



# Nitrogen and carbon export from urban areas through removal and export of litterfall



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## ABSTRACT

We found that up to  $52 \pm 17\%$  of residential litterfall carbon (C) and nitrogen (N;  $390.6 \text{ kg C}$  and  $6.5 \text{ kg N ha}^{-1} \text{ yr}^{-1}$ ) is exported through yard waste removed from the City of Boston, which is equivalent to more than half of annual N outputs as gas loss (i.e. denitrification) or leaching. Our results show that removing yard waste results in a substantial decrease in N inputs to urban areas, which may offset excess N inputs from atmospheric deposition, fertilizer application and pet waste. However, export of C and N via yard waste removal may create nutrient limitation for some vegetation due to diminished recycling of nutrients. Removal of leaf litter from residential areas disrupts nutrient cycling and residential yard management practices are an important modification to urban biogeochemical cycling, which could contribute to spatial heterogeneity of ecosystems that are either N limited or saturated within urban ecosystems.

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## 1. Introduction

In northern temperate ecosystems, deciduous trees drop their leaves during the fall season in response to cooling temperatures to avoid damage caused by over-winter stress (Chabot and Hicks, 1982). In undisturbed rural areas, leaves decompose on the forest floor and nutrients are released, enabling efficient internal recycling of the majority of nutrients with only a small amount typically lost to nearby waterways or as gases to the atmosphere (Bormann and Likens, 1967; Likens and Bormann, 1995). In rural areas disturbed by humans, activities such as stem-cutting can reduce rates of litterfall (Gairola et al., 2009). In contrast, less is known about the controls on litterfall production and litter-derived nutrient cycling within urban areas (Michopoulos, 2011), including the influence of landscape management choices on these processes. In this study, we sought to determine how much C and N is exported via litter removal out of the City of Boston during the fall leaf litter collection period.

Several studies have examined biogeochemical processes in forest patches in urban environments (e.g., Groffman et al., 2006; Pouyat and Carreiro, 2003; Michopoulos, 2011), suggesting that

complex and sometimes counter-balancing factors may control the patterns of leaf litter production in urban landscapes. For instance, while rates of litterfall production were shown to decrease with increased impervious area in Washington state (Roberts and Bilby, 2009), soil fertility was a more important predictor of litterfall production around Baltimore, Maryland (Groffman et al., 2006). To our knowledge, no study has examined litterfall in the developed portions of the urban landscape (e.g., highly urban residential areas), nor the effects on nutrient recycling that are caused by gathering of litterfall from trees by urban residents and landscapers. These activities represent a potentially large export of C, N and other nutrients from urban landscapes, which may disrupt ecosystem recycling of nutrients and carbon.

Urban areas around the world are growing in land area and population and their effect on ecological processes is being increasingly recognized (Pickett et al., 2011; Kaye et al., 2006; Gregg et al., 2003; Metson et al., 2012; Pouyat et al., 2006, 2008; UNDESA, 2008; Hutyra et al., 2014). New and existing urban areas will account for most of the world's population growth over the next 40 years (Seto et al., 2012). Within the United States the transformation of forests by urbanization will be most pronounced in the northeastern U.S., where four states (Rhode Island, New Jersey, Massachusetts and Connecticut) are projected to have more than 60% of their forestland converted to urban land use by the year

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2050 relative to 1992 levels (Nowak and Walton, 2005). Urbanization often occurs at the expense of natural areas, but urban areas can still contain considerable tree canopy cover and biomass stocks. Raciti et al. (2012) found that mean biomass inside the Massachusetts portion of the Boston Metropolitan Statistical Area (MSA) was  $72 \text{ Mg C ha}^{-1}$ , compared to a Massachusetts statewide wide mean of  $84 \text{ Mg C ha}^{-1}$  and to rural forests with a mean of  $117 \text{ Mg C ha}^{-1}$ . Even the highly urbanized City of Boston, with a population density of almost  $5000 \text{ people km}^{-2}$ , contain 26% tree canopy cover and  $29 \text{ Mg C ha}^{-1}$  of tree biomass (Raciti et al., 2014).

Similar to other states in the U.S., Massachusetts mandates that yard waste be recycled. The Massachusetts Department of Environmental Protection (MassDEP) enacted a law in 1991 (310 CMR 190.017) banning incineration or transfer of yard waste (including leaves from trees, grass clippings, weeds, hedge clippings, garden materials and brush) to traditional landfill sites. Residents are encouraged to compost litter or place it in large paper bags or open barrels at their curb-side for pick-up. The City of Boston collects yard waste for six weeks in the fall (mid-October through November 30 each year) and four weeks in the spring of each year (typically end of April through end of May). Residents in the City of Boston recycled 8000 tons of yard waste in FY 2007 (City of Boston, 2007). Yard waste is transported to municipal compost piles and eventually applied to community gardens and/or sold for commercial use.

In this study, we sought to determine how much C and N is exported via litter removal out of the City of Boston during the fall leaf litter collection period and to relate N export from litterfall removal to other ecosystem N fluxes. We examined three census block groups, each in a different neighborhood within the City of Boston, and measured canopy cover, total litterfall mass, litter C and

N concentrations, as well as mass and proportion of C and N exported as yard waste.

## 2. Methods and materials

We monitored the number and mass of yard waste bags left at the curbside for collection in one census block group in each of three neighborhoods in the City of Boston, MA (Fig. 1) over one complete fall yard waste collection season (October 18 to Nov. 26, 2010). The neighborhood census block groups (hereafter referred to as “neighborhoods”) in Allston, Mission Hill, and Jamaica Plain were predominantly residential (>80% by land area compared to City of Boston at 42% residential; Massachusetts Office of Geographic Information [MassGIS], <http://www.mass.gov> 2009) and contained 93, 112, and 122 individual parcels, respectively.

We visited each parcel weekly, just prior to yard waste collection, and recorded the number of yard waste bags placed at the curbside and the approximate proportion that each bag was filled with leaves (e.g., 25, 50, 75, or 100% by volume). To convert bag counts to total dry mass of leaf litter, we collected three loosely packed and three tightly packed yard waste bags (all considered 100% full) and determined that the mean dry mass of litter in these “full” bags was  $3.01 \pm 0.48 \text{ kg}$ . Partially filled bags were presumed to have a dry mass that was directly proportional to their fullness. The total dry mass of leaf litter exported from each parcel was estimated based on the total number and fullness of bags placed at the curb for collection over the course of the fall season.

We collected samples of litter from a subset of yard waste bags in each neighborhood ( $n = 24, 12,$  and  $13$  parcels for Allston, Mission Hill, and Jamaica Plain, respectively) to determine the average concentration of C and N in leaf litter across the three neighborhoods. We limited our litter analysis to Norway maple

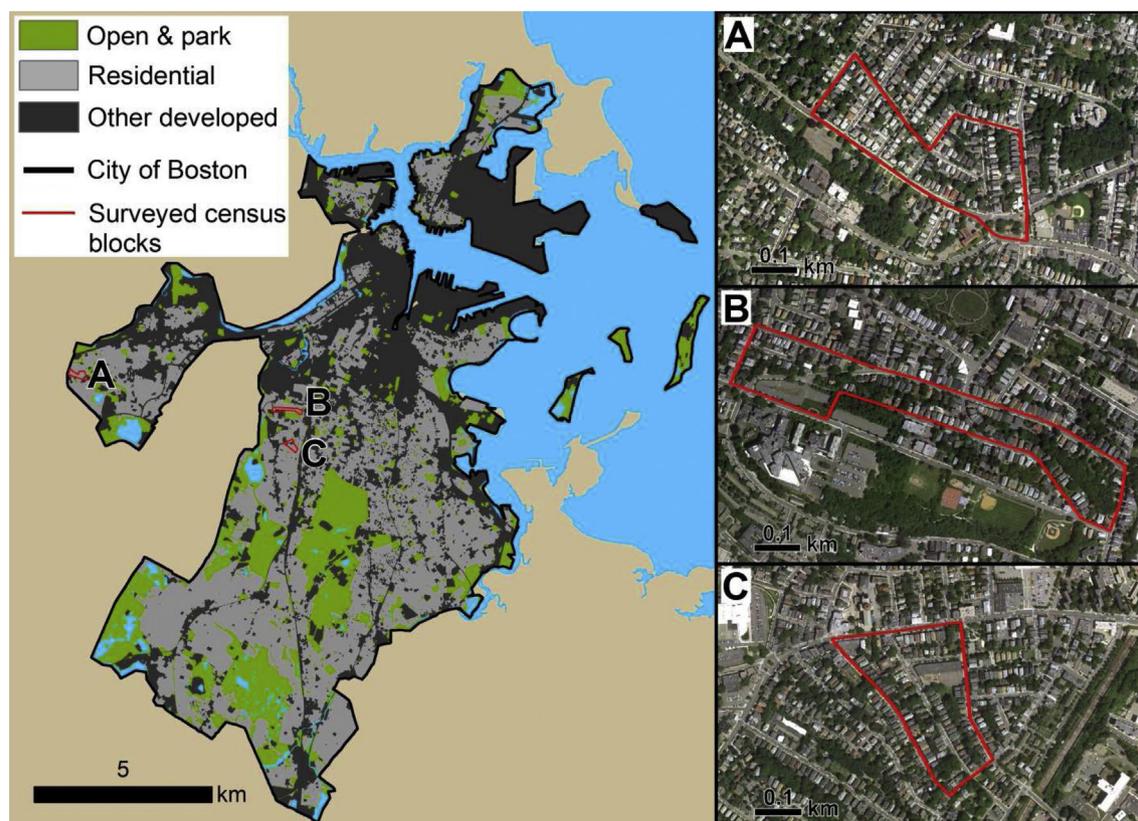


Fig. 1. Map of the City of Boston. Insets include census block groups surveyed within the neighborhoods of (A) Allston, (B) Mission Hill and (C) Jamaica Plain.

(*Acer platanoides*) and oaks, which were the dominant overstory trees in the three neighborhoods. It was not feasible to identify oak trees to species since many leaves were from hybridized red oak (*Quercus rubra*) and eastern black oak (*Quercus velutina*) trees. Leaves for analysis were chosen for being intact with no signs of advanced decomposition thereby indicating that they were from the current year's litterfall. Litter samples were brought back to the laboratory, dried at 45–55° C for 72 h, homogenized using a Spex Sample Prep 5100, and analyzed for C and N concentration by flash-combustion/oxidation using a Thermo Finnigan Flash EA 1112 elemental analyzer (0.06% C and 0.01% N detection limits). We used the mean value of C and N concentration for each species (*A. platanoides*) or genus (*Quercus*) across the three neighborhoods (Table 1) for our calculations of C and N inputs (from leaf fall) and exports (from yard waste collection) since these values did not vary significantly across neighborhoods. Total mass of C and N exported from each parcel was determined based on the estimated dry mass of yard waste bags multiplied by the mean C and N concentration of litter from the dominant overstory trees in the parcel (e.g. Norway maple, oaks, or a mix of both).

To determine tree canopy cover (%) of each parcel, we overlaid the parcel boundaries (MassGIS 2013; <http://www.mass.gov>) onto high resolution satellite imagery in Google Earth (software v6.2.2.6613; imagery dated June 6, 2010) and exported the images into the ImageJ image analysis software (v1.48). We used ImageJ to manually delineate the tree canopies (using the *Freehand selection* tool) and the parcel boundaries (using the *Polygon selection* tool) and to then calculate their relative areas. Tree canopy cover (%) was determined by multiplying the proportional canopy area (from ImageJ) by the parcel area (obtained from the MassGIS parcel data layer; MassGIS 2013).

Total foliar canopy biomass per unit land area was calculated using the following relationship ( $R^2 = 0.71$ ) based on urban data from Rao et al. (2013):

$$B = 0.0029 * C + 0.0025 \quad (1)$$

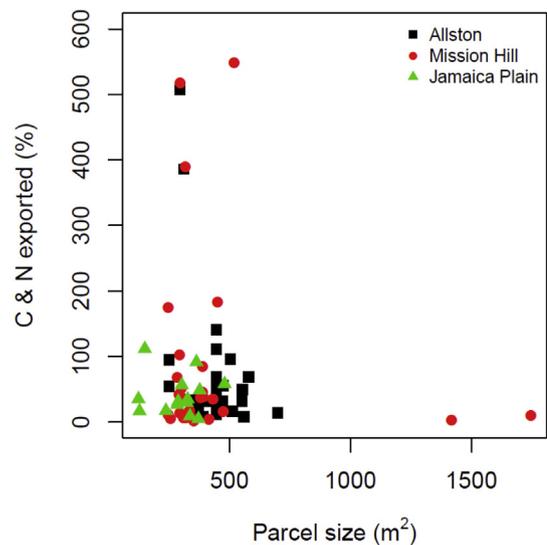
where B = total canopy biomass ( $\text{kg m}^{-2}$ ); C = tree canopy cover (%). We calculated the total litterfall C and N for each address by multiplying total foliar biomass by mean C or N concentration of litter. Finally, we calculated the amount of C and N exported from each address by dividing the total leaf litter left at the curbside for collection by the total litterfall. We report 10% trimmed means for litterfall C and N, litterbag C and N, and export values, a standard approach for minimizing the influence of outliers for data that have a non-normal, long-tailed distribution, such as in this study (Fig. 2).

We extracted basic demographic data from the year 2000 US Census to characterize the socioeconomic character of each neighborhood (Census.gov). The proportions of residential, park and open space, and other land uses (mainly commercial) in each census block group were determined using high resolution spatial data from the Massachusetts Office of Geographic Information (MassGIS 2009).

**Table 1**

Carbon, nitrogen and carbon:nitrogen ratio in leaf litter of Norway maple (*Acer platanoides*) and oak (*Quercus spp*) litter. Values are means with standard error. Sample size refers to the number of bags sampled. Different letters indicate statistically significant differences between tree species ( $p < 0.05$ ).

	%N	%C	C:N	n
Norway maple ( <i>Acer platanoides</i> )	0.75 ± 0.03	45.02 <sup>a</sup> ± 0.26	63.62 <sup>a</sup> ± 1.98	58
Oak ( <i>Quercus spp</i> )	0.78 ± 0.07	49.90 <sup>b</sup> ± 0.29	69.32 <sup>b</sup> ± 4.45	15



**Fig. 2.** Total amount of C and N exported (%) among individual parcels in each of three neighborhoods in Boston.

### 3. Results

The City of Boston has a total land area of 125  $\text{km}^2$ , of which 42% is residential (MassGIS 2009). The three neighborhood census block groups we examined are primarily residential (85.8, 80.4 and 80.1% residential for Allston, Mission Hill, and Jamaica Plain, respectively). The median household income among the census block groups was \$60,662, \$51,875 and \$48,000 and owner occupancy was 33%, 25%, and 18% for Allston, Mission Hill, and Jamaica Plain, respectively. The socio-economic characteristics for these neighborhoods overlap with the City of Boston as a whole, which had an overall household income of \$50,684 and owner occupancy of 35%.

Concentrations of N within leaf litter of Norway maple ( $0.75 \pm 0.03\%$ ) and oak ( $0.78 \pm 0.07\%$ ) trees did not differ significantly, but carbon concentrations and C to N ratios were greater within oak ( $49.90 \pm 0.29\%$  C and  $69.32 \pm 4.45\text{C:N}$ ) than Norway maple litter ( $45.02 \pm 0.26\%$  C and  $63.62 \pm 1.98\text{C:N}$ ; Table 1).

Jamaica Plain residents exported the largest proportion of C and N, despite having the lowest C and N mass in litterbags (Table 2). Canopy cover and biomass were approximately 50% greater in the Mission Hill and Jamaica Plain neighborhoods compared to Allston. We found that between  $38 \pm 8.2$  and  $60.9 \pm 29.2\%$  C and N (Mission Hill and Jamaica Plain neighborhoods, respectively) that falls in litter is exported from residential neighborhoods of Boston. Litterfall C and N content was extrapolated for all of residential Boston ( $75.4 \text{ g C m}^{-2}$ ,  $1.3 \text{ g N m}^{-2}$ ) by using the mean canopy litterfall ( $61.9 \pm 6.0 \text{ g C m}^{-2}$  and  $1.04 \pm 0.10 \text{ g N m}^{-2}$ ) and mean percent residential area (82%) of the three study neighborhoods. We estimate that  $51.8 \pm 17.3\%$  of litterfall C and N is exported from residential Boston as a whole.

### 4. Discussion

Results of this study show that leaf litter removal by urban residents can lead to considerable export of C and N from urban ecosystems. We show that between 38 and 61% of litterfall C and N is exported through yard waste bags removed from three predominantly residential neighborhoods in the City of Boston. We estimate that  $51.8 \pm 17.3\%$  of litterfall C and N is exported from residential Boston as a whole, which is equivalent to more than half of annual N outputs from urban areas as gas loss (i.e.

**Table 2**

Total number of individual parcels examined and parcels with litterbags in each of three neighborhoods in Boston. All estimates for canopy cover, canopy biomass, litterfall and percent export are based on parcels containing litterbags only. For canopy cover, canopy biomass, total litterfall, total litterbag mass and percent C and N exported, ten percent trimmed means (with standard error) are reported to minimize the influence of outliers given the non-normal, long-tailed distribution of our data. Boston canopy cover estimates are based on an Urban Ecology Institute report ([www.urbaneco.org/State%20of%20the%20Urban%20Forest%20Report.pdf](http://www.urbaneco.org/State%20of%20the%20Urban%20Forest%20Report.pdf) accessed July 19, 2009). Due to the highly skewed distribution of the parcel-level data, neighborhood-level means for C and N inputs and exports on a mass basis do not necessarily sum to equal C and N exports on a percentage basis.

	% Residential	Total # parcels	Total # parcels with litterbags	Canopy cover per parcel (%)	Canopy biomass per parcel (kg m <sup>-2</sup> )	Total litterfall C per parcel (g C m <sup>-2</sup> )	Total litterfall N per parcel (g N m <sup>-2</sup> )	Total litterbag C per parcel (g C m <sup>-2</sup> )	Total litterbag N per parcel (g N m <sup>-2</sup> )	C and N exported (%)
Neighborhood 1 (Allston)	85.8	93	29	19.6 ± 2.2	0.12 ± 0.01	54.4 ± 5.9	0.9 ± 0.1	21.4 ± 5.0	0.36 ± 0.08	46.7 ± 20.4
Neighborhood 2 (Mission Hill)	80.4	112	14	28.6 ± 5.2	0.17 ± 0.03	78.5 ± 13.8	1.3 ± 0.2	24.7 ± 4.9	0.42 ± 0.08	38.0 ± 8.2
Neighborhood 3 (Jamaica Plain)	80.1	122	27	24.9 ± 4.4	0.15 ± 0.03	68.5 ± 11.8	1.1 ± 0.2	18.9 ± 3.2	0.32 ± 0.05	60.9 ± 29.2
Boston (City)	42.0				(Residential)	100			27.6	0.17
Boston	75.41	1.26	24.72	0.41		51.79 ± 17.28				

denitrification) or leaching (Fig. 3). Some of the N exported is presumably offset by atmospheric N inputs (Rao et al., 2014; Templer and McCann, 2010), urine from dogs (Baker et al., 2001), fertilizer inputs (Law et al., 2004), and compost that is formed from yard waste and returned to the city for urban gardens. It was not possible to quantify how much C and N is returned to the City of Boston as compost since it is not routinely monitored, but it would likely create hotspots of nutrient availability where it is applied rather than returning C and N to areas where yard waste was removed. Anecdotally, compost is more heavily applied on gardens and landscaped areas, rather than patches dominated by trees. Export of C and N via yard waste removal may create nutrient limitation for some vegetation since recycling of organic matter via litterfall typically makes up more than 90% of the fluxes in terrestrial ecosystems (Fig. 3).

While it could be hypothesized that neighborhood demographics like income and owner occupancy would influence yard management practices, we did not observe any consistent relationships. For example, the Allston census block group had the lowest canopy cover and litterfall mass, highest median household income, and a medium-level proportional export of C and N. Jamaica Plain residents exported the largest proportion of C and N, despite having the lowest C and N mass in litterbags (Table 2). Canopy cover and biomass were approximately 50% greater in the Mission Hill and Jamaica Plain neighborhoods. Given the limited number of neighborhoods examined, additional study is required to draw conclusions about the relationship between neighborhood demographics and C and N export from residential areas.

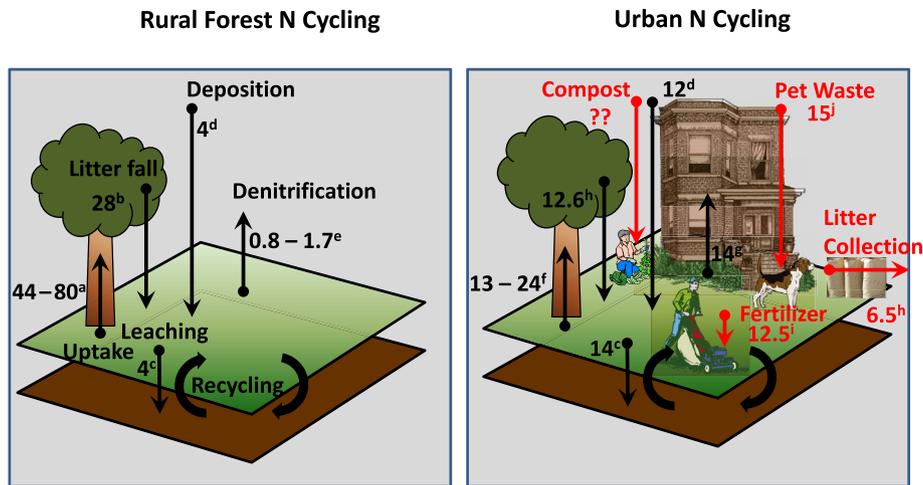
There was variability in the amount of C and N exported relative to parcel size (Fig. 2), which further skewed the data to have a non-normal distribution. For example, a subset of small parcels had very large amounts of C and N exported, likely due to litter blowing in from adjacent parcels. On the other extreme, some very large parcels (>1300 m<sup>2</sup>) had very low amounts of C and N exported, despite relatively large amounts of litterfall. We hypothesize that within large residential parcels leaf litter is less likely to be removed from forested areas compared to from the lawn, garden, and paved areas that dominate the land area of smaller parcels. We overcame the complex relationship between parcel size and %C and N exported by removing outliers prior to calculating the mass of each element exported with litter.

Our estimates represent a lower limit on C and N export from residential areas in the City of Boston due to a range of leaf litter exports that we were unable to quantify, including the loss of

windblown leaves to the street and resultant export via street sweeping and storm drains. We only sampled yard waste placed by residents at their curbside in fall months and therefore did not capture additional litter exported during other seasons, nor the quantity of leaf litter removed by landscaping companies and not left on-site for curbside collection. In some cases, our parcel-level measurements of leaf litter removal are underestimated due to mixed management within a parcel, wherein professional landscapers and homeowners each remove a portion of the leaf litter, resulting in only a fraction of exported leaf litter being left at the curbside (typically only the fraction collected by homeowners). There are also a range of other landscaping activities that result in organic matter removal from developed areas, including lawn mowing, tree trimming, and gardening, which were not quantified in this study. While we surveyed 327 parcels, these sites only represent three neighborhoods in Boston and may not have captured the heterogeneity of urban residential litter management practices.

Kaye et al. (2006) suggest that urban ecosystem models should incorporate anthropogenic effects unique to developed environments, including impervious surface area, landscape choices and human demographic metrics. We argue that litterfall removal via yard waste collection should be included as a significant export of nutrients as well. These N exports are similar in magnitude to annual inputs from atmospheric N deposition in the Boston area (Rao et al., 2014). The removal of lawn clippings may represent an even larger N export due to the high N content of fresh lawn clippings compared to senesced leaves collected through yard waste programs (Kopp and Guillard, 2002; Osmond and Hardy, 2004). Metson et al. (2012) show that a significant portion of phosphorus is removed from the city of Phoenix, AZ through transfer of yard trimmings to landfill.

Our results suggest that the removal of leaf litter from residential areas disrupts nutrient cycling and that residential yard management practices are an important modification to urban biogeochemical cycling. We constructed a N budget within urban ecosystems such as Boston and found that the amount of N exported through litterfall collection and export is equivalent to 6.5 kg N ha<sup>-1</sup> yr<sup>-1</sup>, which is more than half of annual N outputs from urban areas as gas loss (i.e. denitrification = 14 kg N ha<sup>-1</sup> yr<sup>-1</sup>; Raciti et al., 2011) or leaching (14 kg N ha<sup>-1</sup> yr<sup>-1</sup>; Groffman et al., 2009, Fig. 3). Further, our results show that removing yard waste results in a substantial decrease in N inputs to urban areas, which may offset excess N inputs from atmospheric deposition



**Fig. 3.** Ecosystem model showing nitrogen fluxes ( $\text{kg ha}^{-1} \text{yr}^{-1}$ ) in rural forest ecosystems of the Northeastern United States and within urban residential areas. Black text and arrows indicate nitrogen fluxes within both rural and urban ecosystems. Red text and arrows indicate urban-specific fluxes. Letters indicate literature sources for reported estimates of fluxes. <sup>a</sup> Likens and Bormann (1995) and Yanai (unpublished); <sup>b</sup> Urbanski et al. (2007); <sup>c</sup> Groffman et al. (2009); <sup>d</sup> Templer and McCann 2010; Rao et al. (2014); <sup>e</sup> Morse et al. (in press); <sup>f</sup> Scaled from <sup>a</sup> based on 29% canopy cover in Boston compared to 97% canopy cover at Harvard Forest ( $=29/97 * \text{N uptake by trees in rural forest}$ ); <sup>g</sup> Raciti et al. (2011); <sup>h</sup> this study; and <sup>i</sup> Law et al. (2004); <sup>j</sup> Baker et al. (2001). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

( $12 \text{ kg N ha}^{-1} \text{yr}^{-1}$ ; Templer and McCann, 2010; Rao et al., 2014), pet waste ( $15 \text{ kg N ha}^{-1} \text{yr}^{-1}$ ; Baker et al., 2001) and fertilizer application ( $12.5 \text{ kg N ha}^{-1} \text{yr}^{-1}$ ; Law et al., 2004). Removing yard waste removes other nutrients (e.g., phosphorus, cations) in addition to N that are essential for plant and microbial growth and therefore is unlikely to be an effective management practice for reducing N inputs to urban ecosystems on a large-scale. While we do not have fertilizer application data specific to the City of Boston, in a suburban watershed in the Baltimore metropolitan region (i.e. Glyndon watershed; 47% residential compared to 42% residential in the City of Boston), watershed-level fertilizer inputs were approximately  $12.5 \text{ kg N ha}^{-1} \text{yr}^{-1}$ , which is similar in magnitude to atmospheric N deposition (Law et al., 2004). One caveat to consider about scaling up N inputs from lawns to entire cities is that a large amount of heterogeneity exists in rates of fertilizer application by homeowners. Many homeowners do not fertilize at all, some fertilize only occasionally, while others apply N fertilizer at rates similar to high-intensity agricultural systems (Law et al., 2004). Also, many areas are not subject to significant fertilizer inputs (e.g., semi-natural areas, impervious surfaces, most public right of ways, large portions of public parks outside of sports fields and highly manicured areas, etc.).

We hypothesize that removal of leaf litter from urban yards contributes to heterogeneity of urban ecosystems, which may contain hotspots of N limitation (due to removal of leaf litter and lawn clippings) in some locations and N saturation (due to anthropogenic N inputs from deposition, fertilizer application, and pet waste) in others. Understanding fine-scale heterogeneity in N availability and potential losses to nearby waterways and the atmosphere are critical for determining the potential role of urban ecosystems in sequestering carbon and for understanding urbanization effects on water and air quality. Over the past century, human activities have dramatically disrupted the global cycling of N, with some of the most acute changes occurring in urban areas (Vitousek et al., 1997). An improved understanding of C and N inputs, exports, and internal cycling are critical for reducing the impact of urbanization on the environment. Further, understanding how yard waste practices for both litter and lawn clipping removal vary among urban areas (i.e. beyond the City of Boston) could contribute to predictions of homogeneity vs. heterogeneity across the landscape (Polisky et al., 2014). Overall, the results of this study

and future ones will enable stronger understanding of how land management practices alter nutrient limitation and loss in urban environments.

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