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Sources of variation in nutrient loads collected through street sweeping in the Minneapolis-St. Paul Metropolitan Area, Minnesota, USA

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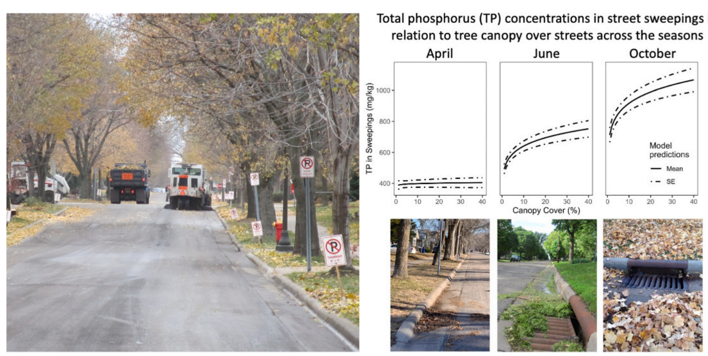
HIGHLIGHTS

- Street sweeping is a potential tool for managing urban surface water eutrophication.
- Nutrients in street sweepings were characterized across five cities.
- Sweeping nutrient loads per curb-km increased with tree canopy cover over streets.
- Nutrient concentrations and loads in sweepings peaked in early summer and autumn.
- Targeted street sweeping holds promise for improving urban water quality.

GRAPHICAL ABSTRACT



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ABSTRACT

Excess non-point nutrient loading continues to impair urban surface waters. Because of the potential contribution of tree litterfall to nutrient pollution in stormwater, street sweeping is a promising management tool for reducing eutrophication in urban and suburban regions. However, nutrient concentrations and loads of material removed through street sweeping have not been well characterized, impeding the development of pollution reduction credits and improvement of models for stormwater management. We evaluated the role of canopy cover over streets, street sweeper type, season, and sweeping frequency in contributing to variation in concentrations and loads of nitrogen (N), phosphorus (P), and solids recovered in street sweepings, using analyses of samples collected during regular street sweeping operations in five cities in the Minneapolis-St. Paul Metropolitan Area, Minnesota, USA. We expected that nutrient concentrations and loads would be highest in seasons and places of higher tree litterfall. We also expected that regenerative-air sweepers would recover higher loads compared to

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mechanical broom sweepers. Total N and P concentrations in sweepings increased most strongly with canopy cover in June, October, and November. Total N and P recovered in street sweepings similarly increased with canopy cover in June, October, and November, and peaked in early summer and autumn, times of high litterfall. In contrast, total dry mass in sweepings was greatest in early spring, following winter snowmelt. However, nutrient loads and concentrations did not differ between sweeper types. Our results add to growing evidence of the importance of street trees in contributing nutrient pollution to urban surface waters. Street sweeping focused on high-canopy streets during early summer and autumn is likely an effective management tool for stormwater nutrient pollution.

1. Introduction

In many urban areas, surface waters sustain critical ecological communities and functions and provide important benefits for urban residents by supplying fresh water and food, regulating water and regional climate, and providing aesthetic, cultural, and recreational opportunities (Phaneuf et al., 2008; Lowe et al., 2022). Yet, the quality of urban freshwaters and coastal systems is widely impaired by eutrophication (Dubrovsky et al., 2010; Le Moal et al., 2019), chemical contaminants (Masoner et al., 2019; Müller et al., 2020), and other stressors (Baker and Newman, 2014). Eutrophication, for example, reduces recreational benefits, drinking water quality, and food provisioning, by degrading biodiversity, creating noxious odor and taste, supporting harmful algae, and causing other impairments.

Despite marked improvements in sewage treatment, eutrophication of urban surface waters has persisted. This eutrophication is increasingly caused by non-point sources of nutrients, especially phosphorus (P) and nitrogen (N) (Le Moal et al., 2019). Non-point sources of nutrient pollution to stormwater runoff and urban surface waters include fertilizer runoff, erosion and leaching of vegetation and soils, atmospheric deposition, pet waste, and human waste, via leaky septic and sanitary sewer systems and illicit discharges from sanitary to storm sewers (Hobbie et al., 2017; Yang and Lusk, 2018).

In addition to the sources mentioned above, growing evidence underscores the role of street trees (trees adjacent to streets) as important non-point sources of nutrients to impervious surfaces via their litterfall (Selbig, 2016). Tree litterfall, dominated by bracts, flowers, and seeds in the spring and early summer and by leaf litter in the autumn or dry season, is relatively rich in bioavailable N and P (Hill et al., 2022). Once in the street, nutrients can leach from litterfall during precipitation events and be released in soluble organic and inorganic forms during decomposition (Cowen and Lee, 1973; Hobbie et al., 2014; Bratt et al., 2017; Wang et al., 2020; Hill et al., 2022). Unless removed through street sweeping, particulate organic matter from litterfall, fragmented by vehicles, can make its way down the storm drainage network and undergo solubilization and decomposition in storm drains and other downstream water bodies.

Accordingly, past studies have found strong evidence of street tree contributions to stormwater nutrient pollution. Across 19 watersheds in the Minneapolis-St. Paul Metropolitan Area, Minnesota, tree canopy cover over streets was positively and strongly related to stormwater event-mean concentrations for total phosphorus (TP) and total nitrogen (TN) (Janke et al., 2017). In one of those watersheds, leaf litter was estimated to contribute 40 % of annual P loading (Bratt et al., 2017). In a paired-watershed study in Madison, WI, USA, each with >40 % canopy cover over the street, intensive sweeping in a treatment watershed reduced stormwater TP and TN loads by 84 % and 74 %, respectively, compared to a control watershed with no sweeping (Selbig, 2016).

Despite their potential contributions to water quality impairment, trees adjacent to streets are valued by city residents because of their benefits for cooling, culture and aesthetics, stormwater volume reduction, human health, and other reasons (Roy et al., 2012; Salmond et al., 2016; Kuehler et al., 2017; Sanusi et al., 2017; Kuo et al., 2018; Selbig et al., 2022), underscoring the need for managing potential negative impacts of street trees on stormwater quality. One management tool available for mitigating the adverse effects of tree litterfall on stormwater quality is street sweeping, which can remove coarse solids and nutrients from streets that would otherwise make their way into storm drainage networks and downstream surface waters (Hixon and Dymond, 2018). Street sweeping may also reduce clogging and overloading of green infrastructure such as stormwater ponds and raingardens and of grey infrastructure such as catch basins by coarse organics. Although some past studies questioned the efficacy of street sweeping as a management tool to improve water quality, such studies used methodologies that were inappropriate to fully characterize nutrient loads that might be captured by street sweeping: either they were discontinued in the autumn (during periods of maximum litterfall) or they failed to collect and analyze coarser organic material (often sieving and discarding coarse material), including larger leaf litter, where nutrients likely are concentrated (Sartor and Gaboury, 1984; Selbig and Bannerman, 2007; Sorenson, 2013).

Here we aimed to build on past work assessing the potential role for street sweeping as a management tool for water quality improvements (e.g., Erdmann et al., 1984; Sartor and Gaboury, 1984; Kalinosky et al., 2014; Kalinosky, 2015; Selbig, 2016; City of Forest Lake, 2018; Hixon and Dymond, 2018). Specifically, we evaluated the role of canopy cover over streets, street sweeper type, sweeping season, and sweeping frequency in contributing to variation in concentrations and total loads of N and P and in total loads of solids recovered in street sweepings, using analyses of sweeping samples collected from five cities in the Minneapolis-St. Paul Metropolitan Area, Minnesota, USA. While past studies have assessed effects of factors such as sweeper type, season, frequency, and land use type on sweeper nutrient loads (Sorenson, 2013), we did not find studies that related the nutrients recovered in street sweepings to tree canopy cover over streets, despite growing recognition of the importance of trees in contributing nutrients to stormwater (Selbig, 2016; Janke et al., 2017). We expected that nutrient concentrations and loads would be highest in late spring and in fall, especially for streets with high tree canopy cover, corresponding to times and places of higher tree litterfall (Winston et al., 2023). We also expected that more frequent sweeping would reduce the amount of material recovered per sweeping event, and that regenerative-air sweepers would recover higher loads than mechanical-broom sweepers, when loads were normalized per unit of distance swept (Selbig and Bannerman, 2007; Sorenson, 2013). Characterization of sources of variation in street sweeping loads can inform street sweeping programs for managing nutrients and solids and guide development of pollution crediting approaches for street sweeping and improvement of models of stormwater pollution and management.

2. Materials methods

2.1. Street sweeping routes

We collected samples from street sweeping events during spring, summer, and fall of 2019 from the regular street sweeping operations of four municipalities in the Minneapolis-St. Paul Metropolitan Area (Table 1). We also collected samples over a 2-year period beginning in summer 2009 from a fifth municipality. Routes were chosen to include different sweeper types, sweeping frequencies, and tree canopy cover

over the street. For Forest Lake, Minneapolis, Roseville, and Shoreview, samples were collected during the warm season in 2019 starting as early as March (Shoreview) and as late as June (Minneapolis) and ending in October (Forest Lake) or mid-November (all other cities) (Table 1). Spring 2019 saw heavy snowfalls, which delayed the ability of Minneapolis to collect samples. For each city, we selected sampling routes from the city's ongoing street sweeping programs to achieve a range of street sweeping frequencies, canopy cover, and sweeper type (Table 1). For Prior Lake, samples were collected over a two-year period from routes swept every one, two, or four weeks, except during periods of snow cover (Kalinosky, 2015).

2.2. Sample collection

Sweeper loads were piled following collection, and samples were obtained from piles of swept material within 24 h of a route being fully swept and before any precipitation events occurred. The length of time it took to sweep a route varied from 1 to 7 days. To ensure collection of a representative sample, the pile was visually inspected before sample collection to estimate the proportions of sediments and plant debris. A small trowel was used to combine at least five small amounts of sample (totaling 3.4–4.5 L) into a 1-gal (4.5-L) plastic bag, walking around the pile and scooping from various points. Care was taken to collect a sample that accurately reflected the composition of the sweeper pile, based on visual inspection. Before sample collection, the outside of the pile was scraped away to avoid sampling material with non-representative moisture content resulting from exposure to air. Large pieces of trash and woody debris were avoided, but smaller pieces, which were easily picked up, were not separated from the sample. Nitrile gloves were worn to prevent contamination of swept material and to protect the collector's hands. The sampling trowel was cleaned with nanopure water, wiped down with 70 % ethanol, and allowed time to air dry fully before being used to collect another sample. Samples were stored in a refrigerator until moisture determination. If moisture was not determined within a day, the sample was frozen.

2.3. Laboratory analyses

Because of the heterogeneous nature of sweeping samples, with wide variation in element concentrations between highly organic vegetative materials and inorganic sediments (Kalinosky, 2015), all samples were fractionated before analysis for wet and dry mass, total carbon (TC), total nitrogen (TN), and total P (TP) concentrations. Element concentrations were determined for different sample fractions that were then used to calculate a weighted-average concentration for the entire sample. To fractionate samples, frozen sweeper samples were thawed under refrigeration and thawed samples were separated into five fractions during processing: garbage, rocks (inorganics ≥2 mm), coarse material (organics ≥2 mm), soluble nutrients leached during isolation of the coarse fraction (see below), and fine sediments (< 2 mm fraction). The wet mass, dry mass, and moisture content (determined by oven drying at 65 °C) of each of the solid fractions were determined for all sweeper samples. We assumed that garbage and rocks did not contribute significantly to nutrient loads, so only the mass of these fractions was tracked, whereas chemical analyses of TP, TN, and TC were performed on the fine, coarse organic, and soluble fractions (see below). The percent moisture content of each sample fraction was determined as the difference between the fresh (wet) weight and the oven dried (65 °C) weight, divided by the dry weight, multiplied by 100.

Coarse material retained on the 2 mm sieve went through a second fractionation using flotation to separate coarse organic material from any adhered sediments. Coarse material was added to 3 L Nanopure water in a clean 5-L plastic bucket. Suspended organics were gently agitated for about 1 min until adhered soil particles appeared to be dislodged. Vegetative material that floated during the process was classified as coarse organic matter. This material was collected by filtering wash water through a 2 mm sieve. To account for nutrients leached during the separation process, wash water was subsampled for nutrient analysis. Settled particles were collected, oven dried, and sieved to separate additional fines (< 2 mm) and the remaining rock fraction (≥ 2 mm). The total coarse organic matter recovered was then oven-dried for nutrient analyses and to determine its dry weight. The wash water was filtered through Whatman 42 filter paper and frozen for dissolved TP analyses or acidified and refrigerated for total dissolved organic carbon and total dissolved nitrogen (DOC and TDN) analysis.

2.4. Chemical analyses

2.4.1. Coarse organic matter and sediment C and N

Prior to element analysis, the coarse organic fraction was processed by grinding through a #40 screen on a Wiley Mill (Thomas Scientific no. 3383 L40). The ground coarse fraction and fine sediment fraction were pulverized by vigorously shaking samples within plastic scintillation vials containing 3/8″ (0.95 cm) steel BBs, with vials packed into a paint can on a paint can shaker. Further homogenization was often necessary for the fine sediment fraction since coarse sand was not fully pulverized after this step. This was achieved by grinding samples by hand using a mortar and pestle. TN and TC contents of the coarse and fine sediment

Table 1
Summary information for the sweeping routes sampled. Characteristics of sweeping operations are summarized by city as well as across all cities (Total). Sweep frequency is the mean number of days between sweeps (min-max). Total distance of routes is presented in curb-miles followed by curb-km. Canopy cover is the mean percent tree canopy over the street (min-max).

City	Number of routes sampled	Number of samples collected	Sweep frequency (days)	Sweeping dates	Total distance of routes (curb-miles, curb-km)	Canopy cover over route (%)	Sweeper types used
Forest Lake	14	107	20.5 (14–35)	04/16/19–10/11/19	239, 385	6.7 (1–17)	Regenerative Air
Minneapolis	6	39	31.3 (29.2–35.5)	06/03/19–11/14/19	112, 180	21.0 (0.75–37.4)	Regen. Air (45 %) + Mechanical (55 %)
Prior Lake	9	394[a]	16.5 (9.77–37.5)	08/09/10–07/31/12	71, 114	8.6 (0.1–19.3)	Regen. Air (99 %) + Mechanical (few)
Roseville	4	16	69.7 (65.3–73.3)	04/01/19–11/08/19	63, 102	15.7 (13.7–19.6)	Regen. Air (~33 %) + Mechanical (~66 %)
Shoreview[b]	7	29	68.8 (45.8–145)	03/25/19–11/18/19	195, 314	15.1 (9.5–22.5)	Regen. Air (~59 %) + Mechanical (~41 %)
Total	**40**	**586**	**21.4 (9.22–145)**		**680, 1098**		

[a] 10 of these samples were excluded from analysis for being outliers (see data analysis in Materials methods section).
[b] Shoreview fall sweeps were sampled on smaller sections of the routes, so the actual miles swept for the city are lower than reported here for fall sweepings.

fractions were determined through combustion-gas chromatography on a Costech ECS 4010 CHNSO Analyzer, using the NIST (National Institute of Standards and Technology) acetanilide standard.

2.4.2. Phosphorus (TP)

TP concentrations in all fractions were determined by a colorimetric method following digestion. Samples of coarse and fine fractions were ashed to liberate organic P prior to digestion in sulfuric acid; digests of fine samples were centrifuged at 2500 rpm for 10 min to remove remaining suspended particles that would otherwise interfere with the colorimetric analysis. Persulfate digestion followed by colorimetric analysis for soluble reactive P was used for digestion of the soluble constituents in the leachate produced during the float separation step (APHA, 1992). Absorbance of digests was measured on a Cary 50 Bio UV Visible spectrophotometer at 880 nm in 1 cm cells using molybdate blue/ascorbic acid reagent method. "Apple NIST 1515" reference standards were used to calibrate the analyses of coarse organic and fine fractions. NIST phosphorus standard solutions (25 mg P/L) purchased in 10 mL voluette ampules from HACH Company (Loveland, CO) were used to calibrate analyses for the leachate samples.

2.4.3. Leachate DOC and TDN

The concentrations of DOC and TDN that leached into the float water were analyzed using a Shimadzu TOC-L analyzer (Shimadzu TOC-V_{CPN}, Shimadzu Scientific Instruments, Columbia, MD). Samples were acidified with 100 μL of 2 M HCl and stored in muffled 20 mL vials with an airtight seal. Samples were refrigerated and analyzed within a few weeks of filtration. Concentrations of TP (i.e. total dissolved P), DOC, and TDN in filtered leachate were multiplied by the leachate volume to determine total mass of these constituents leached out the coarse fraction during the float procedure. This mass was accounted for in reporting the TP, TC, and TN concentrations of the coarse fraction by adding these masses to the masses determined during analysis of the coarse fraction element concentrations.

2.5. Calculations and data analysis

2.5.1. Canopy cover and route distances

We determined total canopy cover for each sweeping route as follows. The city of Forest Lake provided canopy cover information for their routes, and for all other cities, we calculated the percent of street area covered by tree canopy (here after "canopy cover") for each route using ArcGIS Pro (v. 2.4.0, ESRI 2019). Tree canopy information was obtained from the TCMA 1-Meter Urban Tree Canopy Cover Classification (Knight, 2016) and using the Metro Regional Centerlines Collaborative (MRCC) Local Centerlines shapefile (MRCC Collaborative, 2018), both obtained from the Minnesota Geospatial Database (MnGeo: https://gisdata.mn.gov/). The baselayer used was an aerial photograph from the MnGeo Web Mapping Service (Metropolitan Council, 2016).

To calculate canopy cover, we made new layers containing the centerlines for each route from the larger MRCC Local Centerlines shapefile. Street area was approximated by creating a 15-ft (4.6-m) buffer on both sides of the centerline, as 30 ft. (9.1 m) is the approximate street width for most streets on the sweeping routes in this study. We checked the fit of the street area against the aerial photograph and manually corrected the area polygon in cases where it deviated significantly from the aerial photograph of the actual street location. The street area polygon was then used to clip the tree canopy cover raster, and the sum of 1 m × 1 m pixels in each canopy cover class was used to calculate the percent canopy by dividing the total number of tree pixels by the total number of pixels and multiplying by 100. Route distance in curb-km was calculated from the total perimeter of the street area polygon, as the perimeter of each route is what is typically swept. The route distance was used to scale the total sweepings dry solids, TP, and TN so that routes of different distances could be compared directly.

2.5.2. Sweeping load dry mass and nutrients

For the four cities (all cities except Shoreview) that measured and reported wet mass of the sweeping load, we were able to calculate total load dry masses and total nutrient masses recovered in sweeping. To calculate the total dry mass of the sweeping loads from their fresh weights, we determined a weighted-average moisture content for the sweeping load based on the proportion of the load dry mass in coarse and fine sediment fractions and their respective moisture contents. The weighted-average moisture content was used to convert the total sweeping load wet mass to sweeping load dry mass (i.e., total dry solids of sweeping load).

To determine total mass of nutrients recovered in sweeping, we first calculated weighted-average nutrient concentrations for each fraction – the coarse fraction, fine sediments fraction, and the soluble fraction (leached during flotation of the coarse fraction). First, we calculated the mass (in mg) of each nutrient (TN or TP) in each fraction, and these masses were summed to calculate the total mass of the nutrients in the sample. This total nutrient mass was divided by the total mass of the sample to obtain the nutrient concentration of sweepings. We then determined the total mass of nutrients recovered in the whole sweeper load by multiplying the weighted-average nutrient concentration by the total load dry mass.

2.5.3. Statistical analyses

We examined variation in total sweeping load dry mass, TP and TN concentrations of sweepings, TP and TN recovered by sweeping, and the sweeping load moisture content by fitting multiple linear regressions with the *lm* function (*stats* package v. 4.3.0) including each of the following predictor variables: canopy cover (% canopy over the street for the entire sweeping route), month (as a categorial variable, and excluding December, January, February), sweeper type (mechanical broom, regenerative air), sweeping frequency (average days between sweeping events), and city (as a fixed effect). We fit models with all two-way interactions and used backward step-wise selection to drop terms when it lowered the AIC value >2 AIC units. For statistical analyses, we excluded two (out of >500) routes that were swept by more than one sweeper type. All continuous variables in the model were natural-log transformed before model selection as the log-normal distribution fit the data best (determined using the *fitdist* function in R package *fitdistrplus* v. 1.0–14), or model diagnostic plots showed improvement in adherence to model assumptions with the transformation. Model fit and significance tests were performed using the *summary* function and *Anova* function (*car* package v. 3.0–7). Differences among months in percent moisture, total sweeping loads, nutrient concentrations of sweepings, and total sweepings nutrient loads were tested using Tukey's HSD tests on ln-transformed data, with R packages *car* (v. 3.0–7) and *emmeans* (v. 1.4.6). In all tables with summary statistics, the 95 % confidence intervals are the boot-strapped confidence interval (CI) around the sample mean. All analyses were conducted in R version 4.0.0 (R Core Team, 2020).

3. Results

3.1. Total sweeping load dry mass

Sweeping load dry mass (normalized for distance swept, on a per-sweep basis) increased with canopy cover in some months (i.e., there was a relatively weak month x canopy cover interaction but no main effect of canopy cover, Fig. 1, Table 2, Table S1). Months differed strongly in total sweeping load dry mass, with higher sweeping loads in spring and early summer. Sweeping load dry mass increased significantly with the number of days between sweeping events (Fig. S1, Table S1). In other words, increased sweeping frequency reduced the total sweeping load dry mass of each sweep. Total sweeping load dry mass differed significantly among cities, even after accounting for variation in canopy cover, sweeping frequency, and sweeper type, with

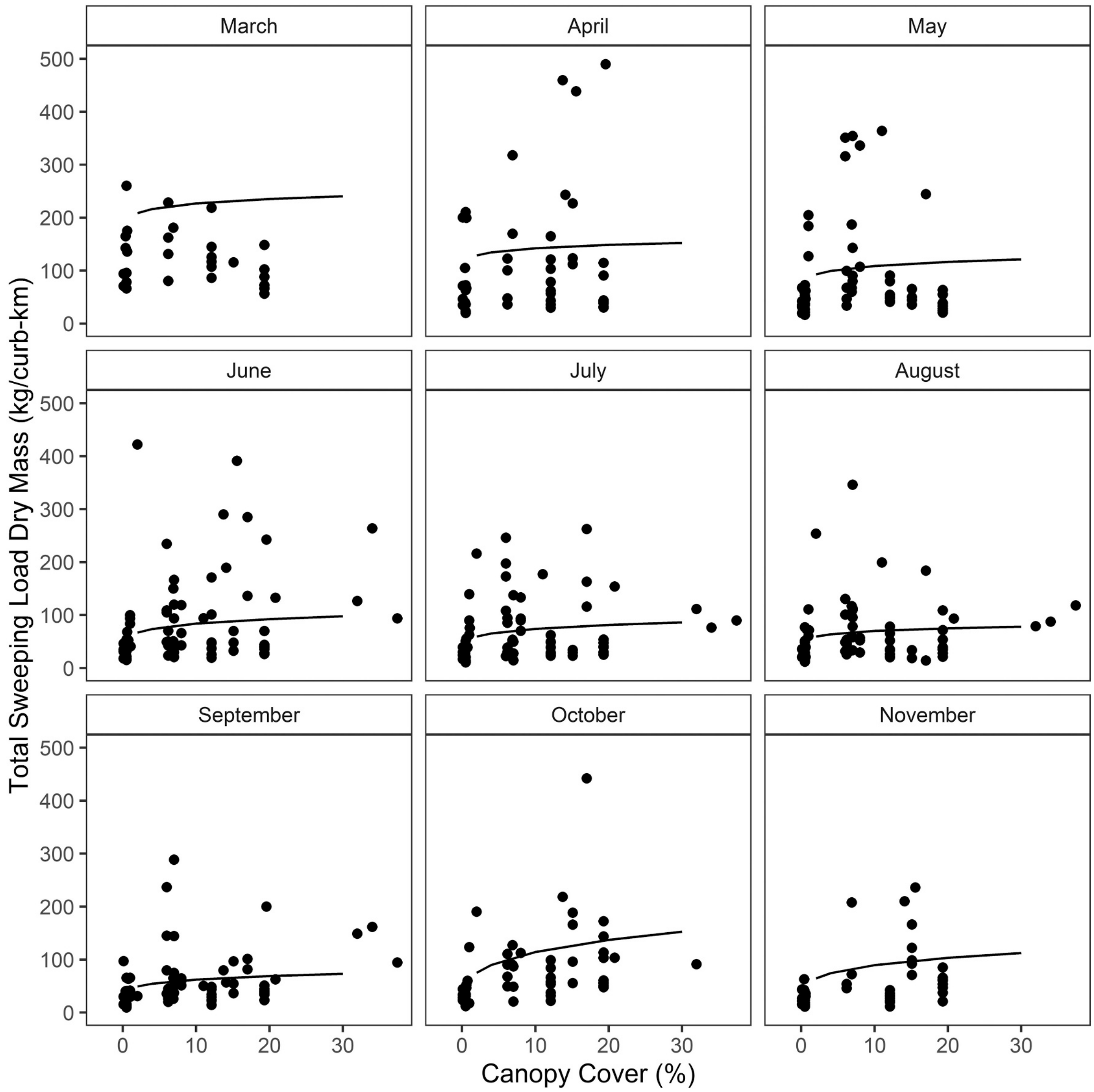

Fig. 1. Total sweeping load dry mass (kg/curb-km per sweep) in relation to canopy cover and month, across sweeping routes. Each point represents a sweeping event and lines are derived from the regression in Table S1 (overall model fit: $F_{22, 489} = 24.1$, $p < 0.0001$, $R^2_{adj} = 0.50$). Sweeping samples came from four cities (Forest Lake, Minneapolis, Prior Lake, Roseville) in Minnesota, USA.

Table 2
Summary statistics for total sweeper load dry mass (kg/curb-km) of sweeping samples. Sweeping samples came from four cities in Minnesota, USA.

Month	Sweeping load dry mass (kg/curb-km)						Sample size
	Mean	Median	Std. Dev.	25 %	75 %	95 % CI	
March [A]	124.0	115.5	52.4	86.9	150.4	105.4–144.1	29
April [AB]	117.1	71.0	115.7	46.3	142.5	83.0–153.5	45
May [BC]	109.0	53.6	194.8	36.3	116.0	66.0–132.2	62
June [BC]	85.8	48.4	85.9	34.4	103.7	65.4–106.5	71
July [C]	65.8	40.0	57.8	28.2	81.4	52.4–79.3	72
August [C]	63.7	48.6	57.6	29.5	78.6	50.9–77.5	67
September [C]	59.4	43.8	52.0	27.4	73.9	48.1–70.9	69
October [BC]	77.0	55.2	70.3	33.6	96.1	60.6–95.4	56
November [C]	63.0	39.7	64.9	24.9	76.2	43.0–81.1	44
Full dataset	**81.4**	**51.0**	**97.0**	**32.7**	**97.6**	**71.7–85.8**	**515**

Different superscript letters (A, B, C) indicate significant differences in mean TP concentration among months (Tukey's HSD on ln-transformed data, $p < 0.05$).

lower sweeping loads in Prior Lake than in other cities on average. There was no effect of sweeper type on sweeping load dry mass. The regression model of total sweeper load dry mass was able to explain 50 % of the variation across all samples.

Sweeping load moisture content increased significantly with increasing canopy cover in October and especially in November (month x canopy cover interaction) and was significantly higher in those months than in other months (Fig. S2; Tables S2, S3). Moisture content also increased with sweeping frequency, with higher sweeping load moisture content at longer sweep intervals. There were not strong differences among cities. There was no effect of sweeper type on sweeping load moisture content.

3.2. TP, TN, and TC concentrations in sweepings

Across all sweeping events in all cities, nutrient concentrations averaged 727.0 mg/kg TP and 3466.8 mg/kg TN (Tables 3, 4). TP and TN concentrations in sweepings were higher in mid to late spring (April, May), early summer (June), and autumn (September, October, November) than in March, July, or August, with the highest concentrations in October (1156.3 mg/kg TP; 6101.1 mg/kg TN) and November (1088.5 mg/kg TP; 5815.8 mg/kg TN) (Tables 3, 4, S4). There were significant interactive effects of canopy x month for both TP and TN (Table S4). TP concentrations increased with increasing canopy cover in the months with the highest concentrations (June, October, November, Fig. 2). TN concentrations increased with increasing canopy cover in all months, but slopes also were steepest in June, October, and November (Fig. 2). Concentrations differed with sweeping frequency for TP, but not for TN or between sweeper types for either nutrient (Table S4). Cities differed significantly in TP and TN concentrations in sweepings, even after controlling for variation in canopy cover, sweeping frequency, and sweeper type (Fig. 2, Table S4). Regression models explained 54 % and 68 % of the variation in TP and TN concentrations in sweepings, respectively. Concentrations of TP and TN were higher in the coarse ($\geq$ 2 mm) compared to the fine ($<$ 2 mm) fractions, in all months (Fig. 3). The total carbon (TC) concentration in sweepings was highest in autumn (September, October, November) with additional smaller peaks in spring (April) and early summer (June) (Table S5).

3.3. Total P and N recovered in sweepings

Across all samples, both total P and total N recovered in sweepings differed among months, with higher recovery in spring, early summer, and fall (Fig. 4, Tables S6-S8). Total P recovered with sweeping increased with canopy cover in June, October, and November (significant canopy cover x month interaction) (Fig. 4, Table S8), while total N recovered increased with increasing canopy cover in all months (significant main effect of canopy cover, and no canopy cover x month interaction). Both total P and total N recovered decreased with increasing sweeping frequency (Table S8). In addition, total P and N recovered in sweepings differed among cities, although more strongly for total N than for total P recovered, even after accounting for variation in canopy cover, sweeping frequency, sweeper type, and month of sweeping. There were no effects of sweeper type on total N or P recovered in sweeping (Figs. S3, S4). Regression models explained 46 and 47 % of the variation in total P and N recovered in sweepings, respectively. The fraction of the total P and N recovered in sweeping that was in the coarse fraction was highest in October and November, when coarse fraction P constituted about 60 % of the total P recovered, and coarse fraction N constituted about 80 % of total N recovered (Fig. S5).

4. Discussion

4.1. Trees as sources of nutrients to stormwater

Herein we report several lines of evidence from measurements of street sweeping indicating that trees adjacent to streets are a significant source of nutrients to streets and stormwater, corroborating other recent findings (Kalinosky, 2015; Selbig, 2016; Janke et al., 2017), and that street sweeping leads to higher removal of nutrients where canopy cover is high. Street sweeping routes with higher tree canopy cover had higher concentrations and loads of nutrients in sweepings in early summer and fall, presumably reflecting greater contributions of tree litterfall to sweeper loads in those streets. The high nutrient concentrations and total nutrients recovered in street sweepings in early summer and autumn match times of peak tree litterfall; in the late spring and early summer, trees drop nutrient-rich flowers, bracts (leaves that cover buds), and seeds, whereas in the fall, trees drop leaf litter (Hill et al., 2022). Carbon concentrations in sweeping samples were highest in April, June, and September–November, and were an order of magnitude higher in the October and November than in other months, consistent with high tree litterfall contributions to swept materials in the early summer and especially in fall. Sorenson (2013) also found higher sweeping loads in fall, especially in residential (compared to commercial) areas in Cambridge, MA, USA. However, concentrations of both N and P reported here were considerably higher than those reported for residential areas in Florida (Sansalone et al., 2011) and for streets and parking lots in Virginia (Hixon and Dymond, 2019), likely because those studies under-sampled the autumn period when litterfall occurs in eastern and southeastern U.S. (Lugo et al., 1978; Orndorff and Lang, 1981; Gholz et al., 1985). Under-sampling of autumn may also explain why Hixon and Dymond (2019) found no seasonal effect on nutrient concentrations in street sweepings. Finally, nutrients recovered in the coarse fraction (comprising mainly leaf litter) dominated sweeper nutrient loads in the autumn, as found in previous studies (Waschbusch et al., 1999; Kalinosky, 2015). The coarse fraction likely represents an underestimate of the contribution of tree-derived materials to nutrients in sweeping loads since some tree-derived materials likely are fragmented by passing cars into <2 mm particles and end up in the fine sediment fraction.

4.2. Sweeper type effects on nutrient concentrations in sweepings

Sweepings from routes swept by mechanical broom and regenerative air sweepers did not differ significantly in terms of nutrient

Table 3
Summary statistics for TP concentrations (mg/kg) in sweepings. TP concentration of sweepings represents a weighted average of the coarse and fine fractions, accounting for P that was leached out of the sample during the fractionation procedure. Sweeping samples came from five cities in Minnesota, USA.

Month	TP concentration in sweepings (mg/kg)						Sample size
	Mean	Median	Std. Dev.	25 %	75 %	95 % CI	
March [AB]	542.0	500.1	250.5	370.7	660.4	457.9–629.8	30
April [AB]	564.1	540.8	149.7	452.5	654.9	524.9–602.8	51
May [AB]	671.6	625.1	292.7	443.7	833.5	610.4–750.3	61
June [B]	705.5	632.5	340.7	468.6	863.3	629.0–782.5	73
July [A]	543.9	504.7	231.9	384.1	656.6	491.6–594.2	74
August [AB]	569.2	546.7	271.9	375.1	700.8	510.9–638.4	71
September [AB]	641.6	578.7	300.2	417.9	793.6	572.1–716.2	71
October [C]	1156.3	1117.3	457.5	744.5	1462.8	1077.4–1278.0	69
November [C]	1088.5	1078.6	382.4	787.0	1317.1	992.9–1192.6	55
Full dataset	**727.0**	**625.0**	**383.0**	**452.3**	**901.1**	**695.4–760.4**	**555**

Different superscript letters (A, B, C) indicate significant differences in mean TP concentration among months (Tukey's HSD on ln-transformed data, $p < 0.05$).

Table 4
Summary statistics for TN concentrations (mg/kg) in sweepings. TN concentration of sweepings represents a weighted average of the coarse and fine fractions, accounting for N that was leached out of the sample during the fractionation procedure. Sweeping samples came from five cities in Minnesota, USA.

Month	TN concentration in sweepings (mg/kg)							Sample Size
	Mean	Median	Std. Dev	25 %	75 %	Lower 95%CI	Upper 95 % CI	
March [A]	544.6	607.4	329.1	261.5	730.4	342.2	769.9	9
April [BCD]	2087.0	1821.3	1364.6	1008.1	2716.7	1625.8	2678.2	30
May [C]	2111.2	1565.6	2072.8	807.9	2637.3	1508.6	2930.4	36
June [B]	3431.7	2390.6	2764.9	1486.4	4329.4	2709.0	4394.9	53
July [D]	1719.7	1354.2	1238.2	808.7	2227.8	1438.9	2117.3	50
August [BD]	2577.4	2460.5	1711.2	1057.7	3464.6	2351.2	3283.1	71
September [B]	3213.9	2761.1	1943.1	1527.9	4261.8	2888.0	3901.6	68
October [E]	6101.1	5505.5	3074.4	2991.0	8330.2	5804.6	7429.6	64
November [E]	5815.8	5423.7	3369.1	2533.8	8107.0	5463.4	7595.1	50
Full dataset	**3466.8**	**2686.9**	**2820.5**	**1254.2**	**4517.7**	**3414**	**4064**	**431**

Different superscript letters (A, B, C, D, E) indicate significant differences in mean TN concentration among months (Tukey's HSD on ln-transformed data, $p < 0.05$).

concentrations or total nutrients recovered in sweepings. We were unable to compare sweepings from these sweeper types with those collected solely by vacuum, as only one route was swept using a vacuum sweeper. Past studies have shown that regenerative air sweepers are more efficient than mechanical broom sweepers in cleaning streets, especially for fine particles (Walker and Wong, 1999; Hixon and Dymond, 2018). Our study did not attempt to determine the efficiency of different sweeper types. However, our results do indicate that sweeper type had little influence on the concentration of nutrients in sweepings, suggesting that mechanical broom sweepers are effective in recovering coarse tree-derived material in the same proportion of total sweeping loads as regenerative air sweepers. This finding likely reflects that both sweeper types are equally effective at sweeping up larger particles (Selbig and Bannerman, 2007; Sorenson, 2013; Hixon and Dymond, 2018, 2019), and nutrients were concentrated in the coarse fraction.

4.3. Generalizing to other regions

An open question is whether the results from this study provide reasonable estimates of nutrient concentrations in leaf litterfall in other urban regions, e.g., for the purposes of estimating nutrient recovery in street sweeping operations. The nutrient concentrations in leaf litterfall in sweepings collected here are likely broadly representative of concentrations in leaf litterfall collected in street sweepings in other high tree canopy areas of northern U.S. cities, given that the tree species and genera planted as street trees in the Minneapolis-St. Paul Metropolitan Area (MSPMA) are commonly planted throughout the upper Midwest and northeastern U.S. The ten most common tree genera in inventories in the MSPMA (many of which comprised mainly street trees) included *Acer*, *Fraxinus*, *Quercus*, *Tilia*, *Ulmus*, *Gleditsia*, *Celtis*, *Picea*, *Malus*, and *Betula* (Keller et al. unpublished), similar to what inventories have shown for cities in Wisconsin, Illinois, and Michigan (Brandt et al., 2021). In the Northeastern U.S., the most commonly planted street tree species included *Syringa reticulata*, *Gleditsia triacanthos*, *Acer rubrum*, *Platanus x acerfolia*, *Liquidambar styraciflua*, and *Ulmus americana* (Doroski et al., 2020), overlapping genera that are common in the MSPMA. Thus, data on nutrient concentrations presented herein could be useful for estimating nutrients recovered in street sweeping operations in other northern U.S. cities when combined with data on street sweeping load masses.

4.4. Implications for stormwater management

If not removed from the street through street cleaning operations, nutrients in tree litterfall in streets contribute bioavailable nutrients to stormwater. These nutrients are released from litterfall through leaching (Schreeg et al., 2013; Wang et al., 2020; Hill et al., 2022) or biological decomposition, when microbes release nutrients in soluble forms (Hobbie et al., 2014). Such release may happen in the street itself or downstream in catch basins or other structural stormwater control measures, storm drains, or receiving water bodies (streams, lakes, rivers, coastal regions). Regardless of where nutrient release occurs, unless nutrients are removed through street sweeping or through downstream management practices (e.g., catch basin sump cleaning, pond dredging, water alum treatment), they can contribute to downstream eutrophication.

Our results suggest street sweeping could be an effective tool for managing stormwater nutrient pollution in high-canopy areas. Promoting street sweeping in places (high-canopy streets) and at times (early summer and autumn) with the highest inputs of tree litterfall to streets will require the development of appropriate pollution reduction crediting schemes that incentivize those practices, for example under Municipal Separate Storm Sewer System (MS4) permits or Total Maximum Daily Load (TMDL) waste load allocations. Our results indicate that relying on general statistical models that include variables such as canopy cover, sweeping frequency, month, and sweeper type to estimate nutrients recovered in sweeping may not be sufficiently precise to form the basis for nutrient pollution reduction crediting schemes for street sweeping. Indeed, despite measuring several potential predictors of variation in nutrient concentrations and total nutrients recovered in sweepings, our regression models were able to explain only 54–68 % of the variation in nutrient concentrations and 46–47 % of the variation in total nutrients recovered in sweepings.

Notably, our work revealed significant variation among cities that we have yet to fully explain. Differences among cities in nutrient concentrations and nutrient recovery in sweepings could not be attributed to differences in canopy cover, sweeper type, sweeping frequency, or time of year or season swept, and must have arisen from unmeasured factors. Such factors could include the species composition of trees planted along street sweeping routes; timing of sweeping relative to the amount and timing of antecedent precipitation, which could have influenced leaching of material in the street, throughfall and stemflow contributions to streets, and transport of material from streets into storm drains between sweeping events; variation in windblown transport of litterfall into streets from surrounding areas; land use history and nutrient status of soils, which could influence tree nutrient uptake and litter concentrations and fine sediment nutrient concentrations; construction or yard management activities that might have contributed erosional inputs to fine sediments in sweepings; and/or contributions of grass clippings or fertilizer to swept materials.

Direct measurements of nutrient loads recovered in sweeping will likely be the most precise and appropriate approach to developing pollutant credits to incentivize nutrient removal in sweepings (King et al., 2020). Such direct measurements could involve measures of load masses, with assumptions about nutrient concentrations (e.g., based on the data presented here). This approach has been adopted by the state of Minnesota (Minnesota Pollution Control Agency, 2023) and recommended by the state of New Hampshire (Houle et al., 2022).

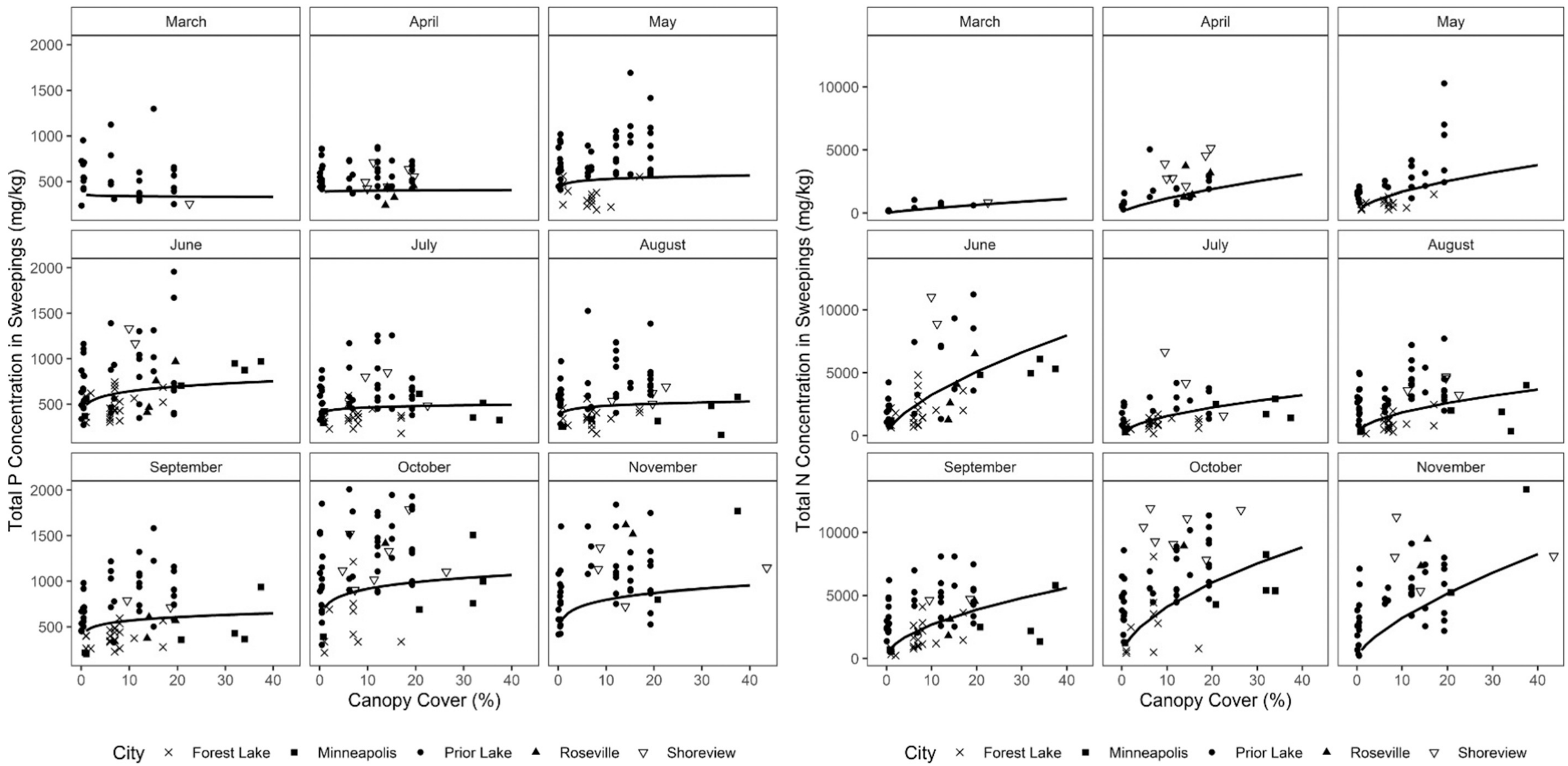

Fig. 2. Total P (left) and N (right) concentration in sweepings in relation to canopy cover and month for all cities and routes. Each point represents a sweeping event and lines are derived from the regression in Table S4. Sweeping samples came from five cities in Minnesota, USA.

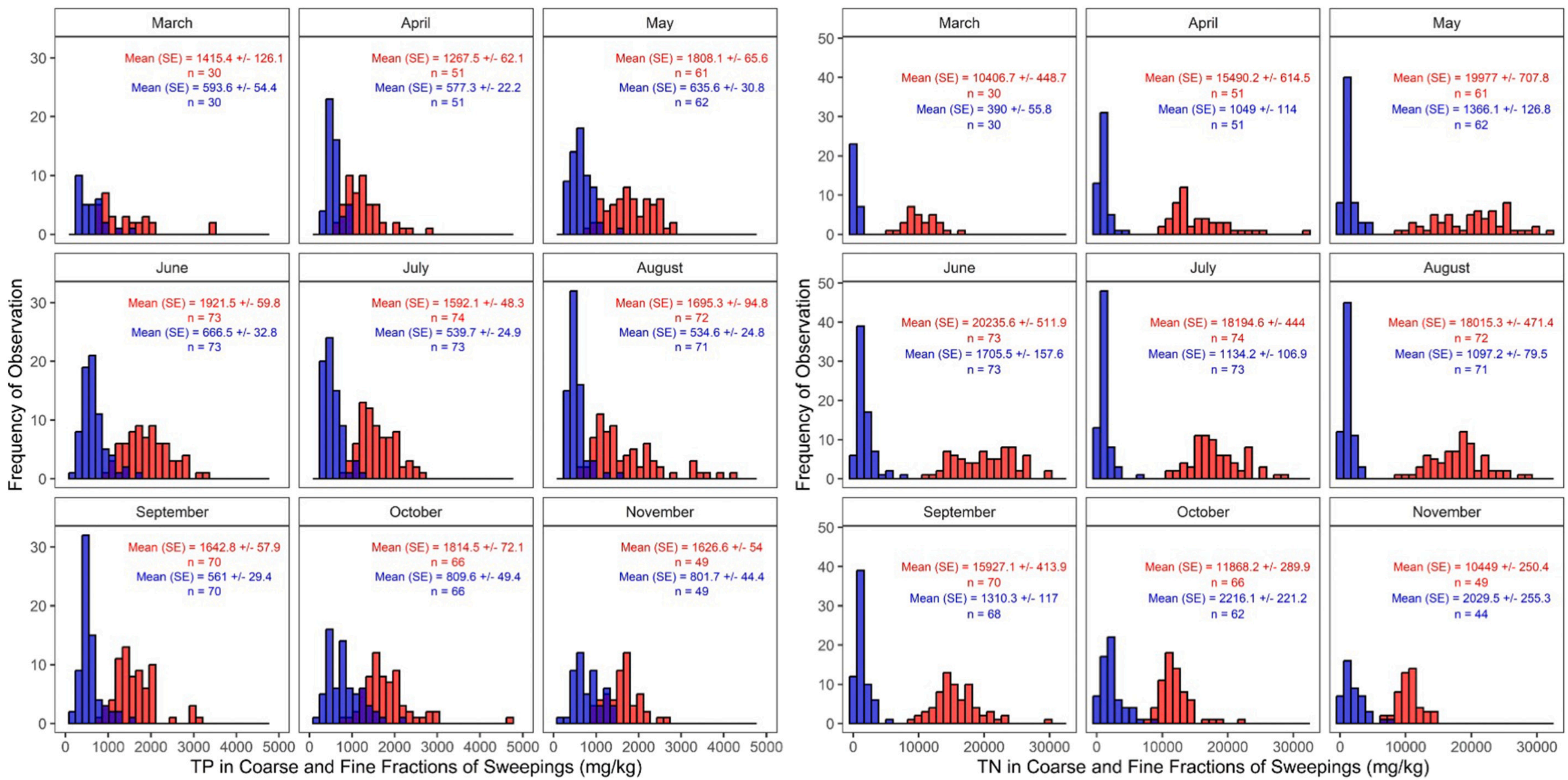

Fig. 3. Total P (left) and N (right) concentrations (mg/kg) in coarse and fine fractions of sweepings collected in different months. Blue bars and text represent the TP or TN concentration in the fine fraction (< 2 mm), and red bars and text show the TP or TN concentration in the coarse fraction (≥ 2 mm) (with overlap shaded in purple). Sweepings came from five cities in Minnesota, USA.

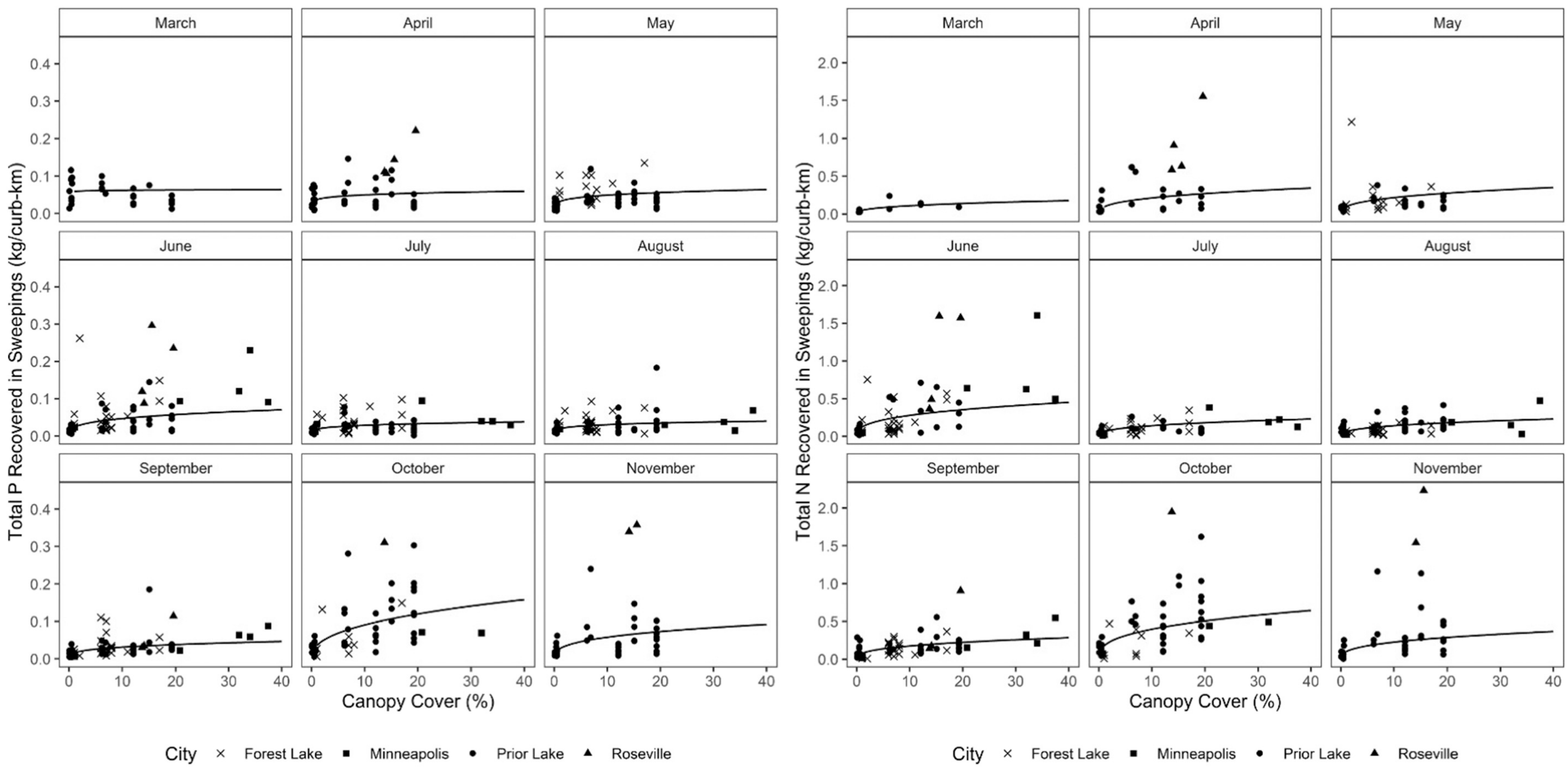

Fig. 4. Total P (left) and N (right) recovered in sweepings (kg/curb-km) by canopy cover and month. Each point represents a sweeping event and lines are derived from the regression in Table S6 (TP) and Table S7 (TN). Sweeping samples came from four cities in Minnesota, USA.

Alternatively, credit could be based on measures of load masses accompanied by direct measures of nutrient concentrations. Note that measuring nutrient concentrations in swept materials is resource-intensive, especially if coarse and fine sediments are analyzed separately, as done here, which may make such analyses cost-prohibitive for permittees.

In addition to stormwater nutrient management, our findings also inform use of street sweeping to manage solids loading of stormwater. Besides contributing to stormwater nutrient pollution, coarse solids that remain in the street can impact downstream aquatic habitats and stormwater management infrastructure, reducing its effectiveness and increasing the need for maintenance. When solids accumulate in stormwater structural Best Management Practices for stormwater pollution (BMPs), they can impair functioning and potentially lead to release of nutrients or flooding (Taguchi et al., 2020; Winston et al., 2023). Thus, targeted street sweeping could help reduce maintenance needs for downstream structural BMPs, such as catch basin sumps, rain gardens, and stormwater ponds. Indeed, management of coarse materials by sweeping has been shown to be cost-effective relative to structural BMP maintenance (Weiss et al., 2007). Our results indicate that the seasonality of total mass versus nutrients in sweepings differed, with peak nutrients occurring in early summer and fall, while total load masses of sweepings were highest in the spring, following snowmelt. In addition, relationships with canopy cover appeared to be stronger for total nutrient concentrations and loads than for total load mass, suggesting that total load mass was less tied to the biological activity of trees. The origin of spring solids is unclear, but probably represents a combination of leaf litter that was not swept the previous fall (consistent with somewhat elevated C concentrations in April sweepings) and wind-borne, erosional, and vehicle-borne sediment from the previous fall and winter. Thus, optimal timing of street sweeping differs for effectively removing coarse solids versus nutrients.

Our results are informative for stormwater modeling, as they provide evidence of higher nutrient loads (i.e., pollutant build-up) in streets where canopy cover is higher. Thus, simple approaches to modeling nutrient pollution in stormwater runoff that assume constant nutrient concentrations in runoff based on type of source area (e.g., streets, impervious cover) and land use are not appropriate if tree canopy cover varies over streets and within land use categories. Such variation will contribute heterogeneity in build-up of nutrients between precipitation events and in nutrient concentrations in stormwater runoff. Also, models that use sediment transport dynamics to estimate sediment-bound pollutant fractions do not account for transport of coarse organic materials like litterfall and release of litterfall nutrients through decomposition. Our results indicate that such models may underestimate nutrient sources to stormwater.

Findings presented here indicate that trees growing adjacent to streets can be significant sources of both N and P to streets and thus contribute nutrient pollution to urban stormwater runoff. Yet, water-pollution costs of urban trees are not usually included in discussions of the disservices of trees in cities (Roy et al., 2012; Roman et al., 2021). Indeed, trees are often assumed to improve water quality because they can reduce stormwater volumes, at least at lower rainfall intensities (Berland et al., 2017; Kuehler et al., 2017; Selbig et al., 2022). However, street sweeping offers a relatively straightforward and cost-effective method for managing the potential pollution challenges associated with street trees (Kalinosky et al., 2014), suggesting that it is possible to enjoy the benefits of urban street trees while managing their contributions to stormwater pollution.

4.5. Conclusions

Total N and P concentrations and loads recovered in street sweepings increased with canopy cover over streets. Concentrations and loads were highest and the relationship with canopy cover was strongest in early summer and in the fall, times of high litterfall. Nevertheless, a large fraction of the variation in street sweeping nutrient concentrations and loads remained unexplained after accounting for variation in canopy cover over streets, month, sweeping frequency, and sweeper type; thus, future research should investigate additional sources of variation in nutrients in street sweepings. Our results add to growing evidence of the importance of street trees in contributing nutrient pollution to urban surface waters, and future studies should compare contributions of litterfall from trees adjacent to streets with those from other non-point nutrient pollution sources. Our findings add to growing evidence that street sweeping focused on high-canopy streets during early summer and autumn is likely an effective management tool for stormwater nutrient pollution.

CRediT authorship contribution statement

Sarah E. Hobbie: Conceptualization, Methodology, Data curation, Writing – original draft, Supervision, Project administration, Funding acquisition. **Rachel A. King:** Formal analysis, Data curation, Writing – review & editing, Visualization. **Tessa Belo:** Methodology, Investigation. **Paula Kalinosky:** Formal analysis, Writing – review & editing. **Lawrence A. Baker:** Conceptualization, Methodology, Writing – review & editing, Supervision, Project administration, Funding acquisition. **Jacques C. Finlay:** Conceptualization, Writing – review & editing, Supervision, Funding acquisition. **Christopher A. Buyarski:** Methodology, Investigation, Data curation. **Ross Bintner:** Conceptualization, Methodology, Funding acquisition.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data are archived and available on the Digital Repository for University of Minnesota (DRUM, Hobbie et al., 2020): https://doi.org/10.13020/39eg-bg21

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.scitotenv.2023.166934.

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