Contrasting nitrogen and phosphorus budgets in urban watersheds and implications for managing urban water pollution

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Managing excess nutrients remains a major obstacle to improving ecosystem service benefits of urban waters. To inform more ecologically based landscape nutrient management, we compared watershed inputs, outputs, and retention for nitrogen (N) and phosphorus (P) in seven subwatersheds of the Mississippi River in St. Paul, Minnesota. Lawn fertilizer and pet waste dominated N and P inputs, respectively, underscoring the importance of household actions in influencing urban watershed nutrient budgets. Watersheds retained only 22% of net P inputs versus 80% of net N inputs (watershed area-weighted averages, where net inputs equal inputs minus biomass removal) despite relatively low P inputs. In contrast to many nonurban watersheds that exhibit high P retention, these urban watersheds have high street density that enhanced transport of P-rich materials from landscapes to stormwater. High P exports in storm drainage networks and yard waste resulted in net P losses in some watersheds. Comparisons of the N/P stoichiometry of net inputs versus storm drain exports implicated denitrification or leaching to groundwater as a likely fate for retained N. Thus, these urban watersheds exported high quantities of N and P, but via contrasting pathways: P was exported primarily via stormwater runoff, contributing to surface water degradation, whereas N losses additionally contribute to groundwater pollution. Consequently, N management and P management require different strategies, with N management focusing on reducing watershed inputs and P management also focusing on reducing P movement from vegetated landscapes to streets and storm drains.

eutrophication | nitrogen | phosphorus | stormwater | urban watershed

Many cities are located on water bodies (lakes, rivers, reservoirs, estuaries, and coastal oceans) that provide important ecosystem services, such as drinking water and food, water cycle and regional climate regulation, habitat to support biodiversity, and aesthetic and recreational opportunities (1, 2). However, as the receiving waters for urban pollution, water quality in and downstream of urban areas is widely impaired by a variety of stressors, especially high loading of phosphorus (P) and nitrogen (N) (3–6). Excessive nutrient loading causes eutrophication, with abundant algal growth, shifts toward noxious cyanobacteria, reduced water clarity, oxygen depletion, bad odor, and loss of key species (4, 7–13).

Improved wastewater treatment and bans on P-containing detergents have strongly reduced sanitary sewer P inputs from cities to surface waters (11). As these point sources of urban water pollution are increasingly controlled, the difficult challenge of controlling nonpoint nutrient runoff from urban landscapes remains. Despite enormous effort spent on structures designed for capturing or infiltrating nutrients to keep them out of surface waters, the problem of urban eutrophication arising from stormwater runoff persists (14). Thus, new approaches to address urban water quality degradation are needed.

"Upstream" solutions, which seek to reduce sources of N and P to urban watersheds, or their inputs to storm sewers and streams, hold promise of being more effective and economically efficient and distribute costs more fairly. However, implementation of upstream solutions has been limited by weak knowledge of urban watershed nutrient budgets. Past efforts to construct nutrient budgets in urban watersheds generally have been limited in scope, quantifying nutrient outputs but not inputs, omitting potentially significant nutrient fluxes, and/or focusing on single elements. Urban watersheds have been shown to retain a relatively high percentage of N inputs (∼65–99%) (8, 15–17, but see ref. 18). However, past studies did not fully quantify potentially important watershed nutrient inputs, such as pet waste (17, 19), nonresidential fertilizer use, and biological N fixation (BNF), or outputs, such as yard waste removal (20) and leaf litter removal via street sweeping (21). Further, most studies of watershed nutrient retention have focused on N. Although urbanization has been shown to increase surface water P export (3, 4), whether such high export results from relatively high P inputs or low P retention is unknown. In natural watersheds, P is thought to be relatively immobile in soils and exhibits high retention (22). The same might not be true in urban watersheds, where impervious surfaces can effectively transport nutrients from vegetated landscapes to streets and storm sewers.

To inform more ecologically based landscape nutrient management, we developed N and P mass balances for seven urban watersheds in the Minneapolis–St. Paul metropolitan area in

Significance

Urban waters remain widely impaired by excess nutrients, despite substantial management efforts. We present a comparison of urban watershed nitrogen (N) and phosphorus (P) budgets. Household actions of lawn fertilization and pet ownership were responsible for the majority of watershed N and P inputs, respectively. N and P exhibited contrasting dynamics within watersheds. Watersheds exported most or all P inputs via stormwater runoff, likely contributing to surface water degradation. High apparent N retention likely resulted from unmeasured watershed N losses to the atmosphere and groundwater. These contrasting dynamics suggest that N management should emphasize reducing watershed inputs, whereas P management should focus on reducing watershed P inputs and transport from vegetated landscapes to streets and storm drains.

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Minnesota (Table 1) and used this knowledge to evaluate ways to reduce nutrient pollution from urban landscapes. We predicted that the greatly altered nature of urban watersheds, with high impervious cover and rapid drainage via stormwater conveyances (23), would offer few mechanisms to retain P in urban watersheds. By contrast, we expected watersheds to exhibit high N retention, as seen in past studies (8, 15, 16, 18).

Results and Discussion

Household Actions Dominate Watershed Nutrient Inputs. Household activities (rather than commercial, municipal, or industrial actions) dominated landscape nutrient inputs to urban watersheds in this region, highlighting the importance of residential landscapes for human–environment interactions in cities (24) and as targets for management improvements for reducing nutrient pollution. Specifically, household lawn fertilizer dominated N inputs (Fig. 1 and *SI Appendix*, Table S2), ranging from 37 to 59% of total N inputs. Lawn fertilizer N inputs exceeded combined fertilizer N inputs to golf courses, cemeteries, parks, campuses, and other nonresidential vegetated areas, reflecting the highly residential nature of these urban watersheds, where yards and boulevards accounted for 70% of total watershed vegetated area. For instance, the average fertilizer N inputs on a watershed area basis were more than twice as high as estimates for urban-suburban watersheds in Baltimore that included significant forested land (25).

Household nutrient inputs from pet (dog) waste contributed up to 76% of total P inputs and 28% of total N inputs (Figs. 1 and 2 and *SI Appendix*, Tables S2 and S3) because high housing density (Table 1) gave rise to high per area rates of pet ownership and state law restricts lawn fertilizer P use. In light of similar restrictions in a dozen or so US states (26), the relative importance of pet waste likely is increasing in other urban watersheds. The range among watersheds was considerable: pet waste N and P inputs in the most residential watershed [Arlington-Hamline Underground (AHUG)] were sixfold as high as in the least residential watershed [Saint Anthony Park (SAP)], underscoring the need to quantify rates of pet waste pickup in urban watersheds better so as to estimate watershed P inputs accurately. For example, our estimate that 40% of dog feces ended up in the landscape (27) was based on a single study of dog owner waste pickup practices in the Chesapeake Bay area (28).

Atmospheric deposition (1,449 kg of N per $km^2 \cdot y^1$) was the second most important N input to watersheds, contributing 19–34% of total N inputs (Fig. 1 and *SI Appendix*, Table S2), and was in the range of estimates for other major US cities (17, 29, 30). As with N fertilizer, some fraction of deposited N [generated from diverse sources, including vehicle and commercial-industrial fossil fuel combustion as well as ammonia (NH_3) volatilization from fertilizer and animal waste] likely resulted from household actions, because total estimated N emissions [nitrogen oxide (NO_x,) and NH_3] from vehicles were 3.6-fold as high as estimated N emissions from all other sources in Ramsey County (31). However, it is unknown what fraction of vehicle emissions in each of the study watersheds came from household versus commercial vehicles and what portion of atmospheric deposition

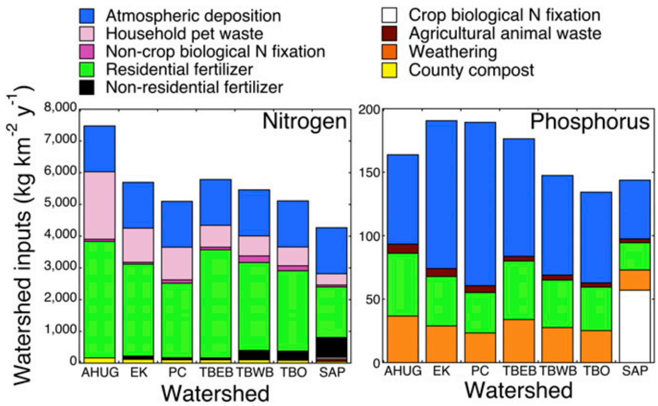

Fig. 1. Watershed nutrient inputs of N (*Left*) and P (*Right*). Watersheds are ordered from most to least residential (left to right), based on housing density. Abbreviations are provided in the legend for Table 1.

in each watershed came from within-watershed versus external emissions sources. Because our estimates of N deposition were modeled at a relatively large grid scale, we also could not account for fine-scale heterogeneity in deposition (e.g., enhanced deposition near emission sources) (32, 33).

Atmospheric deposition was also the second most important P input to the watersheds after pet waste, contributing 13–33% of total P inputs (Fig. 1 and *SI Appendix*, Table S3). However, its origin and importance as a watershed input are uncertain. Estimates of P deposition were derived from published measurements of wet deposition in rural Minnesota and of dry deposition in two small Minnesota cities (34). P deposition might be lower in St. Paul because of less wind erosion from agricultural fields, or it might be higher because of more wind erosion from construction sites. More significantly, we could not distinguish P deposition originating within vs. outside of the watershed (35). Internal sources, such as wind erosion of local soil, vegetation particles, and the like (36), do not represent truly new inputs. More research on the magnitude and origin of urban P deposition is needed, given its potential importance for urban watershed P balance.

Besides pet waste, other nutrient inputs mostly overlooked in past studies, including BNF, nonresidential fertilizer, compost, and weathering, were generally small. BNF in lawns and parks contributed 1–4% of total N inputs (Fig. 1 and *SI Appendix*, Table S2). Compost contributed 2% of total N inputs. Nonresidential N fertilization contributed 0–15% of total N inputs and was highest in the three watersheds with golf courses, campuses, cemeteries, and an agricultural experiment station, which also contributed minor N inputs of agricultural animal waste (manure) and BNF from crops. Weathering and compost were modest P inputs, contributing 4–9% and 6–10% of total inputs, respectively. Nonresidential P fertilizer was not used

Table 1. Select characteristics of seven study watersheds

Watershed	Size, ha	Housing density,* no./km^2	Total vegetated area, ha	Total impervious cover, ha	Street density, km/km^2	Fractional tree cover over streets	Runoff coefficient
AHUG	16	1,538 (97%)	8	8	13.6	0.36	0.19
EK	452	774 (93%)	206	224	15.3	0.30	0.54
PC	580	743 (77%)	252	325	14.8	0.27	0.96
TBEB	327	500 (97%)	184	142	13.2	0.22	0.49
TBWB	2,097	459 (94%)	1,244	746	9.6	0.29	0.51
TBO	3,171	426 (94%)	1,737	1,315	10.9	0.24	0.56
SAP	1,383	258 (90%)	592	739	10.6	0.20	0.38

*Single- and multifamily households (percentage of households that were single-family households). Runoff coefficient = (annual stormwater runoff + baseflow)/annual precipitation. AHUG, Arlington-Hamline Underground; EK, East Kittsondale; PC, Phalen Creek; TBEB, Trout Brook East Branch; TBWB, Trout Brook West Branch; TBO, TB Outlet; SAP, Saint Anthony Park. TBO includes TBEB and TBWB and additional land area.

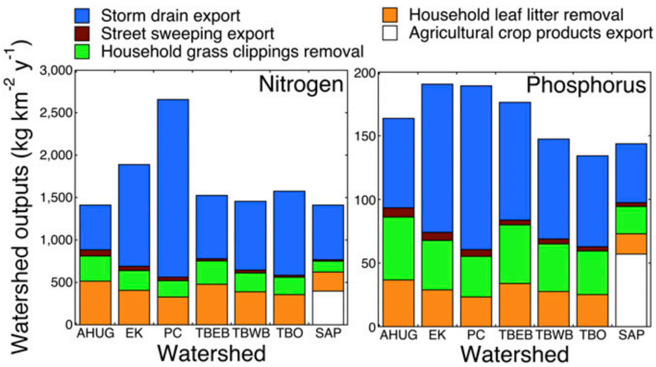

Fig. 2. Watershed nutrient outputs of N (*Left*) and P (*Right*). Ordering and abbreviations are as in Fig. 1.

except on golf courses and in a conservatory, and contributed 3–7% of total P inputs in the corresponding watersheds.

Household Actions and Storm Drain Exports Dominate Watershed Nutrient Outputs. Export of N and P in storm drains dominated watershed outputs, contributing 37–79% of total N and 32–68% of total P outputs (Fig. 2 and *SI Appendix*, Tables S2 and S3). High road densities promoted runoff and losses during snowmelt periods (*SI Appendix*, Table S4). The annual storm drain exports presented here were approximately double warm season estimates of nutrient output for these watersheds (37), demonstrating the importance of wintertime and/or snowmelt processes in nutrient export from northern urban watersheds (38, 39). Storm drain exports were highest in watersheds with high road density and no remnant surface waters (Phalen Creek and East Kittsondale) and lowest in watersheds with lakes and wetlands (SAP, Trout Brook West Branch, and Trout Brook Outlet) (37), which are important features for retaining both N and P (40, 41).

Because of high tree and residential land cover in these watersheds (Table 1), export of N and P in yard waste (grass clippings and leaf litter) was substantial (Fig. 2 and *SI Appendix*, Tables S2 and S3), even exceeding storm drain exports in the most densely residential watershed. Yard waste removal thus represents a substantial nutrient "drain" on the urban ecosystem, particularly for P: Up to half of the total P inputs to watersheds was exported in yard waste. Household leaf litter removal contributed 12–36% of total N and 11–22% of total P outputs and equaled storm drain exports of N in a residential watershed with high tree canopy cover (AHUG). Household grass clippings removal contributed 7–21% of total N and 15–30% of total P outputs, respectively. These findings corroborate direct measurements of yard waste export in Boston, Massachusetts: Our estimates of 354–812 kg of N per $km^2 \cdot y^1$ (clippings plus leaf litter) bracketed the Boston estimate of 650 kg of N per $km^2 \cdot y^1$ (20) and suggest that determining the origins, magnitudes, and fates of yard waste and compost fluxes is necessary to achieve complete understanding of urban watershed nutrient budgets. Exported nutrients from biannual street sweepings were modest: 1–5% of total N and 2–4% of total P outputs. Exported crop products contributed 28% of total N and 40% of total P outputs in the watershed with an agricultural experiment station (SAP).

Urban Watersheds Lose Phosphorus to Surface Waters More Readily than Nitrogen. These northern residential watersheds with high housing and road densities, tree cover, and impervious surface mostly retained little or no net P, with the majority of P that was not removed intentionally as biomass exported in stormwater runoff. Net P retention ranged from −7 to 74% and averaged 22% (watershed area-weighted average; *SI Appendix*, Table S3). P export via storm drains was positively related to net watershed P inputs, and in most watersheds, P exported via storm drains approached (or even exceeded) net watershed P inputs (Fig. 3). This finding contrasts with the findings from undisturbed forested and even agricultural watersheds, which are thought to be highly retentive of P because of biotic uptake and the relative immobility of P in soils (42 and ref. 22 and references therein). High P in stormwater runoff was associated with high impervious cover (∼50%) and street density, consistent with past studies (43); indeed, storm drain P exports were higher (77 kg of P per $km^2 \cdot y^1$, watershed area-weighted average) than in urban watersheds with lower impervious cover (3, 16). P and other nutrients move into streets via (*i*) P-rich litterfall (21, 44); (*ii*) runoff, particularly during snowmelt over frozen soils when plants are inactive (45); (*iii*) runoff and erosion during heavy rainfall events; and (*iv*) throughfall and deposition. Impervious surfaces effectively mobilize P that ends up in the street by preventing entrapment of particulate P by vegetation and soils and by preventing infiltration of soluble P (and subsequent soil sorption and biotic uptake). Thus, P that is mobilized to streets is essentially cut off from ecosystem uptake by impervious surfaces, promoting its flux into storm drains.

In contrast to P, watersheds retained most N inputs (Fig. 3 and *SI Appendix*, Table S2), as found in other studies of urban watersheds (8, 15, 16, 18), exporting only 20% of net N inputs to storm drains (watershed area-weighted average), mostly in baseflow (*SI Appendix*, Table S5). Total N retention (including ecosystem uptake, along with leaching losses and gaseous emissions) ranged from ∼65–99% in past studies, compared with 83% (area-weighted watershed average) in this study. Net N retention, accounting for the large N exports via nonhydrological pathways (mostly yard waste), ranged from 54 to 92% and averaged 80% (watershed area-weighted average; *SI Appendix*, Table S2).

To explore N and P budgets further and determine whether watershed N outputs and accumulation not measured in this study could account for "retained" N, we drew on other studies (including some done in the study region) to estimate denitrification, nutrient leaching to groundwater, and nutrient accumulation in soils and vegetation (Fig. 4 and *SI Appendix*, Table S12). Even accounting for other N losses, these watersheds appear to be retaining N that is not accumulating in soils and biomass in yards, an apparently "missing" residual term in the N mass balance (Fig. 4 and *SI Appendix*, Table S12). Candidate processes that might contribute to residual N retention include (*i*) denitrification in lakes, wetlands, wooded areas, unfertilized parks, and stormwater management infrastructure (e.g., stormwater ponds, storm drain catch basins and pipes) (46); (*ii*) accumulation in lake sediments and vegetated areas other than yards; and (*iii*) leaching to groundwater that bypasses storm drains in fertilized areas, where N leaching likely exceeds the N leaching from the unfertilized city parks used for scaling (Fig. 4 and *SI Appendix*, Table S12).

We further resolved possible fates for residual N retention by comparing the N/P stoichiometry of inputs, accumulation, and

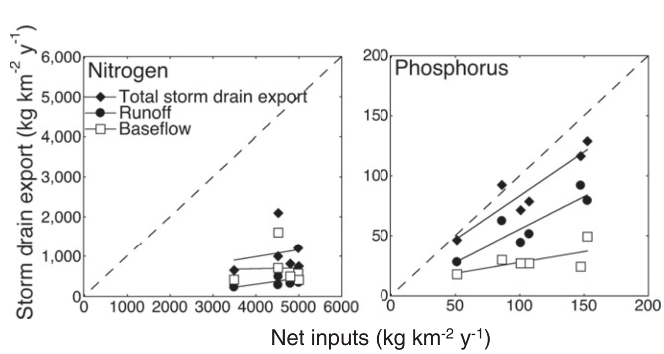

Fig. 3. Relationships between net watershed inputs of N and P and export in storm drains (each symbol represents a watershed, but AHUG is excluded): P in runoff = 0.7 + 0.5 * net P inputs ($P = 0.02$, $R^2 = 0.80$); P in baseflow = 9.7 + 0.2 * net P inputs ($P = 0.15$, $R^2 = 0.44$); and total storm drain P export = 10.4 + 0.7 * net P inputs ($P = 0.009$, $R^2 = 0.85$). Relationships were not significant for N. The dashed line indicates a 1:1 line, where net inputs = outputs.

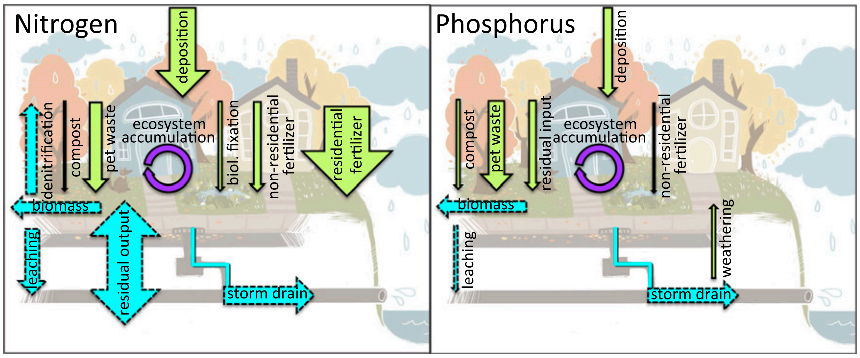

Fig. 4. Conceptual figure showing watershed area-weighted inputs (green, solid line), outputs (blue, dashed line), and accumulation (purple, solid line) of N (*Left*) and P (*Right*). Arrow thickness is proportional to flux (kg of N or P per $km^2 \cdot y^1$, N fluxes = 10× P fluxes). Residual fluxes represent the difference between inputs and accumulation + outputs. Residual P flux indicates unmeasured inputs or depletion of soil P stocks (inputs < accumulation + outputs); residual N flux indicates unmeasured outputs (inputs > accumulation + outputs). "Biomass" includes street sweepings and exported household leaf litter and grass clippings. Details are provided in *SI Appendix*, Table S12.

outputs. The N/P ratio of net inputs was fourfold higher than the N/P ratio of storm drain exports (Fig. 5 and *SI Appendix*, Table S6), a disparity that suggests the residual N retention flux included denitrification (46) and/or nitrate leaching to groundwater that bypassed storm drains, both of which favor N relative to P loss (Fig. 5). Higher rates of either process than we assumed (Fig. 4 and *SI Appendix*, Table S12) could account for the imbalance in the ecosystem budget. An alternative explanation, that the N/P ratio of storm drain exports was lowered by household sewage leaking into storm drains, is unlikely (*SI Appendix*, *SI Discussion*). Thus, the residual N term apparently is not "retention" as storage but, instead, represents unquantified losses to the atmosphere via denitrification and/or to groundwater via leaching. High nitrate concentrations in springs in the region (mean of 2.08 mg of N per L) (37) and a simple water balance (*SI Appendix*, *SI Methods*) further indicate that these watersheds likely have substantial fluxes of water (and N) to groundwater not captured by baseflow in stormwater conveyances. Identifying and quantifying this residual N flux is important for fully understanding and managing urban nutrient pollution, because N leaching to groundwater and denitrification have different environmental outcomes, with nitrate in groundwater potentially entering the Mississippi River. Environmental outcomes associated with denitrification depend on where and when it happens; for instance, denitrification in fertilized lawns produces mostly N_2, with little release of N_2O (a greenhouse gas). However, heavy rain events can increase the relative emissions of N_2O (47, 48).

In contrast to N, accounting for P that accumulates in the landscape or is lost through leaching confirms that these highly residential watersheds lose a large fraction of P inputs, with accumulation plus outputs exceeding inputs in all but one watershed (Fig. 4 and *SI Appendix*, Table S12). Given the P-rich glacial till in these regions (49), as well as P that likely accumulated in soils before the statewide fertilizer restriction enacted in 2004 (42), soils may be able to sustain plant P uptake for some time before plants experience P deficiencies, despite P losses and biotic demand that exceed inputs.

Implications for Managing Urban Water Quality. The contrasting dynamics of watershed N and P suggest that managing N and P to improve urban water quality will require different approaches. P was exported to surface waters primarily through stormwater runoff (Fig. 3 and *SI Appendix*, Table S5). Thus, reducing P exports to surface waters will require decreasing watershed P inputs, reducing sources of P to stormwater (e.g., litterfall to streets, erosion, runoff) (44), and/or increasing stormwater infiltration to promote P sorption by soils.

The positive relationship between watershed P inputs and stormwater P exports (Fig. 3) justifies efforts to reduce surface water pollution by restricting P fertilizer use. Where such restrictions are already in effect, further reductions in watershed P inputs require focusing on dog waste. Policies that regulate pet ownership (i.e., the number and sizes of dogs) would be highly unpopular, but responsible dog waste cleanup and disposal could be encouraged via social norms (50). Most efforts to increase dog waste cleanup have focused on public areas, yet reducing watershed P inputs also requires prompt cleanup of dog waste from yards. The potential P benefits from increasing dog waste cleanup are constrained by the substantial fraction (nearly half) of pet waste landscape P inputs that come from dog urine (27).

In cities with P fertilizer restrictions in place, and given limited options for reducing dog waste P inputs to urban watersheds, management will need to focus also on reducing sources of P to streets and storm drains and promoting infiltration. Space constraints limit options for adding centralized stormwater management infrastructure in the densely residential urban neighborhoods that were exporting the most nutrients to urban waters. Enhancing street sweeping efforts offers more promise (44), because the mass of nutrients removed by the current biannual street sweeping schedule was <5% of total outputs. Following Kalinosky (51), we estimate that increasing the frequency of October sweeping from once to four times would increase the P removed during street sweeping operations to 23% of total outputs in the watershed with the highest tree canopy. Greater control of erosional losses associated with construction, yard work, and other activities could also reduce nutrient fluxes to streets and storm drains.

By contrast with P, N budgets remain poorly constrained, with nearly as much (and possibly much more) N likely being lost to groundwater and to the atmosphere as to surface waters through storm drains. Depending on rates of denitrification along groundwater flow paths, nitrate losses to groundwater in urban watersheds

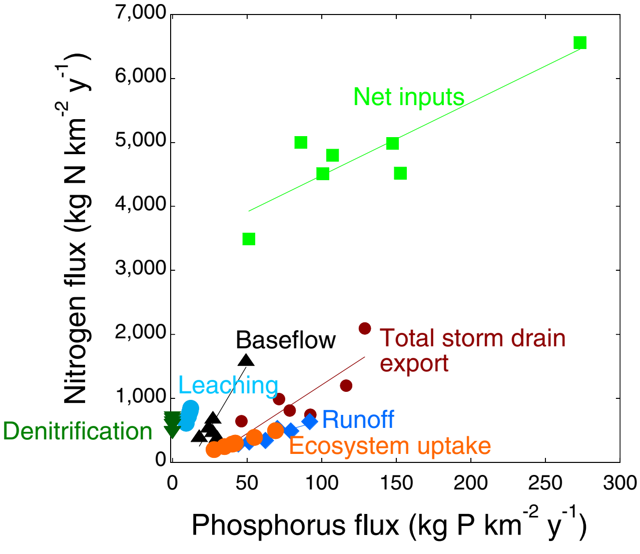

Fig. 5. N versus P stoichiometry of net inputs; storm drain exports (total, runoff, and baseflow); and the candidate missing nutrient fluxes of leaching (54), denitrification, and ecosystem uptake (19) for all watersheds (each symbol represents a watershed).

draining into the Missisippi River and other rivers could ultimately contribute to impaired downstream coastal waters (52). N management focused on reducing watershed N fertilizer inputs could reduce all potential losses to the environment, whereas decreasing sources of N to stormwater would only partly address any potential water quality impairment resulting from N enrichment. In fact, some efforts to reduce stormwater nutrient loading by promoting infiltration could merely trade off one environmental ill (e.g., stormwater P loading) for another (i.e., groundwater nitrate and chloride loading) if such areas do not promote rapid denitrification of N delivered in pulses of stormwater.

Households offer potential opportunities for reducing watershed N inputs. Current fertilization behaviors are highly skewed within the study region, with 24% of households fertilizing at rates higher than the rates recommended by the University of Minnesota Extension Service (53). These households are likely hotspots of local N losses. These losses could be reduced by (*i*) tackling overuse of N fertilizer and tightening nutrient cycles by mulching yard waste into lawns, (*ii*) better matching of fertilizer to plant N requirements, (*iii*) optimizing fertilization timing to avoid losses; (*iv*) cleaning up grass clippings and fertilizer from impervious surfaces (already required under state statute, but not universally practiced), and (*v*) increasing lawn mower blade height to promote deeper grass root growth. Replacing turfgrass with shrubs and trees could reduce N leaching to groundwater (54), although trees near impervious surfaces could inadvertently promote nutrient transport to stormwater via litterfall. Residential yards also offer opportunities for decentralized stormwater management through increased perviousness and small structural control measures; for example, local watershed organizations offer residents technical and financial assistance for redirecting downspouts to pervious surfaces and installing boulevard rain gardens.

Changing fertilizer practices are challenging because they are influenced by numerous factors, including the decision to use a lawn care company, sociodemographic factors, norms, knowledge, beliefs, and homeowner perceptions of ease of fertilizing (55). Knowledge of the linkages between lawn management and downstream ecosystems and of best management practices for improving stormwater quality (56, 57) could be enhanced by outreach and education efforts (58), although norms might be more challenging to change (59, 60). Encouraging best practices by lawn care companies also could prove effective, because 78% of households in the study region that fertilized more than the recommended rate used a lawn care company (53), and these companies might be given incentives or regulated to reduce fertilizer use, with the added benefit of increasing profit margins.

Conclusions

In a comparison of urban watershed N and P input–output budgets, we found contrasting dynamics for these two elements. These urban watersheds, characterized by high housing and road densities, tree cover, and impervious surface, are distinct from other watershed types in having low P retention, with high street densities mobilizing P and promoting losses via stormwater runoff. In contrast, watersheds had high apparent N retention; however, stoichiometric analysis indicated that this retained N was likely being lost from watersheds via leaching to groundwater and denitrification, potentially contributing to ground and surface water pollution. These contrasting dynamics suggest different approaches to managing N and P in urban watersheds. Managing N should focus on fertilizer use, especially by households, whereas managing P should additionally focus on reducing landscape dog waste inputs and P transport from residential landscapes to streets.

Materials and Methods

Study Sites. The study area comprised seven urban subwatersheds of the Mississippi River in the Capitol Region Watershed (CRW) (Table 1), building on past studies of household inputs (19, 27) and storm drain exports (37). The CRW comprises just over 10,000 ha in Ramsey County, Minnesota, and includes the majority of St. Paul and small portions of neighboring suburbs. Nearly all drainage occurs via the storm drain system (which was separated from the sanitary sewer system over a period from 1960 to 1996); there are few unburied stream reaches, and there are several sizeable nutrient-impaired lakes. The seven study watersheds are intensively monitored for pollutant export via storm drains by the Capitol Region Watershed District (CRWD) (37, 61). All include mixed residential, commercial, and industrial land use except the AHUG, which is primarily residential. All watersheds are served by the Metropolitan Wastewater Treatment Plant; effluent is discharged to the Mississippi River downstream of the study watersheds. No households are on septic systems.

Land Cover and Land Use. To scale estimates of nutrient inputs and outputs to the watershed, land cover was obtained from a 0.5-m resolution geographic information system (GIS) land cover map of the CRW (37, 62) that included categories for tree cover, shrubs and turfgrass, open water, bare ground, roadways, rooftops, and other impervious surfaces. A GIS overlay analysis using the land cover data, land parcel data (Ramsey County), and an impervious layer derived from satellite imagery (CRWD) were used, along with tax classes (Ramsey County) and inspection using Google Earth to assign vegetated ground surface (shrub/turfgrass land cover class plus tree canopy that did not overlap any impervious areas in the GIS overlay) to vegetated cover classes (*SI Appendix*, Table S1).

Watershed Nutrient Inputs. Details are provided in *SI Appendix*, *SI Methods*. We simulated atmospheric N deposition with the GEOS-Chem chemical transport model (acmg.seas.harvard.edu/geos) and estimated atmospheric P deposition using published values (34). Residential fertilizer N inputs were estimated from a survey of household fertilizer use in the region (27). Residential P fertilizer input was assumed to be zero because of a statewide restriction on lawn P fertilizer use since 2004. Nonresidential fertilizer N and P inputs were determined from interviews with land managers and land cover data. Nutrient inputs from pets (dogs) were determined from a survey of pet ownership in the region (27). County compost inputs were estimated from data collected by Ramsey County. We estimated BNF by herbaceous legumes from estimates of legume cover and published estimates of BNF of *Trifolium repens* (white clover) (63). Net inputs of N from crop BNF inputs and agricultural animal manure were included for the University of Minnesota St. Paul Campus Agricultural Experiment Station (in the SAP watershed) based on published values and interviews with the station manager (64). P inputs from rock weathering were estimated from published values for local soil parent materials (65). Human food was not included in watershed nutrient budgets, because human waste generated in the study region is routed via a relatively new and well-maintained sanitary sewer to the Metropolitan Wastewater Treatment Plant downstream of the study watersheds. Because of insufficient data, N and P in irrigation water and animal food inputs, aside from dog waste and manure application, were excluded.

Watershed Nutrient Outputs. Details are provided in *SI Appendix*, *SI Methods*. We compared nutrient inputs with known outputs associated with street and yard maintenance and export via storm drainage networks. We present published estimates of denitrification and leaching to groundwater in *Results and Discussion* to provide a complete picture of nutrient outputs. We estimated annual storm drain nutrient export in baseflow and stormwater runoff using data from the CRWD (61) following Janke et al. (37). Crop nutrient exports from the University of Minnesota St. Paul Campus Agricultural Experiment Station were from published values (64). Nutrients exported in yard waste (leaf litter and grass clippings) were estimated from a previous study in the region (19, 27); all yard waste taken to county collection sites is exported from the watersheds. Nutrients exported through spring and fall municipal street sweeping were estimated from tree canopy cover over streets based on a previous study done in a nearby municipality (51).

Nutrient Retention. We calculated watershed N and P retention as 1 − (storm drain exports/total watershed inputs); by this definition, retention includes exports not accounted for in our budgets, such as leaching to groundwater and gaseous emissions. Because inputs are effectively reduced by intentional biomass exports, we also calculated “net retention” as 1 − (storm drain exports/net watershed inputs), where “net” watershed inputs are total watershed element inputs minus the sum of exports via street sweeping, yard waste removal, and agricultural products.

Statistical Analyses. We explored controls over storm drain exports of N and P by correlating storm drain nutrient exports with watershed characteristics, including the fraction of the watershed that was connected impervious surface (37), street density, canopy cover over streets, and housing density. N and P retention were further explored by regressing storm drain exports of

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N and P in baseflow and stormwater runoff against net N or P inputs. All statistical analyses were performed in JMP Pro, v. 12.0.1.

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