0	22–173	0								
Paper	158.2	70.8	39–445	2								
Wastewater§	29.5	14.5	11–84	0	1.8	0.8	0.7–5.7	3	1.6	0.8	0.6–4.8	39
Total input fluxes	8188.5	3489.4			54.4	34.0			4.0	2.0		
b) Output fluxes												
Motor vehicle	3012.7	1942.5		38	11.4†	7.1		29				
Air travel	624.2	1166.5		8	2.9†	6.7		7				
Home energy	3260.5	1073.8		41	1.3†	0.5		3				
Human diet												
Total	306.0	153.9		4	21.7	10.8		53	2.1	1.0		52
To waste water	8.4	4.4			16.8	9.9			1.5	0.8		
To landfill	24.2	13.7			4.2	0.1			0.5	0.3		
Composted	3.7	8.5			0.7	1.8			0.1	0.1		
Respired	269.7	137.8										
Pets												
Dogs	16.8			0	0.2¶	0.3		0	0.1¶	0.3		4
Cats	2.0	3.5		0	0.2	0.4		1	0	0.1		1
Landscape	409.9	860.1		5	1.4	6.0		3	0.1	0.7		3
Plastic	55.4	27.0		1								
Paper	158.2	68.4		2								
Wastewater§												
Various sources	8.4	18.7			16.8	9.9			1.5	0.8		
Detergents, etc.	29.5	14.5		1	1.8	0.8		4	1.6	0.8		40
Total output fluxes	7874.9				39.7				4.0			
Accumulation	313.6				12.9				0.1			

Notes: Values refer to 360 surveyed households. Zero values indicate that the estimated value was <0.05. Accumulation of elements results from the difference between inputs and outputs. In panel (b), values in italics are shown for clarification only, as they are already included in the total for the human diet component.

† Creation of reactive N from fuel combustion.

‡ To avoid double-counting, this value of inputs to the landscape does not include pet waste.

§ Inputs to wastewater as detergents, toilet paper, etc. Various sources to wastewater include C, N, and P as food waste and food used for human nutrition that cycle through wastewater before leaving the household system. These fluxes are accounted for in the human diet component.

¶ A portion of the elements in dog food cycles through the landscape before leaving the household system and contributes to N and P accumulation; hence inputs do not equal outputs.

73%, air travel between 0% and 58%, and home energy consumption between 4% and 81% of total household C input fluxes.

Additional C (Table 2) entered through the landscape, mainly as tree and grass NPP, plus minor fluxes such as pet waste and lawn mower gasoline. On average, 57% of this C input left the landscape through heterotrophic respiration, in situ leaf litter decomposition, and removal of leaf litter and grass clippings, with additional minor export due to dog feces decomposition and lawn mower fuel combustion. The remaining 43% of landscape C inputs accumulated in the landscape (averaging

3.5% of total C inputs), specifically in woody material and soil.

Inputs of human food among households varied mainly in relation to the number of household members and type of diet, and outputs were in the form of respiration, food waste, and wastewater (Table 2). Smaller input fluxes of C to the household came from pet diet and paper and plastic consumption (Table 2). Paper and plastic entirely left the household to recycling and landfill.

There was fourfold variation in total C input fluxes between the 10% of households that showed the lowest

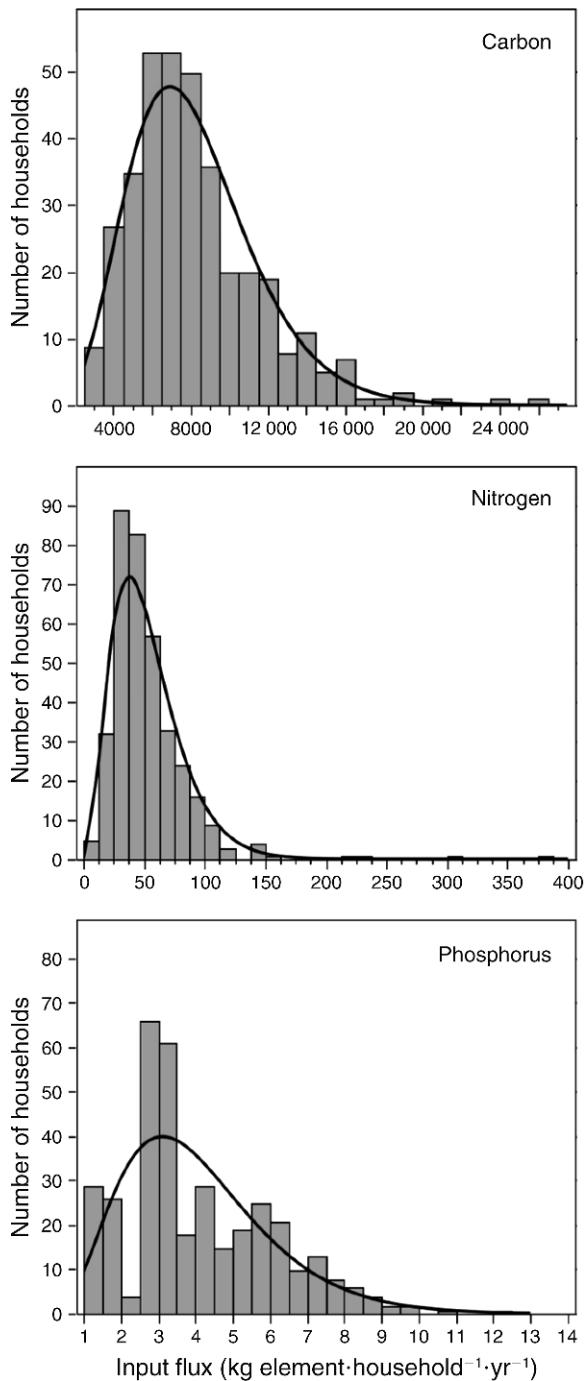


FIG. 3. Histograms of total C, N, and P input fluxes across the sample of 360 households with fitted gamma distributions indicated by solid lines (parameters given in Table 3). Note the different scales on the horizontal axes.

consumption and emissions and the 10% of households with the highest consumption and emissions (Fig. 7). Among the larger component fluxes, motor vehicle transportation, air travel, and landscape C fluxes showed large differences (6-, 16-, and 9-fold variation between these lowest and highest groups, respectively),

TABLE 3. Main statistical parameters describing distributions of total fluxes represented in Fig. 3.

Parameters	Carbon	Nitrogen	Phosphorus
Mean (kg·household ⁻¹ ·yr ⁻¹)	8188	54	4
SD (kg·household ⁻¹ ·yr ⁻¹)	3489	34	2
Skewness	1.4†	4.0†	0.8†
Skewness SE	0.1	0.1	0.1
Normal goodness-of-fit P‡	<0.0001	<0.0001	<0.0001
Gamma distribution			
α	6.2	3.4	4.2
σ	1335.6	15.5	1.0
Goodness-of-fit P§	0.1	0.7	0.018

† Skewed distributions ($P < 0.05$).
 ‡ Shapiro-Wilk test; $P < 0.05$ rejects the null hypothesis that the data were drawn from a normal distribution.
 § Cramér-von Mises W^2 test; $P < 0.05$ rejects the null hypothesis that the data were drawn from a gamma distribution.

whereas home energy C emissions showed only twofold variation between low and high consumption groups (Fig. 7). Proportionally, motor vehicle transportation represented 25% and 37%, air travel 3% and 11%, and home energy use 55% and 28% of total C fluxes in low- and high-consumption household groups, respectively (*data not shown*).

Among the biophysical drivers of component fluxes, greater motor vehicle C emissions were positively related to increased distance from the city center and decreasing housing density, and these C emissions were significantly and positively related to number of household members (Tables 4 and 5). There was a weak, although significant, negative relationship between household air travel C emissions and distance from the city center and a positive relationship with number of household members (Tables 4 and 5). Air travel was typically used

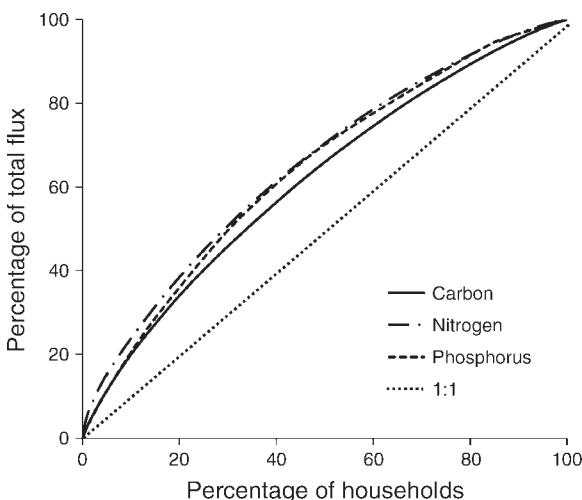


FIG. 4. Cumulative percentage contribution of households to total C, N, and P input fluxes across all households, ranked from highest to lowest contributor. The 1:1 line is also shown, where each household would be contributing equally to the total fluxes.

TABLE 4. Results of bivariate linear regression analyses of total C fluxes and a subset of the component C fluxes with biophysical variables as predictors ($n = 360$ households).

Variable	Components of household activities											
	Air travel				Motor vehicle				Home energy			
	y_0	a	R^2	P	y_0	a	R^2	P	y_0	a	R^2	P
No. household members	179	174	0.03	0.004	1244	691	0.20	<0.0001	2535	283	0.11	<0.0001
Distance from city center (km)	917	-20	0.03	0.001	2495	35	0.03	0.0006				0.5
Housing density category				0.2	4317	-251	0.03	0.0015	3774	-99	0.14	0.024
House finished floor area (m ²)	-700	10	0.17	<0.0001	1589	10	0.07	<0.0001	1808	11	0.24	<0.0001
Landscape area (m ²)				0.7				0.08	3190	0	0.02	0.0073
House age (yr)				0.7	3941	19	0.07	<0.0001				0.2

Notes: Shown are the intercept (y_0), slope (a), and statistics for the regression relationships between biophysical predictors and component or total flux. Significant predictors ($P < 0.05$) are indicated in bold.

by household members for long-distance trips spanning 356–10398 km (on average 2924 ± 1561 km, mean \pm SE) that mostly took place within the United States (81% of all trips). A weak but significant relationship was also found between air and motor vehicle travel patterns across households. Carbon emission due to home energy use was positively related to number of household members and house finished floor area and negatively related to increasing housing density, but was not related to house age (Tables 4 and 5).

Landscape C input was positively related to the landscape area and distance from the city center and negatively related to house age (Tables 4 and 5). Landscape size significantly increased with increasing distance from city center and decreasing housing density.

Nitrogen.—Household N fluxes were dominated by a few components, namely human diet, landscape, and travel-related creation of reactive N via combustion, which represented 40%, 26%, and 25% of total N input fluxes, respectively (Fig. 5, Table 2). Among these, landscape flux distribution was the most skewed, followed by travel and then human diet N fluxes (Fig. 8; Appendix B). The largest flux of N was associated with human food. Food N left the household solely via wastewater and garbage (to landfill or incinerator) or was composted in situ. The second largest N flux was through inputs to the landscape, mostly as fertilizer (Table 2). Per unit area N fertilizer application rates

were variable and skewed. Similarly, the distribution of total household fertilizer applied, which was a function of both per unit application rates and landscape area, was variable and skewed (Table 6, Fig. 8). The removal of grass clippings and leaves from the property represented a loss of N (on average $7\% \pm 27\%$ and $28\% \pm 86\%$ of total N input to the landscape for grass clippings and tree leaves, respectively). Transportation-related and home energy N fluxes as NO_x were a function of fuel consumption and thus followed a similar distribution and were affected by similar biophysical factors as described for C fluxes in *Results: Carbon*. Other significant inputs of N resulted from the use of detergents, toothpaste, and the like that we could not quantify independently at the household level; hence, input and output fluxes were estimated on a fixed per capita basis. Additional minor fluxes of N (<3 kg N-household⁻¹·yr⁻¹) through the household were due to pet food intake (Table 2). Accumulation of N occurred in the landscape, specifically in soil (3.3 ± 9.1 kg N-household⁻¹·yr⁻¹) and wood (1.7 ± 4.0 kg N-household⁻¹·yr⁻¹). An undifferentiated flux of N (estimated as inputs minus accumulation) was presumed to include runoff, leaching, nitrification, and denitrification and to leave the household system. On average, households exhibited undifferentiated N losses; for 82% of households, inputs (plus any exports through leaf litter and lawn clippings) exceeded requirements for

TABLE 5. Multiple regression models of biophysical drivers of component and total household C input fluxes determined using backwards stepwise regression.

Component fluxes	Model	R^2	P
Air travel	$-587.2^{**} - 18.3 \times \text{DI}^{**} + 9.0 \times \text{HA}^{***} + 96.3 \times \text{HH}^*$	0.19	<0.0001
Motor vehicle	$789.6 - 10.2 \times \text{AH}^* + 20.4 \times \text{DI}^* + 6.1 \times \text{HA}^{**} + 622.5 \times \text{HH}^{***}$	0.27	<0.0001
Home energy	$1403.3^{***} + 9.3 \times \text{HA}^{***} + 0.1 \times \text{LA}^* + 204.3 \times \text{HH}^{***}$	0.30	<0.0001
Landscape	$1172.8^{***} + 6.0 \times \text{AH}^{***} - 257.3 \times \text{DS}^{***} + 0.5 \times \text{LA}^{***}$	0.83	<0.0001
Total	$2570.7^{**} - 258.7 \times \text{DS}^* + 24.9 \times \text{HA}^{***} + 0.5 \times \text{LA}^{***} + 1112.6 \times \text{HH}^{***}$	0.56	<0.0001

Notes: Only predictors significant at $P < 0.05$ were included in the models. DI, distance from Saint Paul city center in km; DS, housing density; HA, house finished floor area in m²; HH, number of household members; AH, age of house in years; LA, landscape area in m². Significance of predictors is indicated by asterisks.

* $P < 0.05$; ** $P < 0.005$; *** $P < 0.0005$.

TABLE 4. Extended.

Components of household activities							
Landscape				Total			
y_0	a	R^2	P	y_0	a	R^2	P
-270	70	0.18	0.6	4866	1307	0.20	<0.0001
4394	-701	0.32	0.0001	6908	89	0.6	<0.0001
			0.2	3526	34	0.22	<0.0001
72	1	0.81	<0.0001	7388	1	0.24	<0.0001
1398	-13	0.05	<0.0001	9928	-35	0.07	<0.0001

plant uptake and soil accumulation, resulting in losses of N from the landscape (*data not shown*).

Given our methods, N input fluxes through human diet as food were significantly and positively related to the number of household members ($P < 0.0001$, $R^2 = 0.92$, $n = 360$). Across the surveyed households, 88% of total household members reported having a meat-based diet, 5% were lacto-ovo vegetarian, and none was vegan. Seven percent of household members either did not provide diet information or reported being both vegetarian and meat eaters. For those individuals we assumed a meat-based diet. The flux of N through the landscape decreased with increasing house age ($P < 0.0001$, $R^2 = 0.10$, $n = 360$) and housing density ($P < 0.0001$, $R^2 = 0.26$, $n = 360$) and was also (not surprisingly) positively related to landscape area ($P < 0.0001$, $R^2 = 0.26$, $n = 360$) because we assumed that households using fertilizer applied it to the entire property. Accumulation of N in both soil and wood increased significantly with increasing landscape area. The size of the undifferentiated N flux was positively related to total N fertilizer application rates for the entire landscape area ($P < 0.0001$, $R^2 = 0.73$).

Phosphorus.—As hypothesized, the largest contribution to household P input fluxes derived from a few components of human activities, namely human diet as food, detergents and the like, and pet food, that together accounted for 98% of total P input fluxes through the household (Fig. 5, Table 2). Flux distribution was skewed for pet P inputs while human diet, as already observed for C and N fluxes, was less skewed (Fig. 9; Appendix B). The amount of P input as food varied between 0.5 and 6.6 kg P-household⁻¹·yr⁻¹ and was significantly related to the number of household members ($P < 0.0001$, $R^2 = 0.92$). Inputs of P from detergents, toothpaste, and the like (as already discussed for C and N) were estimated on a per capita basis rather than being directly surveyed or otherwise measured. Among the 360 respondents, 32% were dog owners and 33% were cat owners, which resulted in total inputs of P as pet food between 0.3 and 5.7 kg P-household⁻¹·yr⁻¹, part of which constituted an input of P to the lawn (Appendix B). Accumulation of P in the landscape occurred both in soil (0.5 kg P-household⁻¹·yr⁻¹) and

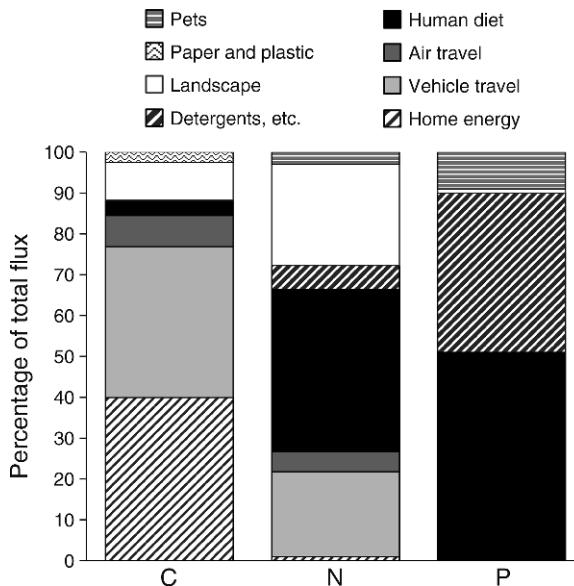


FIG. 5. Relative contribution of different component household activities to total input fluxes of C, N, and P. Stacked bars sum to 100% of total fluxes. Error bars for each component of total fluxes were omitted for clarity. For all fluxes except the landscape, inputs equal outputs; for the landscape, a portion of the input C, N, and P is stored in plants and soils, and the remainder is lost in various forms if inputs exceed requirements for uptake by plants and soils, along with exports in leaf litter and grass clippings (see also Table 2).

wood (0.2 kg P-household⁻¹·yr⁻¹) and was positively related to the landscape area ($P < 0.0001$). On average, for 19% of the households, inputs (plus any exports in leaf litter and grass clippings) exceeded P requirements by vegetation and soils, resulting in losses of P from the landscape (*data not shown*). This percentage of households was much lower than for N (82%).

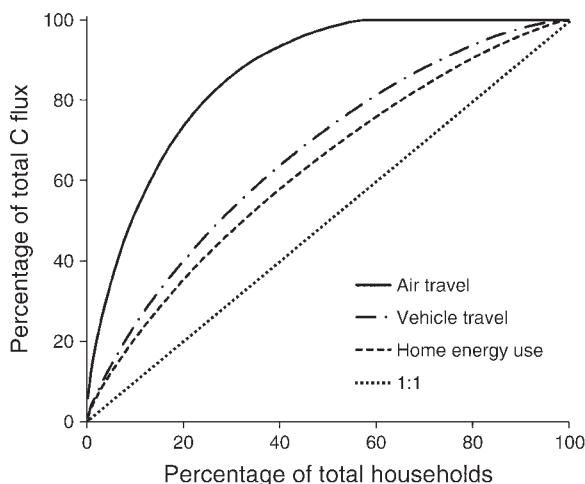


FIG. 6. Cumulative percentage contribution of households to total air, motor vehicle, and home-energy-use C fluxes across all households, with households ranked from highest to lowest contributor. The 1:1 line is also shown, where each household would be contributing equally to the total fluxes.

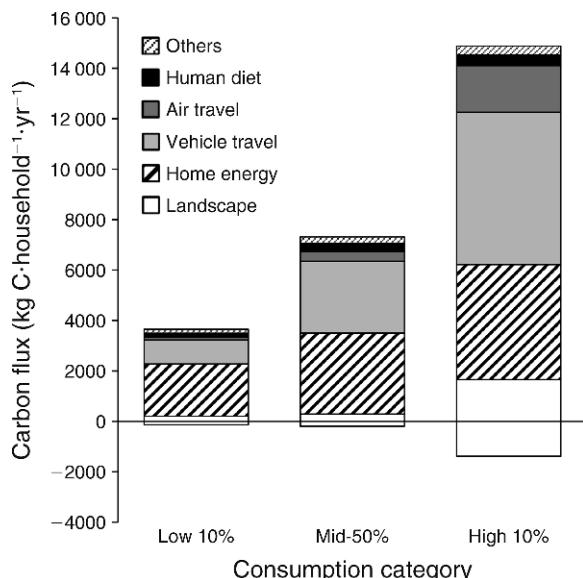


FIG. 7. Output carbon flux variability among households within the 10% lowest (0–10% flux), mid-10% (45–55% flux), and 10% highest (90–100% flux) consumption categories. Landscape C flux was partitioned as C that accumulates (negative bar) and the net output of C resulting from the difference between total input fluxes and total accumulation (positive bar). Error bars for each component of total fluxes were omitted for clarity.

DISCUSSION

Flux distribution and variability

Our study supports our first hypothesis in demonstrating that there is high household-to-household variability in total household macroelement fluxes and

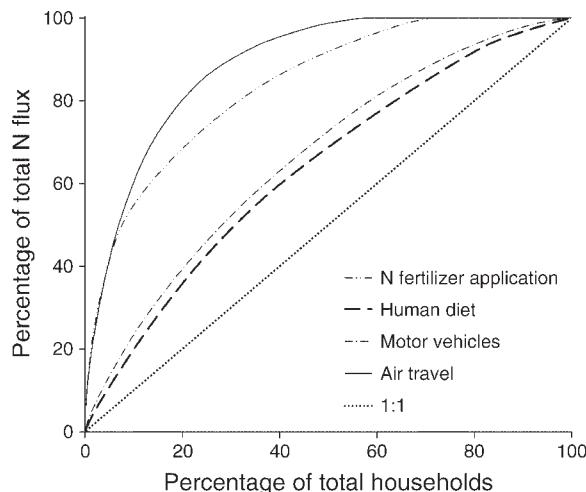


FIG. 8. Percentage contribution of households to total N fluxes associated with fertilizer use, human diet, air travel, and vehicle transportation across all households, with households ranked from highest to lowest contributor. The 1:1 line is also shown, where each household would be contributing equally to each flux.

TABLE 6. Distribution of assumed N fertilizer application rates across the 360 surveyed households.

No. fertilization events/yr	N fertilizer application rates (kg N·ha ⁻¹ ·yr ⁻¹)	Households (%)
0	0	28.1
1–2	73	40.3
N/A†	159†	16.4
3–4	171	14.4
≥5	244	0.8

Notes: Rates are based on number of fertilization events (0, 1–2, 3–4, or ≥5) that homeowners reported on the survey for the year 2007–2008. For application events of 1–2 and 3–4 we used midpoint N application rates, assuming 48.9 kg N·ha⁻¹·yr⁻¹ being applied per event. For reported ≥5 application events/yr we assumed five events.

† This rate was assumed for all households that used a commercial lawncare company because this was the average rate applied by the lawncare company most commonly used by respondents to our survey (TruGreen, personal communication).

that these fluxes departed significantly from the normal distribution and were highly skewed. For example, C and P input fluxes varied 10-fold and N input fluxes varied 30-fold across our sample of 360 households. The variability among 360 households was greater than the range between the low and high consumption scenarios we developed in an earlier study of a smaller sample (35) of households within a single neighborhood of the Twin Cities region (Baker et al. 2007), likely because Baker et al. (2007) modeled household scenarios of two adults and two children within a single city neighborhood. The current study is larger and includes a broader range of household members (1–8 members), house sizes and ages, and distance from the city center, with households distributed along a broad urban-to-exurban gradient. Our results are consistent with the observed 10-fold

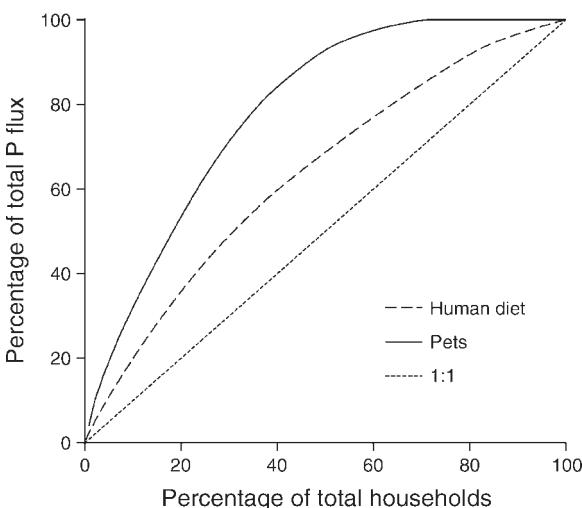


FIG. 9. Percentage contribution of households to P input fluxes associated with human diet and pet food for all households, with households ranked from highest to lowest contributor. The 1:1 line is also shown, where each household would be contributing equally to each flux.

difference between “high and low impact” households from an expenditure-based estimate of household CO₂ emissions for the United States (Weber and Matthews 2008). Similarly, other studies observed a disparity in household CO₂ emissions of 64% between high and low emitter groups (Druckman and Jackson 2009). Such findings are important in the context of urban metabolism (*sensu* Wolman 1965) in that they quantify household-level amounts of energy and material fluxes (and consequently element fluxes) associated with urban human activities that could potentially inform the design of more effective policies to reduce fluxes. A city’s dependence on surrounding ecosystems is a well-known and common characteristic of cities worldwide (e.g., Odum 1989, Rees and Wackernagel 1996) that is likely exacerbated by a general increase in consumption, driven disproportionately by a relatively small fraction of the human population with high consumption patterns, such as those highlighted in our study.

The observation that the total fluxes departed significantly from a normal distribution and instead followed, for the most part, a gamma distribution is in line with the long-standing theoretical view in consumer behavior that consumption by an individual or a household (frequency of purchase of a good) follows a Poisson distribution, but that the rate of consumption varies among consumers, resulting in a gamma distribution for the population as a whole (Ehrenberg 1959, Goodhardt and Chatfield 1973). This suggests that consumer behavior theories could provide modeling approaches that would be useful as part of a predictive model of household element fluxes. Although our flux calculations were driven by a number of factors in addition to the rate at which goods were purchased, the result that nearly all of the fluxes followed a gamma distribution is consistent with the hypothesis that consumption patterns are key drivers of household biogeochemical fluxes.

The right-skewed distribution among total fluxes and several component fluxes indicates that a large number of the households exhibited lower than average consumption and emissions, while a small number contributed a large proportion of the total fluxes. Our results support the notion that complex interactions among a number of factors, including biophysical and socio-demographic factors, contribute to disproportionality (Nowak et al. 2006) and large variation in consumption patterns among households (Druckman and Jackson 2008).

Carbon fluxes.—As we hypothesized, the largest proportion of total C fluxes through the 360 surveyed households was related to a few component fluxes (travel and home energy use), and these components showed high household-to-household variability. For instance, the difference in total C fluxes between the average of the bottom vs. the top 10% of households was in large part due to differences in motor vehicle and air travel, whereas differences in home energy C emissions

were much smaller. Home energy C emissions accounted for a larger proportion of total C fluxes in the lowest 10% of households compared to the highest 10%, whereas air and motor vehicle C emissions accounted for a larger proportion in the high consumption group, likely as a response to different drivers of element fluxes among groups.

On average, 40% of total household C inputs were related to home energy use, which was the largest flux of C through the household. This C flux was near normally distributed across households, reflecting the minimal variation between high and low consumption groups of households. Nearly one-third of the variability in home energy use was explained by a few biophysical variables, particularly the number of household members and the finished floor area of the house, consistent with a study in Ireland (Kenny and Gray 2009). For an average size house, the regression equation for home energy shows that increasing the number of household members from one to four would increase C emissions from household energy use by 20%. Although it is reasonable to expect that energy use might be more efficient with increasing number of household members (e.g., because of shared energy used for heating), home energy C emissions did not level off as the number of household members increased, although this effect may have been difficult to detect because of the small number of households with more than five members. The large and near normally distributed C flux for home energy justifies the increasing attention that this sector has received from both the scientific community and policy makers (Gardner and Stern 2002), in part because of the large potential for reducing emissions in this sector (Dietz et al. 2009).

Household motor vehicle C emissions were the second largest contributor to total household C emissions. Household vehicle travel (in kilometers per year) was very similar to the average reported for the West North-Central Region of the United States (EIA 2005). A large fraction (nearly one-third) of the variability in vehicle C emissions was related to a few biophysical variables, namely, housing location and number of household members. Increased distance from the city center was associated with greater distances driven by family members and consequently greater C emissions, possibly as a response to individuals’ need to access workplaces and services that are typically located near the city center (Khan 2000, Nicolas and David 2009). However, correlations between distance from the city center or housing density and C emissions due to vehicle travel were weak. It is likely that these terms alone did not capture the complexity of the effect of geographic agglomeration of commodities (e.g., clusters of services located in many suburban areas) on household travel patterns (Huisman 2005, Nicolas and David 2009). A larger number of household occupants was associated with substantially more miles driven and vehicle C emissions; for example, adding two members to the

average household increased vehicle C emissions by 40% (estimated using the regression equation in Table 5). Our findings show that larger families owned more vehicles, drove more, and had higher C emissions, in contrast to a study in Ireland that found that C emissions due to transportation and number of vehicles decreased with increasing number of household members (Kenny and Gray 2009).

Household air travel was the third most important contributor to total household C emissions and was characterized by high disproportionality and skewness. Notably, the total air travel C flux for the sample of 360 households resulted from the activity of only about one-half of the respondents. Consistent with other studies (Kenny and Gray 2009), the number of household members was correlated with this flux, with air travel C emissions increasing with increasing number of household members. However, based on our results and on the regression equation in Table 5, adding an additional household member to the household mean (2.6 members) with average finished floor area and distance from the city center added only 15% to air C emissions. This is consistent with the observation that other variables (e.g., income) also likely contribute to variation in household air travel C emissions (Stokes et al. 1994, Druckman and Jackson 2009) and may help explain why our results are higher than the U.S. average (USDOT 2010).

Households were highly variable in terms of inputs of C to the landscape. Not surprisingly, the variability in both inputs and accumulation was mostly related to variation in landscape area, with greater input fluxes and C accumulation in larger properties. Larger properties had more trees and, therefore, higher biomass C. Because larger properties were located at greater distance from the city center, C inputs to and accumulation in the landscape increased along the urban-to-exurban gradient.

Even though the landscape NPP contributed only 9% of total household C inputs, the landscape was the only component that stored elements (in soil and wood). Yet, on average, the C sequestration in the landscape was modest compared to total and component C emissions, only 3.5% of total household C inputs, and equivalent to about one-half of the average air travel C flux. Such quantification of the C sequestration associated with household landscapes can only be determined using the kind of detailed, ground-based vegetation assessments in combination with extensive survey information employed in this study.

Nitrogen and phosphorus.—The most significant N and P inputs to the household occurred as food to support human nutrition. The majority of the respondents in our study reported a meat-based diet. Such homogeneity in diet types among respondents, as well as our practical decision not to resolve meat-based diets further among respondents, was reflected by the fact that the diet-related N and P input fluxes tended toward a normal distribution. For P, we assumed a constant

value of 0.3% (by mass) of diet for all household members. As a consequence, household-to-household variation in these fluxes was primarily related to the number of household members.

Our study indicates that the direct fluxes of elements are substantially influenced by diet choice. For example, if all 813 household members reporting a meat-based diet were to switch to a lacto-ovo vegetarian diet, this switch would decrease direct N fluxes through food intake by 1024 kg N/yr (or 1.1 kg N per capita per year; *data not shown*). This value roughly corresponds to one-fourth of all N applied as fertilizer among the 360 households surveyed or all N derived from air travel emissions. This hypothetical reduction in N flux is significant considering that current N flux through food intake represented 50% of total N input flux to the household and considering the growing concern regarding the sustainability of feeding a population that increasingly relies on meat for its nutrition (Galloway et al. 2002, Smil 2002). Explicit consideration of N used to produce food (in addition to the direct fluxes of N contained in food) likely would exacerbate this difference among diets, as more N is required to produce meat than vegetable protein (Galloway and Cowling 2002).

Landscape N fertilizer application, which was the major input of N to the landscape and the second most important N flux to the households, drove the highly disproportional and skewed flux of N through the landscape (Appendix B). About 75% of all respondents either did not fertilize or applied small amounts of N fertilizer once or twice per year, while the highest 25% of households contributed disproportionately to total N inputs across all households. On a per unit area basis, N fertilizer application was higher in more recent housing developments that were typically located in low-density exurban areas. These findings confirm those by Law et al. (2004), who found that for two suburbs in Baltimore, Maryland, the newest homes received greater fertilizer application. For the majority of households, N inputs to the landscape exceeded N requirements for plant uptake and soil accumulation plus human exports as leaves and lawn clippings, resulting in losses of N from the landscape that potentially have detrimental environmental consequences. Our analysis may have overestimated landscape N losses because we assumed that households using fertilizer apply it to the entire property, an assumption that may be incorrect for large properties. Further analyses of the landscape N budget are planned that will determine under what conditions N entering the landscape as fertilizer is in excess of what is needed to support landscape accumulation. Such findings will have important implications for environmental pollution that extends over the boundaries of urban ecosystems and will provide useful insights into the role of household decision-making on urban N cycling.

In contrast with N, P inputs to the landscape, on average, were less than what was needed to support uptake of P by vegetation and soils along with human

exports in leaf litter and grass clippings, resulting in no additional landscape P losses. Indeed, 81% of households exhibited no P losses besides human exports, suggesting that a 2007 statewide law restricting P in lawn fertilizer (Minnesota Phosphorus Lawn Fertilizer Law) has been successful in reducing landscape P losses and improving water quality. With that restriction in place, wastes produced by dogs (present in one-third of households) represented the dominant source of P to the landscape and contributed 8% of total P input fluxes. Thus, this seemingly negligible and often ignored component of the total household P budget is a significant part of household (and urban) nutrient cycling. This flux may have negative environmental effects given that this P can leave the landscape via stormwater without receiving any treatment and can potentially contribute to pollution of downstream water bodies. With the exception of limited work on the topic, which was mostly conducted in city parks (Sussman 2008, EPA 2009), we are not aware of any other household nutrient budget study that quantifies the contribution of household dogs to the cycling of P in urban ecosystems through the household landscape.

The input data we gathered to calculate the total and component fluxes for each household using the HFC were subject to uncertainties that varied in both source and degree. A large proportion of the input data were self-reported by homeowners who returned a mailed survey. Self-reported information is subject to underreporting (e.g., where questions are complex and time-consuming to answer, or where responses could be embarrassing) and bias (e.g., underestimating mass). Formal quantification of the uncertainty associated with self-reported data is generally unfeasible due to a lack of information concerning the error distribution around each coefficient. In the following paragraph, we discuss the nature of the errors we would expect for key component fluxes.

In the case of vehicle travel, errors in self-reported data may arise from rounding the odometer reading, whereas it is more likely that car make, model, and year of purchase were reported correctly. Such rounding would not be expected to affect the shape of the distribution curve for the population as a whole. Air travel trips could have been underreported, perhaps to a greater degree by frequent travelers (because of difficulty in remembering a large number of destinations or because of the time required to enter a long list of trips into the survey form). To the extent that this type of self-reporting error occurred, we expect it would be reflected in lower-than-actual values in the right tail of the right-skewed distribution. Therefore, we would expect that the true distribution of fluxes due to air travel could be more strongly skewed than we have reported.

In the case of N and P flux distributions, the input fluxes associated with human diet depended on self-reported values of household members' heights and masses, which are typically overreported and underre-

ported, respectively. Similarly, household members' daily activity was likely overreported. It is difficult to predict how such errors may have affected the distributions of the fluxes, but it is reasonable to expect that, in the absence of such errors, human diet N and P would tend to be less normally distributed than we have reported here. The number of N fertilizer application events was likely underreported by medium users. In contrast, we believe that the self-reported data are more accurate for households reporting no fertilizer applications as well as for those at the high end, most of which reported using lawn care companies, which are very systematic in their lawn-management practices. Based on these considerations, we do not believe that adjusting for underreported values would significantly affect the skewness of the distributions of N fertilizer application and human diet N and P fluxes. A large input flux of P is through household chemicals, and this value was obtained from the literature. It is not clear whether this value is an under- or overestimate of the P that actually enters the household in the form of detergents and other household cleaning products. In any case, the resulting flux distribution would not be affected by the adjustment because it was calculated on a per capita basis. The remaining component flux distributions for C, N, and P also are potentially affected by self-reporting error, but their impact on the household totals is small, such that we would not expect them to significantly affect the comparisons among components or our conclusions about their distributions across the population.

Implications for air and water pollution and policies

Analysis of household element fluxes can inform design of more effective policy in two major ways. First, given that households are significant contributors to the total element budgets of cities and regions (e.g., Bin and Dowlatabadi 2005), such analyses can indicate which component fluxes are most important in influencing overall element fluxes and therefore could be effective foci of policy design efforts. For example, mitigating air pollution due to C emissions will require reducing home energy use, first and foremost, along with motor vehicle and air travel, while other fluxes, such as paper and plastics, represent more minor contributions to overall C fluxes. Second, household analyses enable determination of the distribution of fluxes among households, also potentially useful for informing policy design. For example, fluxes that more closely follow a normal distribution among households, with lower variance, might respond best to policies that affect all households more or less equally. By contrast, component fluxes that are highly variable and skewed might respond best to policies that target the small proportion of households with highest emissions. For example, Chakravarty et al. (2009) argued for a global cap on individual, rather than national, CO₂ emissions because high emitters are located in all countries, rich and poor alike. They point to the need for household surveys to better understand

distributions of CO₂ emissions and develop policies to implement a threshold approach. Although our study is a major step in that direction, understanding the distribution of fluxes is only a first step; our ongoing research seeks to understand socioeconomic and behavioral drivers that influence household elemental fluxes.

Our results provide further evidence justifying recent attention to environmental pollution due to motor vehicle and air travel, as a large proportion of total household C and N fluxes in this study was due to transportation. To mitigate the increasing C and N emissions due to air transportation, a suite of approaches has been undertaken or proposed, from the development of new technologies to reduce aircraft fuel use (Clery 2009) to the introduction of abatement policies (Jamin et al. 2004) and the promotion of direct flights. In the United States, two-thirds of air travel is for personal purposes and, therefore, is directly linked to household activities. Our results suggest that strategies that aim to reduce C emissions by reducing air travel might consider the skewed nature of air travel C emissions among households, perhaps by specifically targeting those households with high emissions. However, such an approach would have to consider the underlying social factors responsible for the skewed distribution and, in particular, the level of control that household members have over their air travel activity (e.g., personal vs. business travel).

In contrast to transportation, home energy use, also a large contributor to household C fluxes, was less skewed among households despite high household-to-household variability. The positive relationship between finished floor area and home energy consumption in the context of the cold climate of Minnesota suggests that much of home energy use is for heating, which is likely related to house size. The near-normal distribution of home energy C fluxes among households suggests that the introduction and promotion of energy efficient technologies will likely achieve CO₂ emission reductions from home energy use if applied to the entire population (Ashina and Nakata 2008, Kenny and Gray 2009).

Household N and P fluxes associated with diet and landscapes have the potential to affect regional water quality (Randall et al. 1998, Baker 2009). Cities across several climate regimes “leak” between 5% and 25% of total N inputs (excluding those associated with fossil fuel combustion) to rivers (Baker et al. 2001, Groffman 2004, Gu et al. 2009), with additional N being leached to groundwater (Baker et al. 2001). Nearly one-third of total P input to the Minneapolis-Saint Paul urban region is exported to rivers and of this ~50% is directly associated with household activities (L. Baker, *unpublished manuscript*).

Our study demonstrates that the largest inputs of N to households relate to human diet (i.e., food used for human nutrition) and to N that enters the landscape, mostly as fertilizer. These two input sources have different fates in the environment, with distinct pollution

potential. The majority of N from human diet ends up in septic systems or in sewage treatment, where the pollution effect is mitigated only if a tertiary treatment system is present. By contrast, fertilizer N, if in excess, is exported through stormwater or groundwater, entering lakes and streams in its untreated form. Thus, any reduction in N fertilizer application at the high end of the distribution would potentially improve water quality, and policies regulating N fertilizer application might be most effective if they targeted households with high fertilizer use that are responsible for the majority of landscape N fluxes.

Although small relative to other household fluxes, pet food results in important inputs of N and P to household landscapes. About 40% of total feces and all urine from household dogs enters the landscape (Swann 1999), which in our study translates into 91% of N and 56% of P in pet food. Inputs of N and P to the landscape from pets have the potential to be lost through stormwater if the total inputs exceed plant uptake and soil accumulation and exports of leaf litter and grass clippings. The issues of environmental pollution and potential damage to vegetation due to dog excreta are well known and are often addressed by city planners in relation to dog parks, but the potential contributions to water pollution are typically ignored. Our study shows that this component should be included and further analyzed for its contribution to stormwater pollution. End-of-pipe pollution treatments of urban runoff, such as retention ponds, although widespread, are expensive and insufficient to reduce N and P inputs to surface waters to acceptable levels (Weiss et al. 2007). Our results suggest that reduction of landscape sources of N and P from households represents a potential alternative solution to urban water quality problems.

CONCLUSIONS

In this study we have quantified C, N, and P fluxes through 360 households in the Twin Cities urban region using an extensive sampling approach. Overall, the results show that there is considerable variability among households and that the distribution of fluxes in many cases is skewed and departs from normal distribution such that a small number of households contribute a disproportionately large fraction of the total fluxes. Some of the daily human activities that contribute most to total household fluxes were highly variable and skewed, such as air and motor vehicle transportation C emissions and N inputs to the landscape. Other activities, such as C associated with home energy use and N and P inputs through human diet, tended more toward the normal distribution, indicating greater similarity of behaviors across the sampled population.

The results of this study demonstrate that a comprehensive, integrated approach to the study of household element fluxes, as opposed to a sector analysis, provides necessary data for modeling biogeochemical cycling in

urban ecosystems and should aid in the design of effective policies to reduce urban pollution. However, analysis of flux distributions alone is insufficient to develop effective strategies to reduce pollution and greenhouse gas emissions. For example, Wier et al. (2005) pointed out the risk of penalizing low-income families, which have the greatest share invested in necessary household consumption, when adopting a uniform tax on CO₂ emissions at the household level. And evidence from other fields, from public health to economics (e.g., Penman and Johnson 2006), shows that targeting high contributors to skewed distributions may not achieve the expected results if these fluxes are not flexible. For example, even though air travel represents a large fraction of total C and N fluxes, substantial reduction will be difficult to achieve if, for instance, traveling takes place for business purposes and therefore respondents perceive only limited choice regarding that behavior. Thus, it is essential to include an analysis of the drivers of human activities and element fluxes through households when developing pollution mitigation strategies.

Our study showed that >50% of total C fluxes through the households were related to a few biophysical variables. Future analyses of the Twin Cities Household Ecosystem Project will investigate the link between biophysical fluxes of elements through households and human choice to provide additional critical information on the drivers of household biogeochemical cycling. Such information will provide insight into the role of household decision-making in affecting urban biogeochemical cycling and the degree of flexibility in human activities that drive biogeochemical fluxes in urban ecosystems.

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APPENDIX A

Computations of carbon, nitrogen, and phosphorus fluxes in the household flux calculator (HFC) model (*Ecological Archives* A021-034-A1).

APPENDIX B

Input flux distribution characteristics of total and major components of carbon, nitrogen, and phosphorus (*Ecological Archives* A021-034-A2).