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# Effect of consumption choices on fluxes of carbon, nitrogen and phosphorus through households

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**Abstract** Households are an important scale of analysis for human ecosystems because they are a major source of pollutants and could thus be a new focus for pollution management, particularly for education-based source reduction strategies. The household is also a meaningful unit for analysis of human ecosystems, being common to all human cultures. This study develops a Household Flux Calculator (HFC) to compute C, N, and P fluxes for scenarios intended to represent three levels of household consumption: low, typical, and high. All three scenarios were developed for suburban households with two adults and two children in the Minneapolis-St. Paul (Twin Cities) metropolitan area, Minnesota. Calculated ratios of fluxes between high and low consumption households were 3.5:1 for C, 2.7:1 for N and 1.4:1 for P. Results suggest a high level of discretionary consumption that could be reduced without a substantial reduction in standard of living. Thus, modest changes in behavior in high consumption households would greatly reduce fluxes of C, N, and P without major changes in lifestyle.

**Keywords** Household · Household ecosytem · Lawn · Fertilizer · Emissions · Food · Wastewater · Flux · Carbon · Nitrogen · Phosphorus

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## Introduction

Cities comprise only 1–2% of the world's surface but contain half the world's human population. In 30 years, two-thirds of the Earth's population will live in cities (FAO 2001). Cities are major foci of biogeochemical processes, particularly combustion processes. Moreover, cities impact surrounding landscapes and ecosystems which provide their sustenance and receive their waste products (Luck et al. 2001). The intensification of biogeochemical processes in cities causes air and water pollution, with impacts often extending hundreds of kilometers or more beyond the urban fringe and even to the global scale.

Despite their importance, cities have only recently been conceptualized as "urban ecosystems" with humans as an integral component (Collins et al. 2000; Pickett et al. 1997, 2001; Grimm et al. 2000, 2002). An important aspect of cities that requires greater understanding is biogeochemical cycling. This knowledge could lead to innovative methods of pollution reduction that are more effective and economical than conventional end-of-pipe pollution controls (Baker et al. 2001a). Research to gain this knowledge is accelerating. Several studies have examined flows of energy and nutrients through cities (Baker et al. 2001b; Faerge et al. 2001; Decker et al. 2000) or components of cities (Nilsson 1995; Gray and Becker 2002). Kaye et al. (2006) elucidated mechanisms by which human activities affect biophysical drivers of biogeochemical cycling—hydrology, climate, nutrient loading, vegetation patterns, climate, and land use. Other recent studies have examined nitrogen movement in urban streams (Groffman 2004), spatial heterogeneity of inorganic nitrogen in urban soils (Hope et al. 2005), groundwater nitrate and salt pollution in the Phoenix, Arizona ecosystem (Baker et al. 2004; Xu et al. in press) and carbon sequestration by urban trees and lawns (Kaye et al. 2005; Nowak and Crane 2000, 2002; Milesi et al. 2005; Qian and Follett 2002; Qian et al. 2003). Research on flows of energy and materials through individual households has examined in-home energy, waste production, water use and overall resource utilization (Mayer et al. 1999; van der Wal and Noorman 1998; EIA 1999; Carlsson-Knyama et al. 2005; Bin and Dowlatabadi 2005; Liu et al. 2003). There has been little research on fluxes of major elements in household systems.

In this paper, we demonstrate that households are a useful scale of analysis to gain deeper insights regarding biogeochemical cycling in cities. Knowledge regarding variability of fluxes among households and the human behaviors that affect these fluxes would be valuable to understanding the genesis of urban pollution and developing solutions to reduce pollution. We developed a spreadsheet model, the Household Flux Calculator (HFC) for carbon (C), nitrogen (N), and phosphorus (P). We used the HFC to calculate element fluxes for three scenario suburban households in the Minneapolis-St. Paul metropolitan area: a "typical" household, a "low-consumption" household and a "high-consumption" household.[1] Although we focus here on the macroelements C, N and P, the approaches could be applied readily to other chemicals. In a parallel paper, Nelson et al. (manuscript) discuss how decisions regarding environmental behaviors within households are made.

## The importance of households

The household is a meaningful and important scale of analysis that would fit well into the emerging concept of ecosystems as hierarchical systems (Wu and David 2002) as a "local"

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[1] These household consumption typologies are culturally based. What is low for one country or culture may be high for another.

ecosystem. There are several important reasons to study households in this project. First, households account for a substantial fraction of element fluxes in urban ecosystems. Residential vehicles account for half of total transportation energy consumption in the United States, hence half of the transportation C emissions (EIA 1999). In the Twin Cities, Minnesota, nearly 100% of N and 80% of P in municipal wastewater comes from human excretion (Baker, in prep). The relative contribution of households to the total nutrient fluxes of urban areas likely will increase in the future, as economies of US cities continue to transform from resource-intensive, polluting industries to light manufacturing and services.

Second, understanding the magnitude of element fluxes from households and how they are related to social factors could lead to more effective approaches to reduce pollution. Traditionally, pollution control has relied largely on “end-of-pipe” solutions, treating pollutants after they are generated. We propose that closer examination of nutrient fluxes in households will lead to novel approaches to pollution control, probably with greater emphasis on source reduction. This knowledge could be used in several ways, for example: (1) to provide information/feedback to households regarding the effects of their decisions on the local environment (adaptive management); (2) to inform regulatory policies, as was done prior to Minnesota’s restriction on P-containing lawn fertilizers; and (3) to develop targeted incentive-based policies, such as “green” subsidies or “brown” taxes.

Third, focusing on households enables us to elucidate the ultimate causes of human biogeochemical perturbations. One of the “Grand Challenges in Environmental Science” (NRC 2001) is to increase understanding of human perturbations of biogeochemical cycles. However, the vast majority of prior biogeochemical research has focused on the impacts of human action rather than human behaviors that lead to biogeochemical impacts. The household is an excellent scale for this analysis, because both behaviors and fluxes can be measured at multiple points (many households), potentially revealing relationships between the two.

Fourth, the household is a socially meaningful and practical unit of measurement. The household is a meaningful unit of study across many disciplines. Households in most cultures have property lines. Electric meters can be read, inhabitants can be surveyed, and a household’s garbage can be picked up and analyzed. The conceptual boundary can be extended for purpose of analysis, while still considering a particular flux as part of a household. For example, we consider fluxes associated with household transportation as part of the household system, even though the transportation occurs outside the physical boundary of the house.

Finally, the HFC could become a valuable pedagogical tool to enable citizens to understand the impacts of their activities on their surrounding environment. Such a tool might be part of an adaptive management strategy, allowing homeowners to identify important feedback loops and take actions to reduce undesirable impacts of their actions. A homeowner living near a lake might pay special attention to lawn runoff because he/she utilizes the lake for recreation and wants to prevent eutrophication, whereas another homeowner might use the HFC to compare his or her household’s emissions with those of similar households.

## HFC development

The HFC is a spreadsheet accounting model intended to represent fluxes of C, N and P through a household system. We use the HFC in this paper to develop scenarios for owner-occupied, suburban households in the Minneapolis-St. Paul (Twin Cities), Minnesota metropolitan area, using various sources of information to create “typical consumption”, “high consumption” and “low consumption” scenarios. In subsequent papers, the HFC will be used to compute C, N and P fluxes for individual households, based on data collected in a household survey of Falcon Heights, a suburb of St. Paul, Minnesota (Nelson et al. in prep; Hartzheim et al. in prep). Inputs are therefore constrained to information that could readily be collected using survey questionnaires, rapid measurements of biological and physical features of a household and its landscape and public databases. For example, in our pilot survey of 35 households in Falcon Heights, data sources included (1) an in-home questionnaire with approximately 70 questions, (2) energy bills provided by the local utility for these homes (with approval of the homeowners), (3) odometer readings from household cars, (4) measurements of lawn size, garden areas and the number and dimensions of trees, and (5) information contained in municipal plat files.

The boundary of a household is conceptual rather than strictly physical. The boundary includes the property line in the horizontal plane, the soil to the bottom of the root zone and the atmosphere above the height of the tallest vegetation in the vertical direction. However, we also include activities of individuals who live in the household but spend time outside the property. Our household system therefore includes energy used for transportation (by household vehicles, airplanes and buses) and food consumed outside the property. Limitations of this system boundary definition will be discussed below.

## Household energy consumption

Nearly all household energy (heating, cooling, lighting and appliances) in the Twin Cities is provided by natural gas and electricity (AHS 2001). Records can easily be acquired with permission from homeowners. To develop model scenarios we used a national compilation of energy data gathered from over 4,800 households (EIA 2001). This database includes total household energy use in five major climate zones, with additional data on house size, age, value, number of occupants, occupant-reported temperature settings (day and night/absence) and numerous other energy parameters. Electrical energy in Minnesota is derived from a mix of coal, nuclear, hydropower, and wind. Composite emissions factors for Minnesota are (all per kW.h): 0.69 kg (1.52 lb) $CO_2$, 0.0071 kg (0.0157 lb) $CH_4$ and 0.0112 kg (0.0247 lb) $NO_x$ (EIA 2002).

## Household vehicles

Information on household vehicles is also readily obtained from surveys. Requisite information includes the age, model and engine type (number of cylinders) of the vehicle, current mileage, percentage of highway and city driving, mileage at the time of purchase and length of ownership. For most makes and models of passenger vehicles going back to 1978 (cars, light trucks, SUVs, etc.), average fuel mileage economy can be estimated from the EPA Fuel Economy Guides. Fuel mileage is broken into “city” and “highway,” where city represents urban driving, in which a vehicle is started in the morning (after being parked all night) and driven in stop-and-go rush hour traffic. “Highway” represents a mixture of rural and interstate highway driving in warmed-up vehicles, typical of longer trips in free-flowing traffic (USEPA 2005a). The negative bias in EPA fuel economy data from the 1980s (reported mileage higher than actual performance) has been corrected for newer vehicles to better reflect the mileage that real-world drivers can expect. Gasoline produces 2.347 kg $CO_2$ $L^{-1}$ (19.56 lb $CO_2$ $\text{gallon}^{-1}$) combusted and diesel gasoline produces 2.686 kg $CO_2$ $L^{-1}$ (22.38 lb $CO_2$ $\text{gallon}^{-1}$) (EIA 2005).

Estimates of $NO_x$ and CO emissions were based on outputs from the MOBILE 6.2 emissions model (USEPA 2005b). Average emission rates for $NO_x$ were 0.95 g $mile^{-1}$ (0.6 g $km^{-1}$) and 1.22 g $mile^{-1}$ (0.8 g $km^{-1}$) for passenger cars and light-duty trucks, respectively. The corresponding CO values were 12.4 g $mile^{-1}$ and 15.7 g $mile^{-1}$. These figures assume an average, properly maintained vehicle on the road as of July 2005, based on the current distribution of automobile types and ages, and also accounts for the fact that older model vehicles are typically driven less than newer models (USEPA 2005a). In addition, these emission rates account for a representative mix of four different types of driving/roadway conditions, ranging from free flowing conditions to sharp acceleration and deceleration in heavy traffic of varying speeds.

### Air travel

Fuel combustion for air travel was based on estimates of passenger miles and fuel consumed for both domestic and international US-based flights for 2003 (USDOT 2004). Combustion of jet fuel releases 2.53 kg $L^{-1}$ of $CO_2$ (21.1 pounds $gallon^{-1}$) (EIA 2005). This translates into average values for jet service of 247 g of $CO_2$ per passenger mile for domestic flights, and 277 g of $CO_2$ per passenger mile for international flights. For a given flight, mileage can be estimated using either airport information or map coordinates. Flight routes typically follow a geodesic or "great circle" route, which is the shortest distance between two points on a sphere, which can be calculated from the departure and destination airport's latitude and longitude coordinates using the Haversine formula (Sinnot 1984).

We used estimates of $NO_x$ emissions for air travel from studies by Schulte and others (Schulte and Schlager 1996; Schulte et al. 1997). These studies determined $NO_x$ emissions from six common short/mid-range aircraft and ten long-distance aircraft by measuring $NO_x$ plumes in exhausts. Average values were 8.68 g $NO_x$ $kg^{-1}$ of jet fuel burned for the short/midrange aircraft and 19.6 g $NO_x$ $kg^{-1}$ jet fuel for the long-distance aircraft. Although these emission factors were derived from cruising altitude aircraft, they are assumed for the entire duration of the flight in the HFC, due to difficulty in measuring emissions during takeoff, landing and airport taxiing. Applying these emission factors to the entire mileage of a flight will likely underestimate overall emission that would actually be realized, since ~10% of all aircraft emissions are estimated to occur during ground level operations, including takeoff and landing (FAA 2005).

Air travel gas emissions for a household are based on the number of individual trips, the round-trip distance, and the type of aircraft. We assumed that short/midrange aircraft were used for domestic flights and that long distance aircraft were used for international flights.

### Human food

Food inputs are based on national average consumption of protein, fat, carbohydrate and fiber by age and sex strata obtained by the US Department of Agriculture's Continuing Survey of Foods (USDA 2005). Because our scenarios are for suburban households in the Twin Cities, which are predominately white, we used average food consumption data compiled for the "white" race. Food consumption for each household was computed as the sum of consumption by each resident, as determined by age range (<5, 6–11, 12–19, 10–39, 40–60, 60 and over) and sex. Carbon conversion factors (g C $g^{-1}$ source) were 0.5 for protein, 0.43 for carbohydrates, 0.77 for fats and 0.49 for fiber (Klass 2004). The N content of protein was assumed to be 16%. All N and P was assumed to be excreted and to enter the

**Table 1** Components of household wastewater stream

| Element | Average wastewater without in-sink grinder | Human excretion | Garbage grinder | Uncharacterized inputs |
|---|---|---|---|---|
| C | 41 | 13 | 22 | 28 |
| N | 12 | 13 | 1.2 | −0.5 |
| P | 2.0 | 1.6 | 0.14 | 0.4 |

All values in g capita$^{-1}$ day$^{-1}$

wastewater stream. Wastewater C outputs include excretion of dietary fiber (about 3% of total C) and C in excreted urea, using a calculated C:N (wt:wt) ratio of 0.43. All other food C was assumed to be respired (converted to $CO_2$).

Food waste is disposed to landfills, on-site compost bins or in-sink garbage grinders. Average disposal of residential food to landfills for the Twin Cities is 0.11 kg wet weight capita$^{-1}$ day$^{-1}$ (Beck, Inc. 1999). We assumed the following characteristics of landfill food waste: water content=70%; C content=48% of dry weight (DW); N content=2.6% DW; P content=0.3% DW (Tchobanoglous et al. 1993). We assumed the average P content of food waste was the same as that of food. Homes that have in-sink grinders dispose 0.05 kg capita$^{-1}$ day$^{-1}$ (dry weight basis) via the grinder (Metcalf and Eddy, Inc., 1991). Forty eight percent of homes in the Twin Cities have in-sink grinders (AHS 2001). Using weighted averages, we estimated landfill waste for homes without in-sink grinders (0.075 kg capita$^{-1}$ day$^{-1}$) and those with garbage disposal (0.0125 kg capita$^{-1}$ day$^{-1}$).

### Wastewater

Wastewater is an output from the household. It comprises human excretion (discussed under "human food," above), food waste from in-sink garbage grinders, and uncharacterized wastes (Table 1). The latter includes various detergents and soaps, toilet paper, other household chemicals, dirt brought into the house and washed into drains, etc. These represent both an input to the household and an output from it. For total wastewater fluxes of C and N, we used estimated per capita loadings for biological oxygen demand (BOD) and N in wastewater without in-sink grinder waste and a BOD:C conversion ratio of 0.5 (Tchobanoglous and Burton 1991; column 2 in Table 1). Estimated food input to in-sink grinders (0.05 kg DW capita$^{-1}$ day$^{-1}$; see "human food," above) was used in conjunction with C, N and P contents for average food composition (column 4 in Table 1). The C and N flux of "uncharacterized waste" was computed by subtracting human excretion from total wastewater flux in homes without in-sink grinders (column 5 in Table 1). For P, we used a recent estimate of non-fecal, non-grinder P input to wastewater from Barr Engineering (2004).

### Dog food and waste

Dog food can be a significant source of macroelements to households. The general approach for estimating dog waste was to estimate food intake. For adult dogs, excretion of N and P is approximately equal to food consumption. Waste C is essentially dietary fiber. Caloric consumption was estimated from dog weight using the equation (Purina Corp., per. comm.):

$$ME = 110(W)^{0.75} \tag{1}$$

Where ME=metabolizable energy, kcal day$^{-1}$ and W = weight, kg.

**Table 2** Estimated composition of dog food

| | Mean | Std. dev. |
|---|---|---|
| Kcal per 100 g | 336 | 17 |
| Protein, % | 23 | 3 |
| Fat, % | 11.2 | 3 |
| Moisture, % | 12 | 1 |
| P, % | 0.8 | 0.0 |
| Carbohydrate, % | 43 | 5 |

Nutrient content of dry dog foods was determined by an informal survey of the nutrient contents of a dozen popular dry foods. Protein, fat, fiber and moisture content were listed on all products, and the P content was listed on some. The carbohydrate content was computed by difference (Table 2). ME was computed from protein, fat, and carbohydrate contents using the following energy conversion values (kcal $g^{-1}$) (NRC 1985): protein (3.5), fats (8.46) and carbohydrates (3.5). C contents of proteins, fats, carbohydrates and fiber were taken from Klass (2004).

Equation 1 was used to calculate ME from dog weight. ME was used to compute daily food intake and intake of protein, fat, carbohydrates, fiber and P using values in Table 2. Table 3 shows annual N and P consumption/excretion rates for several sizes of dogs.

### Paper and plastic waste

Paper and plastic represent significant fluxes of C moving through a household. A reasonable estimate of both can be derived by combining outputs to landfills and recycling. Beck, Inc. (1999) estimated fluxes of paper and plastics entering landfills from residential waste collection. The residential recycling rate was estimated from data compiled by the Minneapolis recycling program. Inputs of paper and plastics to households were estimated by summing fluxes to landfills and recycling (Table 4). Elemental compositions were taken from Tchobanoglous et al. (1993).

### Lawns

Fluxes and accumulations of C for household landscapes were estimated from two models. First, to estimate turfgrass net primary production (NPP) and net ecosystem production (NEP), we used output from a study of lawn productivity modeled using BIOME-BGC (Milesi et al. 2005, C. Milesi, pers. comm.). Milesi et al. modeled lawns as unmanaged or with two levels of fertilization (moderate-73 kg N $ha^{-1}$ $year^{-1}$, high-146 kg N $ha^{-1}$ $year^{-1}$) and two management practices (grass clippings left on, grass clippings removed). We used average model output parameterized with climate data from 1980–1997 for Minneapolis,

**Table 3** N, P, and C intake for several weights of dogs, in kg $year^{-1}$

| Dog weight, kg | N | P | Total C | Fiber C |
|---|---|---|---|---|
| 10 | 2.5 | 0.5 | 27.9 | 1.5 |
| 20 | 5.6 | 1.2 | 46.8 | 2.6 |
| 30 | 8.2 | 1.7 | 63.5 | 3.5 |
| 40 | 10.7 | 2.3 | 78.8 | 4.4 |

**Table 4** Average consumption of residential paper and plastics for households in the Twin Cities metropolitan area

| | Paper (all types) | Plastic (all types) |
|---|---|---|
| Entering landfill | 110 | 33 |
| Recycled | 50 | 10 |
| Total entering household | 160 | 43 |

All values in kg capita$^{-1}$ year$^{-1}$

MN (C. Milesi, pers. comm.) for NPP, C in bagged clippings (if removed), heterotrophic respiration (HR), and NEP, where NEP is:

$$NEP = NPP - \text{clippings} - HR(\text{with clippings removed}) \tag{2}$$

Or

$$NEP = NPP - HR(\text{with clippings left on})$$

Because Milesi et al. did not run the model for moderate fertilization and clippings removed, we estimated the values for this management option by multiplying the ratio of the values in the clippings removed:clippings left on in the high fertilization scenario by values for the moderate fertilization and clippings left on model run (Table 5). NEP is primarily C sequestered in soils, because little C is sequestered in biomass in herbaceous turfgrass. Because Milesi et al. (2005) modeled lawns that were relatively young and still accumulating C (C. Milesi, pers. comm.), and other studies have shown that soil C sequestration in turfgrass systems levels off after 30 to >100 years (Qian and Follett 2002), we assumed that lawns only sequester C until they are 75 years old (after establishment) after which HR equals NPP and NEP=0.

Net primary production of trees was modeled using the US Forest Service's UFORE model (Nowak and Crane 2000). Data on 403 trees from 35 households were collected in a separate Falcon Heights, Minnesota survey (Hartzheim et al. in prep.). Data on species, height, diameter at breast height, dieback and crown light exposure (CLE), were compiled for each tree and sent to David Nowak (USFS) for analysis by the UFORE model. For model scenarios presented in this paper, we use four levels of tree density: none, low (1–5 trees), medium (6–10 trees) and high (>10 trees). From the UFORE model results in Falcon Heights, mean annual C accrual in woody biomass was 0, 35, 75 and 138 kg C year$^{-1}$ per lawn for tree densities of none, low, medium and high, respectively. Annual leaf production was estimated as 3% of total tree biomass (McPherson 1998), yielding values of 0, 48, 95 and 195 kg C year$^{-1}$, respectively, for the four categories of lawn tree density. For simplicity, we assumed that all trees were deciduous (i.e., that they lost all of their leaves annually, so annual leaf production equals annual litterfall).

**Table 5** Estimates of lawn NPP, clippings, heterotrophic respiration and NEP

| Flux (g C m$^{-2}$-year$^{-1}$) | No management | Mod Fert-clippings left on | Mod Fert-clippings removed (interpolated) | High Fert-clippings left on | High Fert-clippings removed |
|---|---|---|---|---|---|
| NPP | 97 | 283 | 230 | 427 | 347 |
| Clippings | 26 | 88 | 71 | 136 | 109 |
| Heterotrophic respiration | 100 | 245 | 146 | 357 | 213 |
| Net ecosystem production | −3 | 38 | 13 | 70 | 25 |

Data from Milesi et al. (2005)

**Table 6** Elemental ratios used to compute N and P fluxes from C fluxes

| | C:N | C:P |
|---|---|---|
| Wood | 210 | 2423 |
| Tree leaves (prior to abscission) | 25 | 266 |
| Grass | 15 | 150 |
| Soil | 12 | – |

Sources: (Rodin and Bazilevich 1967; Horgan et al. 2002; Kopp and Guillard 2002).

The HFC allows tree leaf litter to be exported from the household for off-site composting or mulched or composted on-site. A simple model assuming exponential decay and constant litterfall (Olson 1963) showed that litterfall inputs and decomposition approached equilibrium after 10 years, given leaf litter decay rates of commonly planted trees in the region (S.E. Hobbie, unpublished data). We therefore assumed that litterfall and decomposition of leaf litter were equal, with no accumulation of C in soil due to tree production.

Plant and soil N and P fluxes were estimated using C fluxes and the C:N and C:P ratios for wood, leaves and grass presented in Table 6, assuming that half of leaf N and P is retranslocated before abscission. If fluxes of N and/or P into soil were in excess of what could be stored given soil C:N and C:P ratios, then we assumed that N and P were exported or stored in inorganic form.

We considered dog excretion (Table 3) to be an input to the household lawn. A dog may excrete outside the boundaries of its owner's lawn, but dogs from other households excrete within our dog's lawn. We presumed a balance and considered dog excretion to be occurring within the boundaries of their household.

Wet deposition of N was based on the National Atmospheric Deposition Program's Cedar Creek site, located just north of the Twin Cities. We assumed dry deposition was equal to wet deposition. P deposition was based on the study of Barr Engineering (2004). Deposition to the entire household lot (including impervious surfaces) lot was assumed to enter the lawn.

We developed three categories of lawn maintenance that could be determined by home interviews. Because homeowners generally do not know the quantity of fertilizer they apply, we based our classification on the number of times fertilizer is applied per year. A study by Barten and Jahnke (1997; Table 7) was used as a basis for estimating runoff concentrations from fertility level. This study measured N and P in runoff from functional (residential) lawns. It is unique because lawns were stratified based on measured soil fertility (adsorbed P) and current fertilization (fertilized or not fertilized during the past year).

The HFC has three classes of lawn maintenance, low (not fertilized), medium (fertilized once or two per year), and high (fertilized more than three times per year). Using Table 7 as a guide, we assumed the following runoff concentrations: low maintenance ($TP=0.5\ mg\ l^{-1}$ and $TN=3\ mg\ l^{-1}$); moderate maintenance ($TP=1.5\ mg\ l^{-1}$ and $TN=5\ mg\ l^{-1}$); and high maintenance ($TP=2\ mg\ l^{-1}$ and $TN=6\ mg\ l^{-1}$). Export was calculated as the product of concentration and runoff volume. Runoff volume was estimated using an annual runoff coefficient (0.1 was used in HFC model runs presented in this paper) and annual precipitation (we used average annual precipitation for the Twin Cities, 75 cm $year^{-1}$; NCDC 2005).

For N and P, a "difference" term describing net flux was computed as:

$$D = \text{Inputs} - \text{outputs} - \text{OM sequestered} \tag{3}$$

Where inputs = fertilizer + dog feces + composted garbage + atmospheric deposition outputs = runoff + exported tree leaves + exported grass clippings. Sequestration of N and P was based on calculated C sequestration and ratios of C:N and C:P in grass, wood and

**Table 7** Average total phosphorus (TP) and total nitrogen (TN) concentrations in lawn runoff from 26 lawns in Minneapolis, in mg $l^{-1}$

| | Moderate fertility, no fertilization (MF) | High fertility, not fertilized (HFN) | High fertility, fertilized (HF) | Very high fertility, not fertilized (VHFN) | Very high fertility, fertilized (VHF) |
|---|---|---|---|---|---|
| Total P | 0.94 | 1.31 | 1.01 | 1.53 | 2.18 |
| Total N | 3.39 | 5.35 | 5.22 | 6.00 | 5.83 |

Source: Barten and Jahnke (1997)

leaves (Table 6). The difference term includes change in inorganic soil storage, errors in directly measured inputs and outputs, and missing terms, such as gas losses for N.

Emissions from lawnmowers were based on reasonable estimates of gasoline use (~8 L) and the number of hours of lawn mowing per season (20), together with NOx emissions rates calculated from Christensen et al. (2001).

## Scenario development

We first applied the HFC to a suite of scenarios intended to represent a range of consumption behaviors (“typical,” “low” and “high”) for suburban households (Table 8). Our intent is to develop credible scenarios, not statistically representative consumption profiles. The latter cannot be developed using existing public databases because no database compiles all necessary consumption data by household. The “typical” scenario is intended to represent a single-family household with two adults and two teenagers in the Twin Cities living in an owner-occupied, detached house. The basis of this scenario is the fact that the average fertility rate in Minnesota is 1.98 (McCury 2000) and about two-thirds of Minnesota households live in detached, owner-occupied houses (AHS 2001). Many inputs for our typical family were based on central measures (means or medians) for this type of family from national or state databases.

Food consumption was estimated as described above, for two adults (ages 40–60) and two teenagers (ages 12-19). Average fuel efficiency and annual mileage for passenger cars and SUVs were based on national transportation statistics (USDOT 2004). The number and types of vehicles was based on the assumption that a typical family often owns one SUV and one passenger car. Because a small percentage of the population uses mass transit, we assumed that our typical family commuted to work by car. This assumption is embedded in the use of average annual mileages for auto travel. Per capita air travel is based on our survey of Falcon Heights (Hartzheim et al. in prep.; Nelson et al. in prep.). The average annual per capita air travel for all Falcon Heights households was nearly 6,000 miles (9,656 km), more than twice the national average (2,500 miles (4,023 km); USDOT 1995). However, per capita values for households of 3–5 residents in our Falcon Heights survey were substantially less, about 2,800 miles (4,506 km), about one-third of the per capita value for households with 1–2 residents. We used a value of 2,500 miles (4,023 km) per family member for our typical scenario and assumed (based on the distance) that this translates to one domestic trip per year. Consumption of household natural gas and electricity are weighted averages for detached homes with four residents living in Climate Region 1 (EIA 2001), characterized as having <2,000 cooling degree days and >7,000 heating degree days (both computed for 65°F; 18.2°C). Lacking data, we assumed reasonable values for consumption of wood, charcoal and bottled propane. Average lawn

**Table 8** Typical, high consumption and low consumption scenarios.

| | Typical | High consumption | Low consumption |
|---|---|---|---|
| Passenger cars | | | |
| mpg (km $l^{-1}$); distance, miles (km) | 1 @ 22.3 (9.5); 12,200 (19,642) | 1 @ 20 (8.5); 14,640 (23,570) | 1@ 40 (17); 8,220 (13,234)<br>1@ 30 (48); 6,690 (10,771) |
| SUVs | | | |
| mpg (km $l^{-1}$); distance, miles (km) | 1@17 (7.2); 11,500 (18,515) | 2 @ 15 (6.4); 13,800 (22,218) | None |
| Bus travel, miles (km) | 0 | 0 | 3840 (6182) |
| Per capita domestic air travel, miles (km) | 5,000 (8,000) | 2,500 (4,025) | 1,000 (1,610) |
| Per capita inter. air travel, miles (km) | 0 | 2,500 (4,025) | 0 |
| Electricity, kW h (joules) | 10,783 ($3.9\times10^{10}$) | 15,242 ($5.5\times10^{10}$) | 5,466 (2.0×1010) |
| Natural Gas, ccf[a] ($m^3$) | 909 (25.7) | 1,324 (37.4) | 5,466 (154.7) |
| Propane, gallons (L) | 10 (37.8) | 30 (113) | 0 |
| Charcoal, pounds (kg) | 25 (11.3) | 100 (45.4) | 0 |
| Wood, pounds (kg) | 50 (22.6) | 150 (68) | 0 |
| Area of lot (lawn), $ft^2$ | 7,400 | 18,480 | 3,726 |
| Lawn maintenance | Moderate; clippings and leaves returned | High; clippings and leaves exported | Low; clippings and leaves returned |
| Dogs, # and weight, pounds (kg) | 1@44 (20) | 2@44=88 (40) | 0 |
| Tree density | Medium | Medium | Medium |
| Food intake (kcal $cap^{-1}$ $day^{-1}$) ( % protein, % fat; % carbs) | 2,190 (15/34/52) | 1,930 (22/30/49) | 2,320 (10/32/59) |
| Paper, pounds $yr^{-1}$ (kg $yr^{-1}$) | 350 (160) | 530 (240) | 180( 80) |
| Plastic, pounds $yr^{-1}$ (kg $yr^{-1}$) | 43 (19.5) | 65 (29.5) | 22 (10) |
| Garbage disposal | In-sink grinder + landfill | In-sink grinder + landfill | In-sink grinder + on-site compost |

Transportation distances are annual

[a] CCF=$100^3$ ft

size, lot size, percent impervious surface and age of home were derived from our Falcon Heights survey. Typical lawn care for suburban homes was based on several local surveys (Creason and Runge 1992; Barten 1994; Schultz and Cooper 1995; Morris and Traxler 1996; Lake Access 2001). The typical scenario was: clippings returned, moderate N fertilization, no P fertilization (due to P restriction) and tree leaves composted off-site. For dichotomous variables (e.g., presence or absence of in-sink garbage grinder) we used the most common situation for the typical home based on AHS (2001).

We then constructed high consumption and low consumption households intended to represent alternative consumption patterns for our family of four. Inputs for the high and low consumption households are intended to be reasonable estimates within the constraints of a suburban lifestyle. Values for natural gas and electricity represent upper and lower 10th percentiles for high consumers and low consumers, respectively. We note that neither electricity nor natural gas use in the EIA Climate Zone 1 database is significantly related to house size. The types of cars were again based on informal observation: many low consumption households eschew SUVs and were therefore allocated two passenger cars, one with 30 MPG (12.7 km $l^{-1}$) and one with 40 MPG (16.9 km $l^{-1}$). Similarly, the high consumption household was assigned two SUVs and one passenger car. Auto mileage for the low consumption scenario assumes that two adults work outside the home and that one commutes by carpool (driving every other day) and the other commutes by bus. Other driving is reduced by 20%. For the high consumption household, two adults commute by driving alone (same as the typical scenario); other mileage was increased by 20% compared with the typical scenario. In both cases, we used an average commute-to-work distance for the Twin Cities (8 miles; 12.8 km) (Met Council 2000). Our high and low consumption scenarios for air travel were based on the five highest and five lowest air travel miles, respectively, in our Falcon Heights households with 3–4 occupants. For the low consumption household we assumed this translated into one short domestic trip. For the high consumption household, we allocated air mileage into one domestic trip and one international trip (in this region, it is reasonably common practice for families to take winter trips to warmer climates such as Mexico). For most other inputs we relied on general knowledge to develop inputs. Food consumption was adjusted based on expert judgment. We increased the caloric content of the diet of the low consumption household by about 5% to allow for several miles of extra walking and decreased the caloric intake of the high consumption household to allow for decreased walking. The diet of the high consumption household was modified to include slightly more protein and less fat (i.e., more lean meat consumption) than the typical household and the low consumption household consumed slightly less protein and fat (i.e., less meat consumption). After adjusting protein and fat consumption, caloric adjustment was done using carbohydrate consumption. For consumption of plastics and paper we simply increased or decreased the average input by 50%. The low consumption household had no dog and the high consumption household had two large dogs.

## Results

### Household biogeochemical pathways

C, N and P move through household ecosystems via four distinct systems (Fig. 1). We illustrate the relative magnitude of these fluxes using the "typical" household scenario. First, large inputs of fuel (mostly natural gas, gasoline, coal to produce electricity and airplane fuel for travel) produce $CO_2$, CO and $NO_x$, the latter derived from abiotic $N_2$ fixation and oxidation of fuel organic N during combustion. These combustion-derived fluxes account for 85% of total C flux and 30% of total N flux for the typical household scenario. These gaseous end products of combustion leave the household ecosystem via atmospheric transport, altering the regional and global atmospheric environment.

The second major system is food for humans and household pets. Taken together, these account for 61% of total N input and 85% of total P inputs, but only 5% of C input. Most of the C in food is respired (87%), but nearly all P and N is excreted, either to sewers (human excretion) or lawns (dog excretion). Our household's dog consumes 13% as much C, 21% as much N, and 37% as much P as its owners.

The lawn, which includes turf, trees and soils, is the most complex system. External inputs to lawns include photosynthesis (fixation of $CO_2$), atmospheric deposition and

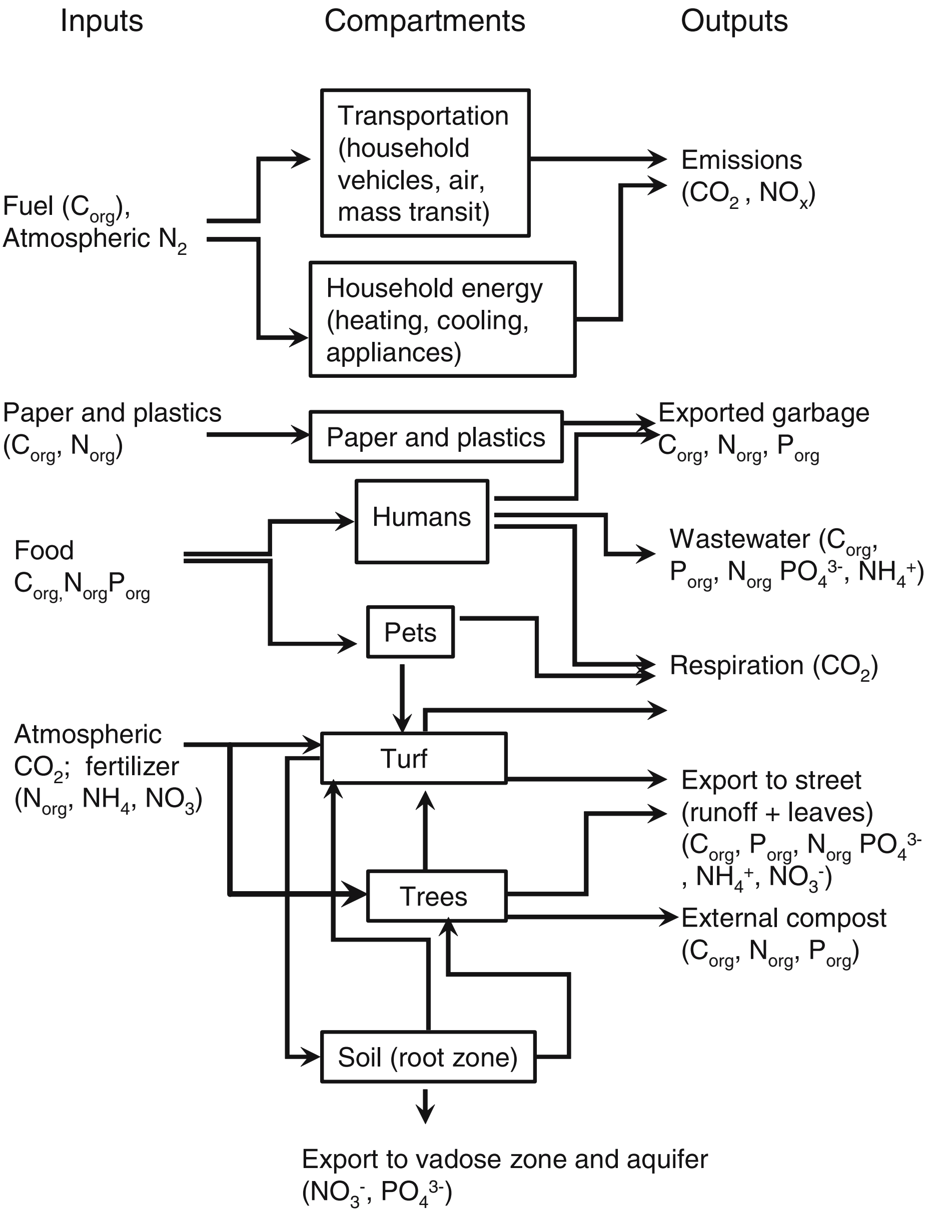


**Fig. 1** Flowpaths of C, N and P through a suburban household

applied fertilizer. Lawn photosynthesis ($CO_2$ fixation) is only 4% of the household's total C input. N and P enter lawns from outside the household boundary by atmospheric deposition and fertilizer addition (N only, due to the fertilizer P restriction). These inputs are small relative to total household inputs—15% of total household N input and 0.4% of total household P input goes to lawns. Additional N and P are added from dog excretion and composted garbage (internal transfers). With the fertilizer P restriction in place, the main source of P to lawns is now dog excretion. Elements entering the lawn system either accumulate (in soils and trees) or are exported as runoff or gaseous emissions (not directly accounted for here). In the typical household scenario, input N was 20% higher than output N. For the lawn only, N outputs were only about one-fifth of inputs. About one-third of the difference between inputs and outputs was accounted for by sequestration of organic N in soils and trees. The remaining two-thirds (7 g m$^{-2}$ year$^{-1}$) is likely denitrified (additional loss as $N_2$ or $N_2O$), accumulated as inorganic N (e.g., via ammonium adsorption), or leached as nitrate. A long-term modeling study of N in turf suggested that nitrate leaching losses could account for a substantial fraction of fertilizer N in mature lawns (Qian et al. 2003). Input of lawn P was about one-third higher than outputs. After accounting for OM sequestration, there was a "difference" term (D in Eq. 3) of -1.5 kg year$^{-1}$. This difference probably represents depletion of inorganic soil P which occurred because the turf was "mining" P following cessation of fertilizer P inputs.

## Comparison of calculated C, N and P fluxes among scenarios

HFC outputs show C, N and P movement vary tremendously among scenarios (Table 9). Ratios of inputs to the high consumption household compared to the low consumption household were 3.5 for C, 2.7 for N and 1.4 for P.

The magnitude of C inputs followed the order: vehicles > household energy (gas + electric) > air travel. The ratio of C inputs between the high consumption and low consumption households was 5.0:1 for vehicles, 2.6:1 for household energy and 5.3:1 for air travel. In absolute terms, the difference in C input between the high and low consumption households was 5,000 kg C year$^{-1}$ for vehicles, 1,140 kg C year$^{-1}$ for air travel and 2,990 kg C year$^{-1}$ for household energy. In all three scenarios, lawn photosynthesis was about 5% of organic C input and $CO_2$ (from combustion and respiration) was 93–94% of C output.

For N, the magnitude of inputs was: food > vehicles > (pets; air travel). Ratios of N inputs between the high and low consumption households were 1.6:1 for food, 2.9:1 for vehicles, and 8.1:1 for air travel (the low consumption household did not have a dog). In absolute terms, the differences between the high and low consumption households were 9.6 kg year$^{-1}$ for vehicles, 10.0 kg year$^{-1}$ for human food, 5.9 kg year$^{-1}$ for air travel and 7.1 kg year$^{-1}$ for dog food.

Human food was the major source of P input to all three households, followed by dog food in the two scenarios with dogs (typical and high consumption). There was no difference in human food P input, because we knew of no reasonable way to estimate differences in the P content of diets among scenario households and therefore used the same values. The main difference in P inputs among scenarios was dog food. For the high consumption household, input of dog food P (for two large dogs) was 62% of human food P input. In states without a fertilizer P ban, the difference in P inputs between low and high consumption households would be much larger.

Calculated inputs did not equal calculated outputs for C, N or P in any scenario. The difference between C inputs and outputs to lawns was the result of organic C sequestration, which accounted for 0.8% of total C input in the high consumption household and 1.7% of total C input to the low consumption household. Sequestration is therefore a very small term relative to combustion-related C fluxes. The difference between inputs and outputs was much larger for N, ranging from 4% of N inputs in the low consumption household to 17% of N inputs in the high consumption household (Fig. 2), which we assumed to be organic N accumulation in trees and soils along with unaccounted losses. For the low and

**Table 9** Summary of fluxes (kg year$^{-1}$) in low consumption, typical consumption and high consumption scenario households

| Scenario | Description | Carbon | | | | Nitrogen | | | | Phosphorus | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | Input | | Output | | Input | | Output | | Input | Output |
| | | Organic C | $CO_2$ | Organic C | $CO_2$ | Organic N | Inorg. N | $NO_x$ | Other N | – | – |
| Low | Vehicles | 1,290 | 0 | 0 | 1,290 | 0.0 | 4.9 | 4.9 | 0.0 | 0.00 | 0.00 |
| | Air travel | 270 | 0 | 0 | 270 | 0.0 | 0.8 | 0.8 | 0.0 | 0.00 | 0.00 |
| | Electricity | 1,028 | 0 | 0 | 1,028 | 0.0 | 0.0 | 0.02 | 0.0 | 0.00 | 0.00 |
| | Natural gas | 823 | 0 | 0 | 823 | 0.0 | 0.0 | 0.0 | 0.0 | 0.00 | 0.00 |
| | Food | 423 | 0 | 0 | 351 | 16.0 | 0.0 | 0.0 | 0.0 | 2.58 | 0.00 |
| | Lawn and trees | 2 | 204 | 0 | 155 | 0.0 | 0.6 | 0.0 | 0.7 | 0.01 | 0.22 |
| | Pets | 0 | 0 | 0 | 0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.00 | 0.00 |
| | Wastewater | 0 | 0 | 92 | 0 | 0.0 | 0.0 | 0.0 | 19.7 | 0.00 | 3.02 |
| | Paper and plastic | 189 | 0 | 189 | 0 | 0.6 | 0.0 | 0.0 | 0.6 | 0.00 | 0.00 |
| | Other | 43 | 0 | 0 | 0 | 4.9 | 0.0 | 0.0 | 0.0 | 0.58 | 0.00 |
| | Total | 4,068 | 204 | 281 | 3,916 | 21.5 | 6.3 | 5.8 | 20.9 | 3.18 | 3.24 |
| | Total (inorg. + org.) | 4,271 | | 4,197 | | 27.8 | | 26.7 | | 3.18 | 3.24 |
| | Difference | 74 | | | | 1.1 | | | | −0.07 | |
| Typical | Vehicles | 3,105 | 0 | 0 | 3,105 | 0.0 | 7.8 | 7.8 | 0.0 | 0.00 | 0.00 |
| | Air travel | 674 | 0 | 0 | 674 | 0.0 | 2.1 | 2.1 | 0.0 | 0.00 | 0.00 |
| | Electricity | 2,028 | 0 | 0 | 2,028 | 0.0 | 0.0 | 0.03 | 0.0 | 0.00 | 0.00 |
| | Natural gas | 1,357 | 0 | 0 | 1,357 | 0.0 | 0.0 | 0.0 | 0.0 | 0.00 | 0.00 |
| | Food | 370 | 0 | 2 | 317 | 20.5 | 0.0 | 0.0 | 0.1 | 2.45 | 0.01 |
| | Lawn and trees | 3 | 373 | 0 | 275 | 0.0 | 6.2 | 0.0 | 2.3 | 0.02 | 0.68 |
| | Pets | 47 | 0 | 0 | 46 | 4.2 | 0.0 | 0.0 | 0.0 | 0.90 | 0.00 |
| | Wastewater | 0 | 0 | 92 | 0 | 0.0 | 0.0 | 0.0 | 19.7 | 0.00 | 3.02 |
| | Paper and plastic | 378 | 0 | 378 | 0 | 0.6 | 0.0 | 0.0 | 0.6 | 0.00 | 0.00 |
| | Other | 100 | 0 | 0 | 59 | −0.7 | 0.0 | 0.0 | 0.0 | 0.58 | 0.00 |
| | Total | 8,062 | 373 | 472 | 7,861 | 24.6 | 16.1 | 9.9 | 22.7 | 3.96 | 3.72 |
| | Total (inorg. + org.) | 8,435 | | 8,333 | | 40.7 | | 32.6 | | 3.96 | 3.72 |
| | Difference | 102 | | | | 8.2 | | | | 0.24 | |
| High | Vehicles | 6,492 | 0 | 0 | 6,492 | 0.0 | 14.5 | 14.5 | 0.0 | 0.00 | 0.00 |
| | Air travel | 1,414 | 0 | 0 | 1,414 | 0.0 | 6.7 | 6.7 | 0.0 | 0.00 | 0.00 |
| | Electricity | 2,866 | 0 | 0 | 2,866 | 0.0 | 0.0 | 0.05 | 0.0 | 0.00 | 0.00 |
| | Natural gas | 1,976 | 0 | 0 | 1,976 | 0.0 | 0.0 | 0.0 | 0.0 | 0.00 | 0.00 |
| | Food | 344 | 0 | 2 | 288 | 26.0 | 0.0 | 0.0 | 0.1 | 2.45 | 0.01 |
| | Lawn and trees | 4 | 766 | 282 | 372 | 0.0 | 27.1 | 0.0 | 20.9 | 0.04 | 3.59 |
| | Pets | 79 | 0 | 0 | 77 | 7.1 | 0.0 | 0.0 | 0.0 | 1.52 | 0.00 |
| | Wastewater | 0 | 0 | 105 | 0 | 0.0 | 0.0 | 0.0 | 19.7 | 0.00 | 3.02 |
| | Paper and plastic | 569 | 0 | 569 | 0 | 0.6 | 0.0 | 0.0 | 0.6 | 0.00 | 0.00 |
| | Other | 249 | 0 | 0 | 197 | −6.3 | 0.0 | 0.0 | 0.0 | 0.58 | 0.00 |

**Table 9** (Continued)

| Scenario | Description | Carbon | | | | Nitrogen | | | | Phosphorus | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | Input | | Output | | Input | | Output | | Input | Output |
| | | Organic C | $CO_2$ | Organic C | $CO_2$ | Organic N | Inorg. N | $NO_x$ | Other N | – | – |
| | Total | 13,993 | 766 | 958 | 13,683 | 27.5 | 48.2 | 21.2 | 41.3 | 4.60 | 6.62 |
| | Total (inorg. + org.) | 14,759 | | 14,641 | | 75.7 | | 62.5 | | 4.60 | 6.62 |
| | Difference | 118 | | | | 13.2 | | | | −2.03 | |

Negative numbers indicate net losses from the system

typical consumption scenarios, the HFC indicated unaccounted losses (nitrate leaching; denitrification or inorganic N accumulation). Denitrification (to $N_2$ or $N_2O$) can be an important loss pathway for N, accounting for as much as 21% of fertilizer losses from turfgrass systems (Horgan et al. 2002).

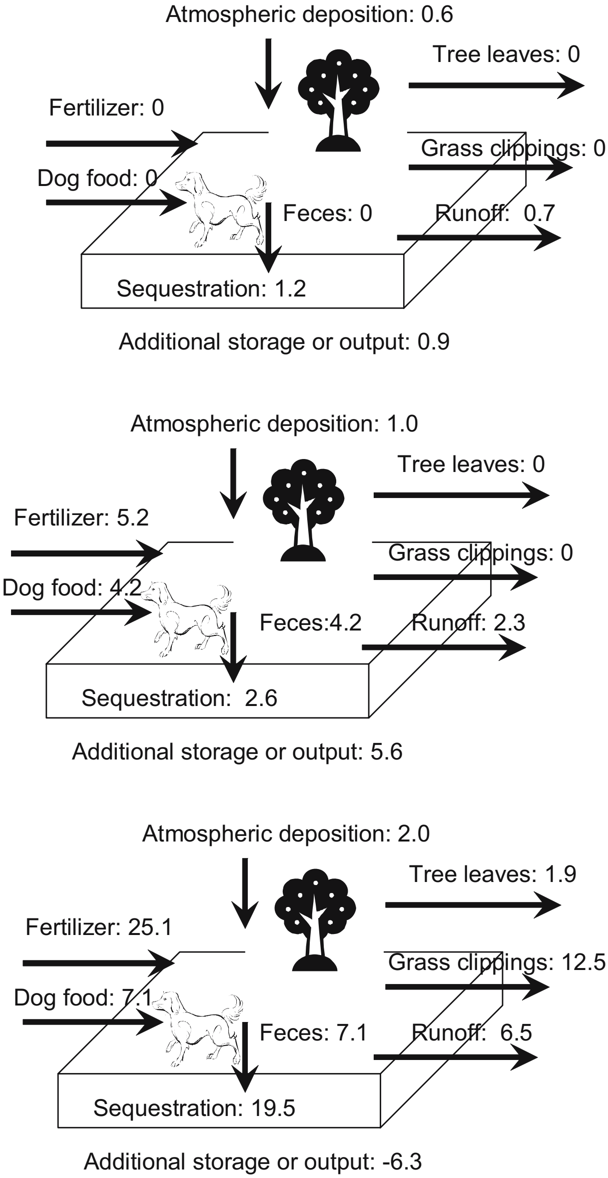
Emissions of $N_2O$ are particularly important in the context of global climate change; results from a study by Kaye et al. suggest that urban land cover can account for a significant proportion of $N_2O$ emissions on a regional basis (Kaye et al. 2004). Losses of N through nitrate leaching also have consequences in terms of regional water quality. The magnitudes of leaching and gaseous losses of N from urban landscapes require further work to be better constrained. For the high consumption scenario, sequestration plus exports (tree leaves, grass clippings and runoff) were greater than inputs. The difference (6.3 kg $year^{-1}$) could represent depletion of inorganic N from the soil pool. Finally, P accumulation varied among household scenarios. For the low consumption scenario, there was a small loss of P to runoff, which would be expected since there was no P input other than atmospheric deposition. For the typical consumption scenario household, there was a slight gain of soil P, reflecting additional input from dog feces. Although the high consumption scenario household had larger input from dog feces, it also had greater deliberate export of P in the form of grass clippings and tree leaves; hence HFC calculations indicated net loss of P, presumably due to decline in soil P.

## Discussion

All three scenario households shared many common characteristics: all had two adults and two children, all lived in detached, single family homes, all were located in the same neighborhood, at the same distance from work, and all would have had normal conveniences of modern life in a US suburb. Despite this, inputs of C and N varied by factors of 3.5 for C and 2.7 for N. Sixty percent of the variation in C fluxes between the low and high consumption households was caused by differences in transportation-related combustion. The largest difference in N fluxes between the low and high consumption households was fertilizer use, followed by human and pet food. P fluxes were not as variable, in part because we assumed that no P fertilizer was used. These differences suggest that there is considerable “discretionary pollution” in modern households, which we define as pollution associated with specific types of consumption that could readily be reduced without a major change in lifestyle.

Results from this analysis show that changes in household consumption behavior have varying affects on elemental fluxes and impacts. For the typical household, combustion

**Fig. 2** N fluxes through lawns of low consumption (*top*), typical consumption (*middle*) and high consumption (*bottom*) scenario households. Units are kg/year?



accounted for 85% of all C output, but only 24% of N output. Vehicles alone accounted for 37% of C output and 19% of N output. $CO_2$ produced by combustion is important in the context of global climate change, whereas the NOx output plays a major role in urban ozone formation. By contrast, 61% of N and 85% of the P, but only 5% of C input, occurs via household food. However, the impact of food consumption choices occur in the agricultural systems that provide food to the urban area and were not accounted for in this study.

We analyzed several scenarios to reduce fluxes from the high consumption household through stepwise reductions over the period of a decade. Reduced Scenario 1 was intended to represent changes that could occur within one year. In this scenario, we reanalyzed inputs to

**Table 10** Calculated impact of choices available to the high consumption household

| | Change in C input, % | Change in N input, % |
|---|---|---|
| Reduced scenario 1 (short-term) | −13 | −17 |
| Reduced scenario 2 (3–5 year horizon) | −38 | −29 |
| Reduced scenario 3 (10 + year horizon) | −71 | −63 |

the high consumption household after eliminating the family airplane trip, reducing driving distance per vehicle to the average, and changing the diet to that of the low consumption household (more calories and reduced protein). In Reduced Scenario 2, intended to represent changes over 3–5 years, both SUVs are converted to 30 MPG passenger cars, two large dogs are replaced with one small dog, and household gas and electricity was reduced by 20%. Finally, Reduced Scenario 3 converts the high consumption household to the low consumption household, a process that could take a decade.

Results show that the impact of choices made by the homeowner have a substantial impact on overall inputs of C and N. Based on this, a rough estimate of plasticity of C and N fluxes would be: 10–20% almost immediately, 30–40% within 3–5 years, and 60–70% over a period of 10 years (Table 10). This analysis shows that high consumption households can substantially reduce their C and N fluxes while still maintaining most aspects of their current lifestyle.

We note the special importance of lawns, particularly with regard to water pollution. Although the amount of C, N and P entering lawns is small relative to total household inputs, lawns are directly connected to the local water environment via runoff. More N and P enter household sewers than lawns, but sewage is treated. In the Twin Cities, sewage treatment reduces N and P levels in raw wastewater by 89% and 81%, respectively, (Baker, unpublished data); hence the absolute quantity of N and P entering the water environment from a typical household's lawn (to stormwater) and treated sewage (to the Mississippi River) is virtually identical. However, homeowners could readily change lawn management practices to reduce lawn runoff of N and P, whereas only limited future improvement in sewage treatment can be expected in the Twin Cities. Reduction of nutrient outputs from lawns ("source reduction"), which could be accomplished through policies which encourage "low input" lawns may also be highly cost-effective compared to construction of structural best management practices at the end of storm sewers.

The HFC is preliminary and will be refined in several ways. First, the temporal and spatial boundaries of the HFC are limited. We have not yet considered the embedded fluxes associated with construction of houses, cars and appliances; the manufacture of paper or other consumable goods; or the production of food. These fluxes may be large and may occur at some distance from the household yet can be substantially affected by choices made within a household. We are currently attempting to merge concepts from industrial ecology (Suh 2005) to expand the temporal and spatial dimensions of the HFC, with a focus on food production and processing. Second, the lawn component of HFC is essentially a simple mass balance that utilizes outputs from other models of turf and urban tree productivity. This mass balance approach revealed that outputs from lawns are a substantial fraction of total N and P output. It would therefore be useful to develop a dynamic model, or adapt an extant ecosystem model (as done by Qian et al. 2003) for inclusion in the HFC to provide greater realism. Such a model might be particularly useful to analyze the effects of Minnesota's lawn P restriction over time.

Ultimately the HFC will reasonably depict direct and indirect (embodied) C, N and P fluxes associated with households. As the biophysical model develops, we also seek to understand factors that control human consumption choices. We are currently analyzing household surveys designed to provide inputs to the HFC model regarding homeowner knowledge, norms and perceived control while simultaneously compiling information regarding behavioral intentions and actual environmental behaviors. This understanding will be needed to develop a public interface for the model that encourages adaptive management by homeowners who seek to reduce their pollution impact and allows policy makers to use the HFC to inform policy.

Since the modern era of pollution control started in the 1970s, the main focus has been to remove pollution at the "end of the pipe." This focus started with municipal and industrial pollution treatment, but remains the main focus for most efforts to reduce urban stormwater pollution. Most practices to remove stormwater pollutants, for example, rely on detention basins, wetlands, infiltration basins and other constructed devices. This approach is often ineffective and expensive. Understanding the penultimate sources of pollutants and how they move through our human systems will lead to novel approaches for pollution control based on reduction of sources of pollutants and understanding "discretionary pollution," rather than removal after formation. We propose that policies directed toward reducing household consumption and pollution production may be particularly fruitful because households are a major source of pollutants and there is sufficient flexibility in household choices to allow significant reduction of consumption to occur without requiring major lifestyle changes. The HFC model presented here is one example of the types of tools that are needed to accomplish this paradigm shift.

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