Environmental Science & Technology

Article

pubs.acs.org/est

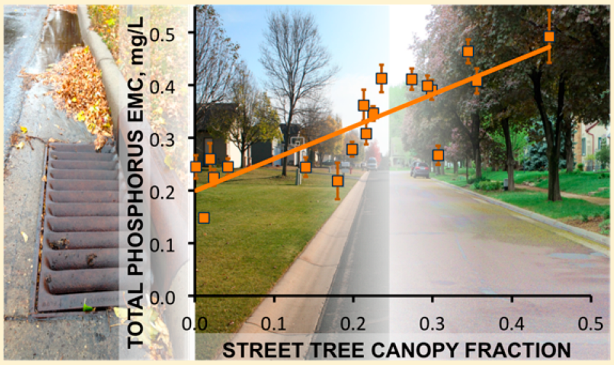
Trees and Streets as Drivers of Urban Stormwater Nutrient Pollution

Benjamin D. Janke,* Jacques C. Finlay, and Sarah E. Hobbie

Department of Ecology, Evolution and Behavior, University of Minnesota, 140 Gortner Laboratory, 1479 Gortner Avenue, St. Paul, Minnesota 55108, United States

Ⓢ *Supporting Information*

ABSTRACT: Expansion of tree cover is a major management goal in cities because of the substantial benefits provided to people, and potentially to water quality through reduction of stormwater volume by interception. However, few studies have addressed the full range of potential impacts of trees on urban runoff, which includes deposition of nutrient-rich leaf litter onto streets connected to storm drains. We analyzed the influence of trees on stormwater nitrogen and phosphorus export across 19 urban watersheds in Minneapolis-St. Paul, MN, U.S.A., and at the scale of individual streets within one residential watershed. Stormwater nutrient concentrations were highly variable across watersheds and strongly related to tree canopy over streets, especially for phosphorus. Stormwater nutrient loads were primarily related to road density, the dominant control over runoff volume. Street canopy exerted opposing effects on loading, where elevated nutrient concentrations from trees near roads outweighed the weak influence of trees on runoff reduction. These results demonstrate that vegetation near streets contributes substantially to stormwater nutrient pollution, and therefore to eutrophication of urban surface waters. Urban landscape design and management that account for trees as nutrient pollution sources could improve water quality outcomes, while allowing cities to enjoy the myriad benefits of urban forests.



INTRODUCTION

Urban ecosystems are characterized by high levels of nutrient inputs associated with humans[1−3] and by amplified hydrologic transport due to extensive impervious surfaces and storm drains. Aquatic ecosystems within and downstream of cities are subject to excessive stormwater loading from the landscape, leading to flooding, loss of ecosystem function, and degradation of habitat.[4−7] The most pervasive effect of excessive stormwater nutrient loading to lakes, streams, and coastal waters is eutrophication, which results in abundant algal growth including harmful cyanobacterial blooms, as well as low oxygen, fish kills, and noxious odor, leading to degradation of aquatic habitat, recreation, and water supply.[8]

Efforts to improve water quality of urban lakes and streams have focused heavily on the reduction and treatment of stormwater runoff, typically through installation of end-of-pipe management structures such as detention ponds and infiltration trenches. However, widespread improvement of urban water quality has not been achieved, despite the substantial resources invested in stormwater management.[9] Therefore, there is increasing interest in strategies both for reducing nonpoint source nutrient pollution within watersheds and for restoring more natural hydrologic regimes.[10−13] Particular emphasis is placed on the expansion of "green" infrastructure,[14] often defined as engineered structures such as bioswales and vegetated rooftops, but also including urban vegetation in lawns, parks, and boulevards. Green infrastructure is appealing for stormwater management because it provides reduction of runoff volume and peak flows via interception of rainfall, infiltration of stormwater, and evapotranspiration, which potentially decrease associated runoff nutrient loads.[12,14,15] Green infrastructure, and trees in particular, also have cobenefits, improving flood control, air quality, mental health, recreational opportunities, property and aesthetic values, and climate change resiliency.[16−22]

Trees are a crucial component of green infrastructure, and the expansion of tree cover has been widely promoted in cities.[23,24] Trees potentially improve water quality by decreasing nutrient export when used in bioswales and planter boxes,[25−27] and by reducing stormwater volumes and peak flows (and presumably nutrient export) at watershed scales.[28−31] However, few studies have quantified a nutrient reduction benefit to downstream waters of expanded tree cover. While trees and other vegetated areas near streets promote nutrient uptake,[27] large pools of nutrients in plant biomass and soils could serve as sources of nitrogen (N) and phosphorus (P) transported to stormwater systems via erosion, litterfall, and leaching.[32−35] If trees, as an integral part of green infrastructure, contribute nutrients to stormwater, then disentangling the opposing influences of runoff volume reduction and increases in stormwater nutrient concentrations is essential. Furthermore, incomplete understanding of nutrient sources to streets and storm drains,

Received: May 29, 2017
Revised: July 20, 2017
Accepted: July 29, 2017
Published: July 30, 2017

DOI: 10.1021/acs.est.7b02225

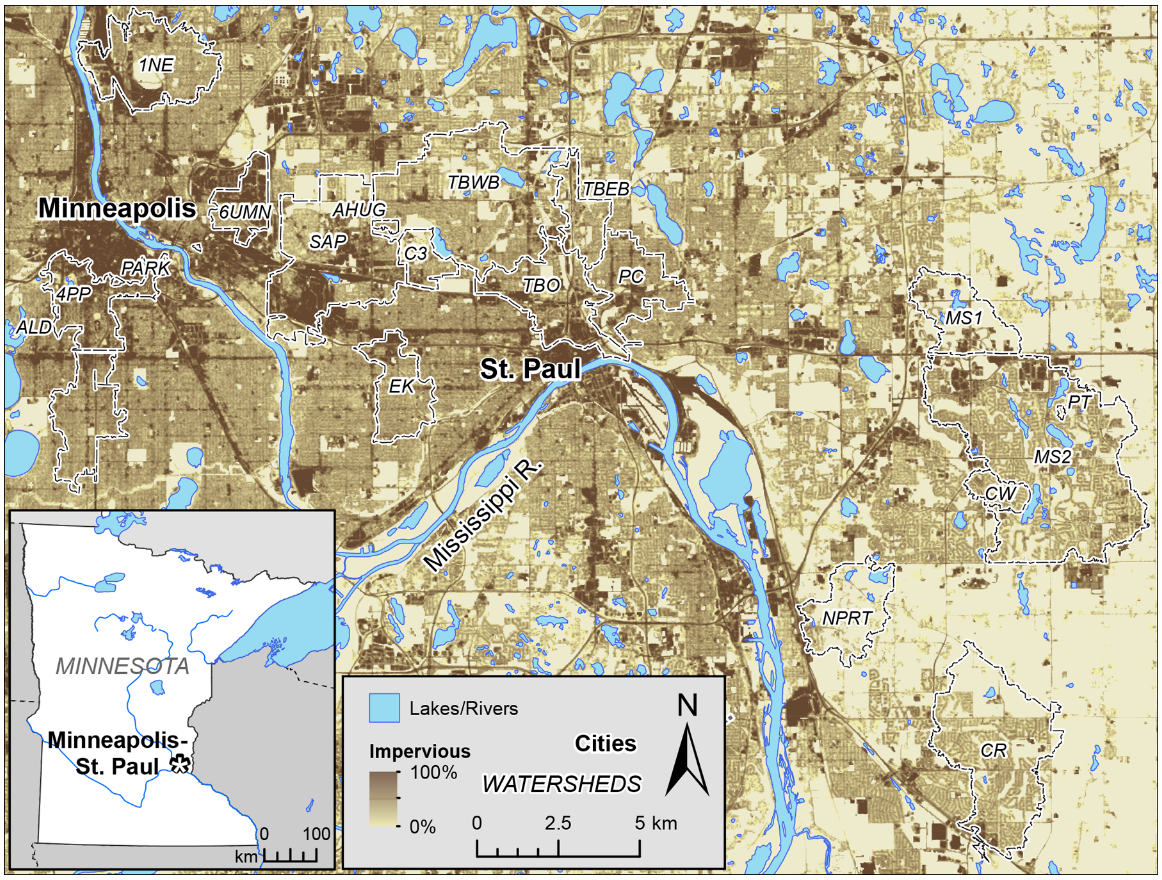


Figure 1. Monitored watersheds included in this study, located in the metropolitan area of Minneapolis−St. Paul, MN, U.S.A.

Table 1. Watershed and Drainage Characteristics Used to Describe Potential Nutrient Sources to Stormwater in the Study Watersheds

characteristic	units	mean (min−max)[a]	description	nutrient or water sources
population density (POP)	*no/km^2*	2803 (*315−10 960*)	intensity of human habitation	pets, food, cars, spills
street density (STDEN)	*km/km^2*	11.9 (*3.9−23.0*)	urban drainage intensity	runoff volume, deposition
traffic (TRAF)	*AADT*	7.0× 10^5 (*5.7× 10^3−3.8× 10^6*)	vehicle counts on major roadways	deposition
residential area (RES)	*fraction*	0.40 (*0.0−0.91*)	low-density residential parcel area	fertilizer, pet waste, yard waste
total impervious area (TIA)	*fraction*	0.44 (*0.20−0.80*)	streets, alleys, parking lots, rooftops	runoff volume, deposition
total vegetation (VEG)	*fraction*	0.52 (*0.20−0.78*)	grass + tree canopy	vegetated litter, soil erosion, interception
tree canopy (TREE)	*fraction*	0.29 (*0.14−0.62*)	tree canopy	leaf litter, interception
street canopy (SC)	*fraction*	0.20 (*0.0−0.45*)	street area covered by tree canopy	leaf litter on streets, interception
SC within 1.5m (SC_1.5)	*fraction*	0.23 (*0.02−0.46*)	near-street tree canopy	leaf litter on/near streets
SC within 6.1m (SC_6.1)	*fraction*	0.30 (*0.06−0.48*)	near-street tree canopy	leaf litter on/near streets

[a] Mean, minimum, and maximum values across 19 study sites.

including vegetation as well as atmospheric deposition,[36,37] pet waste,[3] and fertilizer and erosion from lawns,[38,39] is a major impediment to development of effective nutrient pollution management strategies,[11] and to understanding the potential water quality consequences of increasingly "green" urban environments.

In this study, we assessed the role of vegetation, and trees adjacent to streets in particular, on urban stormwater runoff quality by analyzing factors that control stormwater nutrient levels across a large urban area, the Minneapolis−St. Paul metropolitan area, Minnesota, U.S.A. (TCMA). We used extensive stormwater monitoring data sets based on over 2300 measurements taken from 2005 to 2014 in 19 watersheds to compare nutrient concentrations and loading across gradients of tree, vegetation, and impervious cover typical of urban residential watersheds. We used these robust data sets to address the following questions: (1) How does the cover of vegetation, and especially trees adjacent to streets, affect nutrient loads and concentrations in stormwater? (2) Does the volume reduction provided by street trees offset the potential enhanced nutrient inputs to streets from leaf litter (e.g., leaves, seeds, pollen, and flowers)? (3) How important are "green" nutrient sources relative to other factors associated with nutrient inputs to urban areas, such as atmospheric deposition?

■ BACKGROUND AND METHODS

Study Sites, Data Acquisition, and Collection. We focused on understanding nutrient sources at two spatial scales dominated by urban land use in the Twin Cities Metropolitan Area of Minneapolis-St. Paul (TCMA), Minnesota, U.S.A. (Figure 1). We used an extensive, multiyear data set for 2,362 stormwater runoff events across 19 urban subwatersheds of the Mississippi River (Table S1 of the Supporting Information, SI) along with high-resolution land cover data to assess the influence of urban vegetation and other potential drivers of nutrient pollution (Tables 1 and S2). We complemented these analyses with investigations at the scale of individual streets with varying street tree canopy cover within a single residential watershed. Study watersheds were small, ranging in size from 4 ha to 3170 ha, with generally mixed urban land use dominated by low-density residential. In some watersheds, remnant surface water features (lakes, ponds) were present. Development age across sites ranged from roughly 20 years old in the outer suburbs, where street tree canopy tended to be minimal due to development in former agricultural lands, to 100 years or older at sites in the urban core, where tree canopy was older and denser. Drainage infrastructure was on average older in the urban core than in areas of younger development; however, storm drain systems in the study watersheds have been completely separated from sanitary sewers since 1996, and both storm and sanitary systems are tested for leaks and maintained by municipalities and watershed managers. These features, along with the lack of evidence for gross contamination of sewage at sites with baseflow[40] suggest that leaking sanitary sewers did not influence our study sites. Use of P in lawn fertilizer has been restricted for individual household use since 2004, while N fertilizer use is not regulated.

Stormwater nutrient chemistry and hydrology data from five watershed management organizations were integrated into our analyses (Figure 1; Table S1). Data were collected as part of regional stormwater monitoring programs initiated as early as 2001, but more typically since 2005. Monitoring was usually conducted during the April to November warm period of each year. Cross-site comparisons used only the data collected from 2005−2014, restricted to the warm season (April 1−October 31) when the majority of annual precipitation occurs (79% on average from 1981−2010).[41] Monitoring protocols, including sample collection, chemical analyses, and quality control procedures, were similar among organizations (Table S1). Nine sites did not have baseflow. For most of the other 10 sites, the influence of baseflow on stormwater was small since runoff rates were generally larger during storms than during baseflow by an order of magnitude or more;[40] for sites with appreciable baseflow (MS1, MS2), sliding-interval baseflow separation was applied to hydrologic data.[42]

Stormwater samples were primarily composite samples (n = 1895), combined from subsamples within an event to provide a single, volume-weighted composite. Roughly 17% of the samples (n = 330) were grab samples; however, the potential bias of including grab samples was minimal, as the significance of regressions (see below) were unchanged when grab samples were excluded from the data set. Samples were analyzed for concentrations of total phosphorus (TP), total dissolved phosphorus (TDP), nitrate- plus nitrite-nitrogen (hereafter NO_x−N), ammonium nitrogen (NH_4−N), and total Kjeldahl nitrogen (TKN). Total nitrogen (TN) was estimated as the sum of TKN + NO_x−N, and total organic nitrogen (TON) as TKN−NH_4−N. The majority of samples were analyzed by the Metropolitan Council Environmental Services Laboratory (St. Paul, MN), using standard U.S. E.P.A. protocols.[43] Soluble reactive phosphorus (SRP) was not consistently measured at most sites, so TDP was used in the data analysis. For the CRWD sites, for which SRP was generally measured instead of TDP, we estimated TDP from SRP using a linear regression applied to a subset of 641 runoff samples that had been measured for both forms (TDP [mg/L] = 1.20 × SRP [mg/L] + 0.012, R^2 = 0.91; unpublished data).

Stormwater event mean concentrations (EMC) observed in this study for N and P (Table 2) were typical of urban runoff,[44] and similar to previous observations in the TCMA.[45] TP and TN greatly exceeded that measured in precipitation in the study area, including in rainfall at the AHUG watershed during 2011−2013 (0.03 mg/L for TP, 1.05 mg/L for TN, n = 27 samples; unpublished data), and in wet deposition measurements of TP across the TCMA in a 1980 study[46] (TP = 0.06 mg/L, n = 5 sites). Stormwater NO_x−N (0.45 mg/L) was similar to mean wet deposition at AHUG (0.25 mg/L) and in Payne et al.[46] (0.46 mg/L), while NH_4−N (0.24 mg/L) was much lower than observations in the two precipitation data sets (0.69 mg/L at AHUG and 0.92 mg/L in Payne et al.[46]).

Table 2. Mean, Standard Deviation, Minimum, And Maximum of Site Stormwater Event Mean Concentrations, and Yields, Warm Season (April−October)[a]

parameter	sites (n)	mean ± SD	min	max
site event mean concentration, mg/L				
TP	19	0.32 ± 0.09	0.15	0.49
TDP	19[b]	0.09 ± 0.04	0.03	0.19
TN	19	2.36 ± 0.37	1.74	3.12
TON	19	1.66 ± 0.32	0.96	2.19
NO_x−N	19	0.44 ± 0.17	0.15	0.91
NH_4−N	19	0.26 ± 0.18	0.11	0.80
site event mean nutrient yield, kg/km^2 or water yield, cm				
TP	12	1.21 ± 0.72	0.33	2.46
TDP	12[b]	0.27 ± 0.20	0.05	0.76
TN	12	7.93 ± 4.0	2.65	16.9
TON	12	6.09 ± 3.2	1.80	13.4
NO_x−N	12	1.25 ± 0.68	0.42	2.44
NH_4−N	12	0.61 ± 0.28	0.31	1.30
water	12	0.37 ± 0.16	0.16	0.70
RC	12	0.18 ± 0.10	0.07	0.39

[a] Total Kjeldahl Nitrogen (TKN) data not shown. TN calculated as TKN + NO_x−N, TON calculated as TKN − NH_4−N, RC = runoff coefficient. [b] For CRWD sites (Table S1), TDP was estimated from SRP based on a linear regression fit to a subset of samples (n = 641) for which both SRP and TDP had been measured (see Methods).

Continuous flow was recorded at all sites but quality-controlled data for stormwater runoff volumes were available only for a subset of 12 sites. Nutrient yields (kg/km^2) were estimated for each sampled event at these sites by multiplying the observed volume by the observed concentration (typically from a volume-weighted composite, but sometimes represented by a grab sample), and normalized by watershed area.[3,40,42]

We also investigated the street scale in a small (17 ha) residential watershed in St. Paul, MN (AHUG; Table S1). During several late spring (post leaf-out) and fall (post leaf-drop) events from fall 2012 through spring 2015, we sampled street gutter runoff from 9 blocks within the watershed that varied in street canopy coverage due to differences in tree species and age. Runoff was sampled using a 1-L plastic bottle by collecting water as it entered the catch basins at the end of each major block. Water samples were analyzed for major nutrient forms including

TP, SRP, NO_x−N, NH_4−N, total dissolved N (TDN), and particulate N (PN) at the University of Minnesota (UMN) using similar laboratory methods as MCES.[40] For these samples, TN was estimated as TDN + PN, and TON as TN − NO_x−N − NH_4−N.

Data Analysis and Model Selection Approach. *Land Cover, Land Use, and Hydrologic Connectivity.* In cities, primary new sources of N and P to the landscape include fertilizer, pet waste, and atmospheric deposition from automobiles and industrial activities,[3] all of which may be exported to stormwater during runoff events. Much of the N and P from these sources may also be assimilated by plants and microbes, and bound to soil, where it can later become a source of nutrients to runoff through leaching of vegetation and surface soils, leaf (and other) litter, grass clippings that fall or are washed or blown into streets, and eroded soils. Urban stormwater hydrology, which influences the magnitude of nutrient loading, is primarily controlled by the extent and configuration of impervious surfaces,[47,48] which also serve as accumulation areas for atmospheric deposition. Although we did not have direct information to trace these sources, to gain insights into the importance of potential nutrient sources to stormwater and the factors that influence stormwater runoff volume, we analyzed relationships between stormwater nutrient (and water) export and watershed characteristics related to streets, impervious cover, traffic, population, housing density, and vegetation cover (Tables 1 and S2). The variables used in analyses, and the potential sources of nutrients and runoff that they represent, are summarized in Table 1 and described briefly below (see SI for details on data sources and calculation of characteristics). All spatial analyses were completed in ESRI ArcGIS 10.1.

Land cover and land use attributes that potentially influence stormwater N and P included vegetation and factors associated with human activities such as traffic volume (average annual daily traffic), population density (people/km^2), and low-density residential parcel area (as a fraction of total watershed area). Vegetation was described by total vegetation (open lawn + tree) cover, total tree cover, and tree canopy over the street as well as tree canopy over and within 1.52 and 6.10 m of the street (Table S2). Limitations of the spatial data prevented the estimation of total or near-street turf grass cover (see SI). Traffic density is related to the potential input of local inorganic N by deposition from combustion by vehicles, and is concentrated near roadways.[36] Population density (people/km^2) is associated with nutrient inputs from pets and vehicles, and potentially food waste or trash. Low-density (three families or fewer) residential parcel area is closely associated with lawn area and with household nutrient inputs such as lawn fertilizer or pet waste. Without explicit numbers on pet ownership or lawn fertilizer application rates in the study watersheds, we acknowledge that residential parcel area integrates the potential effect of both nutrient sources. A recent study[3] found that the largest new inputs of N and P to our study watersheds were fertilizer and pet waste, respectively. However, past fertilization may have accrued in soils, which complicates source tracing of P.

Drainage intensity, which exerts a dominant influence on stormwater runoff volumes, was characterized by total impervious area, total street area, and street density (length per unit area watershed). Street density was assumed to represent the most directly connected impervious areas, as a true effective impervious area (EIA) could not be determined for all watersheds due to limitations of spatial and hydrologic data. Additionally, incomplete storm drain maps for many watersheds prevented the characterization of the extent of storm sewer connectivity of the drainage areas.

Statistical Analysis. The influence of near-street tree canopy on stormwater nutrient concentrations, and its importance relative to other human and landscape factors in the urban study area, was assessed using two sets of analyses. First, the across-site relationships of stormwater volumes and nutrient concentrations to individual watershed characteristics (Table 1) were investigated with simple linear regression (SLR). Event mean nutrient concentrations (EMC) by site were used in the regressions, with data restricted to the typical monitoring season (i.e., April 1−October 31) since not all sites were monitored year-round. Mean event runoff and nutrient yields by site were used in the regressions for the subset of sites with event hydrology data (n = 12; Table S1). Statistical significance is reported at $p < 0.05$ and $p < 0.001$.

Multiple linear regression analysis (MLR) was used to assess the influence of street tree canopy relative to the other watershed factors on nutrient concentrations and yields. Candidate factors were assembled separately for each nutrient form by first selecting those variables hypothesized to influence stormwater nutrients that also had high correlation coefficients from SLR. For sets of highly collinear factors (Pearson $|r| > 0.7$), such as street density and street area, the factors with the lowest correlation to the nutrient of interest were excluded. The full model for each nutrient was then tested exhaustively for every combination of candidate factors (main effects only; no interactions), with submodels ranked by sample size-adjusted Akaike Information Criterion (AIC_c). Models for which constituent factors exceeded a variance inflation factor (VIF) of 5.0 were rejected. Adjusted R^2 was then computed for all models within AIC_c 2.0 of the best model.[49] Best model selection, including estimates of coefficients, significance, and effect size (as provided by η^2), is shown in the SI along with model fits to observations. R was used for all statistical analyses (MLR and SLR).

Analyses of the net influence of trees on stormwater nutrient yields via effects on runoff reduction and on stormwater EMC were complicated by our relatively small data subset for nutrient loads (n = 12 sites), and by covariance of street canopy cover with street density (and with runoff volume) among these 12 sites (R^2= 0.40; Table S2). To examine the influence of tree canopy on nutrient loading via effects on both concentration and runoff, we constructed a nutrient yield model from the MLR analyses for water yield and for EMC of TP and TN (see Results and SI). Nutrient yields were estimated as a product of predicted EMC and predicted water yield for hypothetical watershed configurations (combinations of street canopy and street density within ranges present in our data set).

■ RESULTS AND DISCUSSION

Urban Trees As a Major Source of Nutrients to Stormwater. Our results indicate that trees adjacent to streets were a dominant factor in determining N and P concentrations in stormwater during the warm weather period (April−October), when typically 60−80% of annual runoff and nutrient loading from stormwater occurs in our study sites (n = 7 sites). Analyses of stormwater concentration data provided strong evidence for this conclusion; variation in event mean concentration (EMC) of TP across sites was explained significantly in simple linear regression (SLR) by tree canopy over ($r = 0.84$, $p < 0.001$) and near the street (Table S3), and TP in the watersheds with the greatest street canopy cover was up to 3-fold higher than in those with negligible street canopy (Figure 2). Street canopy was also the dominant influence on TP when considered with other factors in multiple linear regression (MLR; Table 3), as all candidate models within 2.0 AIC$_c$ units (n = 5) included street canopy. Similarly for nitrogen, EMC of TN was strongly related to street canopy ($r = 0.68$, $p < 0.05$; Figure 2; Table S3). N was primarily delivered as organic N (71% of TN on average across sites), which was even more strongly influenced by street canopy ($r = 0.71$, $p < 0.001$). Street canopy, along with total impervious area (TIA) and residential area, were the dominant influences on TN when all variables were considered (Adj. $R^2 = 0.69$; Table 3). TON was most closely associated with street canopy (present in all 3 models within 2.0 AIC$_c$ of the best model; Table 3), which along with residential area comprised the best model by AIC$_c$ (Adj. $R^2 = 0.55$).

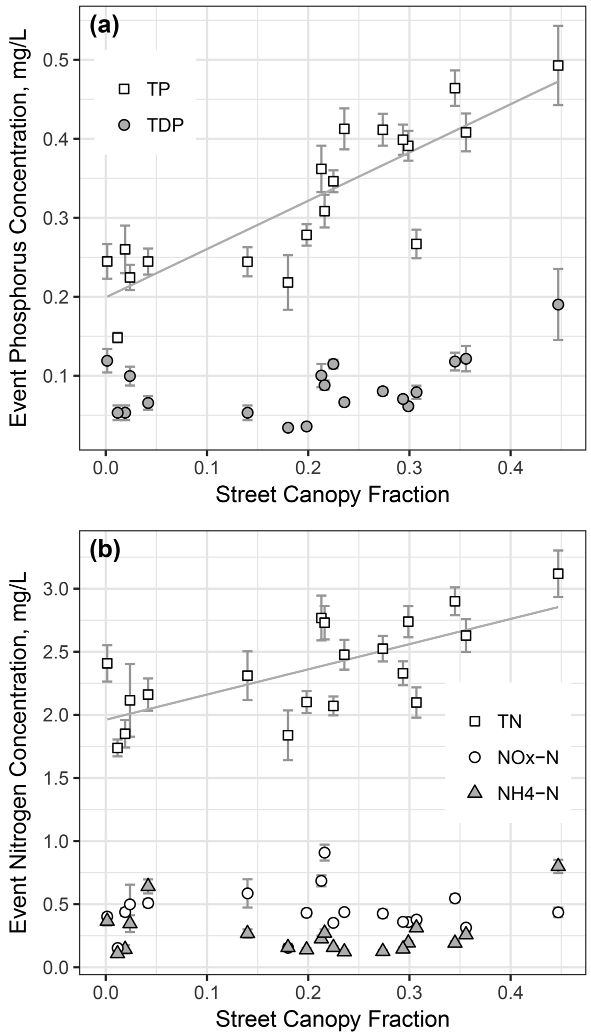


Figure 2. Site mean ±SE of (a) event TP and TDP concentration, and (b) event TN, NO_x−N, and NH_4−N concentration vs fraction of street covered by tree canopy (n = 19 sites). Trend lines indicate significant relationships as described in the text.

Concentrations of N and P in gutter runoff in the AHUG watershed showed strong positive (but seasonally variable) relationships with street canopy (Figure 3), confirming the influence of street canopy on nutrient concentrations observed at the watershed scale (Table S3). In fall, the influence of street canopy on stormwater N and P concentration was especially strong ($r = 0.95$, $p < 0.001$ for TP; $r = 0.96$, $p < 0.001$ for SRP; $r = 0.77$, $p < 0.05$ for TN; $r = 0.81$, $p < 0.05$ for TON). For TP and SRP, the relationship was not significant in late spring (leaf-out); however, TN and TON were positively related to street canopy during this period ($r = 0.75$, $p < 0.05$ for TN; $r = 0.73$, $p < 0.05$ for TON).

Seasonal patterns in stormwater P and N concentrations at the watershed scale further indicated trees and vegetation as major sources of nutrients to stormwater. These seasonal patterns mirrored the phenology of urban vegetation with seasonal peaks in means of P and N that coincided with autumn leaf drop and with spring leaf-out and flowering (Figure S1), and were strongly related to presence of street trees in the study watersheds. For example, elevated spring TP and TN concentrations across sites (characterized by mean May-minus-September difference in concentration) were significantly related to street canopy ($R^2 = 0.38$, $p < 0.05$ for TP; $R^2 = 0.26$, $p < 0.05$ for TN). Less variable and decreasing concentrations of TP and TN over summer (Figure S1) are consistent with establishment of lawns and trees during the growing season, accompanied by low rates of litterfall.[34] The subsequent increase of mean event TP and TDP concentrations from September to October were significantly correlated with street canopy ($R^2 = 0.30$, $p < 0.05$ for TP; $R^2 = 0.44$, $p < 0.05$ for TDP). A similar pattern was observed in a recent study of comparable residential watersheds in Madison, WI (U.S.A.), in which leaf litter contributed substantially to both dissolved and total forms of P and N in stormwater, in spring and especially in fall.[34] Tree litter (e.g., leaves, seeds, flowers) decomposing in street gutters contributes particulate P and N after fragmentation by vehicles and movement into storm drains during rainfall events, while dissolved nutrients are leached from freshly fallen litter by runoff. P remaining in senesced litter is especially soluble, with losses of up to 88% during initial leaching.[35,50−52]

Although trees can contribute directly to stormwater nutrient pollution via litterfall, the positive associations between tree canopy and stormwater P and N may have also been mediated through indirect effects of trees on underlying lawns. Poor turf quality often results from low light conditions beneath dense tree canopy, for example, and poor lawn conditions lead to increased erosive export of P and N from turfgrass.[39] This effect, if present, would not be differentiable from street tree inputs to stormwater as characterized by the street canopy and near-street canopy metrics in our analyses. A recent study of urban land cover configuration suggested that lawns and trees should be considered separately when assessing water quality benefits of vegetation, due to greater capacity of trees for pollutant processing and to more intense management of lawns.[53] Although our results suggest a strong role of street trees in nutrient pollution of stormwater, further work is clearly needed to distinguish effects of near-street lawn vs street trees.

Nontree Nutrient Sources to Stormwater. While stormwater nutrient concentrations were most strongly related to canopy cover, and were substantially lower in watersheds with low street tree cover, the positive y-intercepts in the relationships between street canopy and stormwater TN and TP (Figure 2) were well above rainfall concentrations observed at AHUG (TP = 0.03 mg/L, TN = 1.05 mg/L; see Methods). Such results imply the presence of "background" nutrient sources to rainfall runoff (i.e., sources that may be less variable across watersheds, and are not directly related to street trees), such as lawns and atmospheric deposition.

DOI: 10.1021/acs.est.7b02225
Environ. Sci. Technol. XXXX, XXX, XXX−XXX

Table 3. Assessment of Multivariate Models for Explanation of Variance in (a) Event Mean Nutrient Concentrations (mg/L) and (b) Event Water (cm) and Nutrient (kg/km^2) Yields Across Sites As a Function of Watershed Characteristics (Tables 1 and S2)[a]

(a) model	adj R^2	AICc	ΔAICc	weight	relative likelihood
		TP concentration, n = 19			
SC + ST_DENS	**0.73**	**-52.7**	**0**	**0.29**	**1**
SC	0.70	−52.6	0.1	0.28	0.96
SC − VEG	0.71	−51.6	1.1	0.16	0.57
SC + TIA	0.71	−51.4	1.3	0.15	0.52
SC + POP	0.70	−50.9	1.8	0.12	0.41
		TDP concentration, n = 19			
POP	0.26	−67.7	0	0.28	1
SC + POP + RES	**0.42**	**−67.5**	**0.1**	**0.26**	**0.94**
POP + RES	0.32	−67.2	0.4	0.22	0.80
SC + POP	0.28	−66.2	1.4	0.13	0.49
VEG + POP	0.27	−65.9	1.8	0.11	0.41
		TN concentration, n = 19			
SC + TIA + RES	**0.69**	**5.4**	**0**	**0.72**	**1**
SC + TIA	0.59	8.1	2.8	0.18	0.25
SC + ST_DENS	0.57	9.4	4.0	0.10	0.14
		TON concentration, n = 19			
SC + RES	**0.55**	**3.5**	**0**	**0.47**	**1**
SC	0.48	4.3	0.9	0.30	0.65
SC − POP	0.52	4.9	1.5	0.23	0.48
		NO_x−N concentration, n = 19			
−VEG − POP	**0.43**	**-16.3**	**0**	**0.46**	**1**
−VEG	0.34	−15.5	0.8	0.31	0.67
−POP + TIA	0.39	−14.9	1.5	0.22	0.48
		NH_4−N concentration, n = 19			
POP − TRAF	**0.80**	**−34.2**	**0**	**0.69**	**1**
−TREE + POP − TRAF	0.80	−31.3	2.8	0.17	0.24
−SC + POP − TRAF	0.80	−31.1	3.1	0.15	0.21

(b) model	adj R^2	AICc	ΔAICc	weight	relative likelihood
		water yield, n = 12			
ST_DENS	**0.75**	**−16.1**	**0**	**0.63**	**1**
ST_DENS − SC	0.78	−14.4	1.7	0.26	0.42
ST_DENS − VEG	0.75	−12.5	3.6	0.11	0.17
		TP yield, n = 12			
ST_DENS	**0.73**	**19.8**	**0**	**0.83**	**1**
ST_DENS − SC	0.71	24.3	4.5	0.09	0.10
ST_DENS − VEG	0.70	24.4	4.6	0.08	0.10
		TDP yield, n = 12[b]			
ST_DENS	**0.49**	**-3.5**	**0**	**0.23**	**1**
−SC + POP	0.61	−3.3	0.2	0.21	0.91
POP − RES	0.58	−2.2	1.3	0.12	0.53
POP − TIA	0.58	−2.2	1.3	0.12	0.52
POP − TREE	0.57	−2.0	1.5	0.11	0.47
2 additional models within 2.0 AICc					
		TN yield, n = 12			
ST_DENS	**0.79**	**58.7**	**0**	**0.79**	**1**
ST_DENS − SC	0.78	62.5	3.8	0.12	0.15
ST_DENS − VEG	0.78	62.9	4.3	0.09	0.12
		TON yield, n = 12			
ST_DENS	**0.78**	**53.4**	**0**	**0.79**	**1**
ST_DENS − SC	0.78	57.1	3.8	0.12	0.15
ST_DENS + RES	0.77	57.8	4.4	0.09	0.11
		NO_x−N yield, n = 12			
ST_DENS	**0.62**	**22.5**	**0**	**0.46**	**1**
TIA	0.61	22.9	0.4	0.38	0.81
ST_DENS − VEG	0.66	24.6	2.1	0.16	0.34

DOI: 10.1021/acs.est.7b02225

Table 3. continued

(b) model	adj R^2	AICc	ΔAICc	weight	relative likelihood
		NH_4–N yield, n = 12			
ST_DENS	**0.71**	**-1.1**	**0**	**0.79**	**1**
ST_DENS − TRAF	0.71	2.5	3.6	0.13	0.17
ST_DENS + RES	0.68	3.6	4.7	0.08	0.10

[a]The top 3 models, or all models within 2.0 AIC_c of the best model are shown for each constituent. Bold text indicates the "best" model for each nutrient, selected based on adjusted R^2, coefficient significance, and effect size (η^2) of constituent parameters (Table S4). [b]2 additional models within 2.0 AICc.

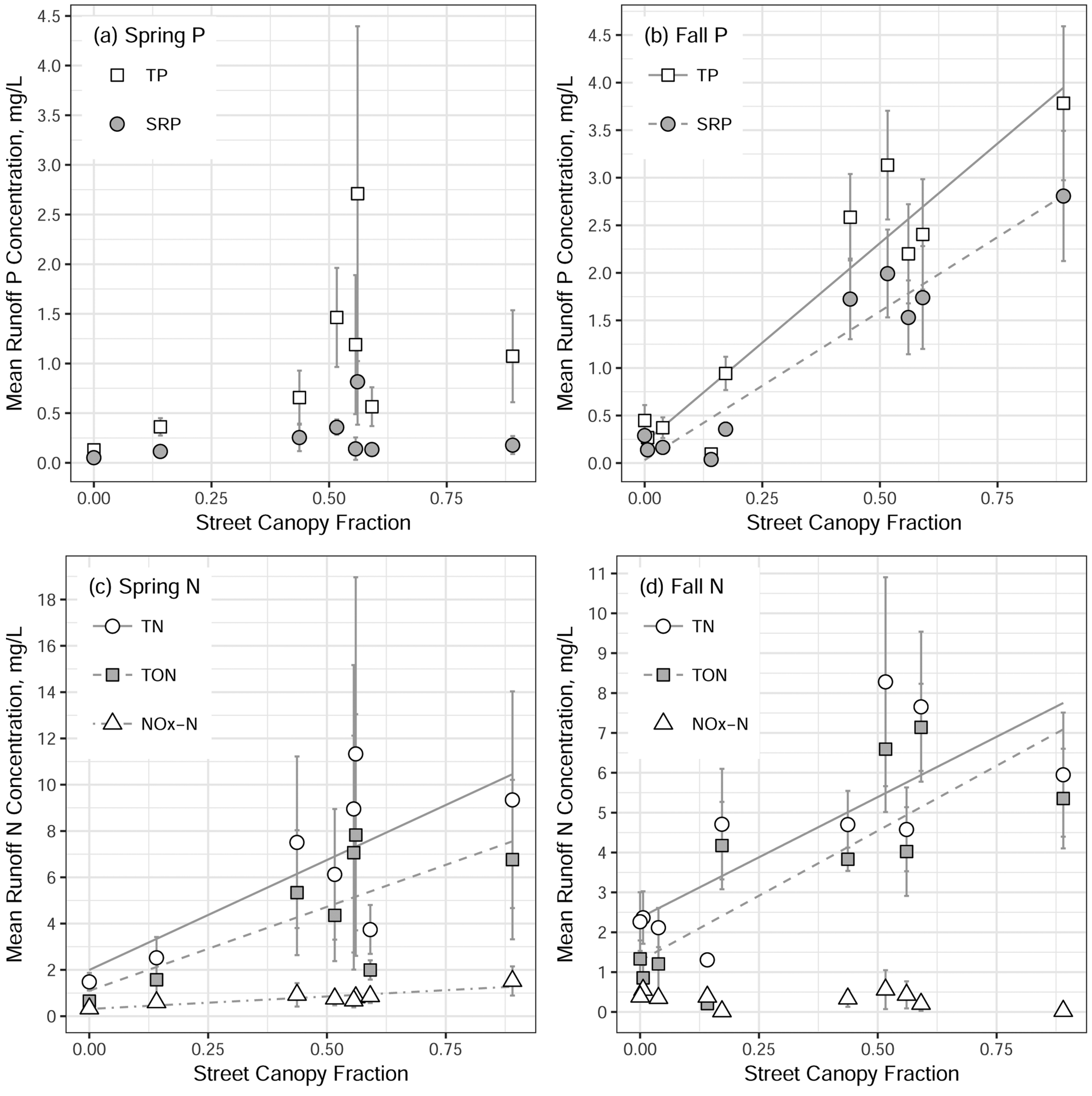


Figure 3. Concentrations of N and P (mean ± SE; mg/L) observed in street gutter runoff vs fraction of street covered by tree canopy during several rainfall events in late spring (leaf-out/flowering; $n = 3$ events) and in fall (leaf drop; $n = 6$ events) in the AHUG watershed: (a) Spring TP and SRP, (b) Fall TP and SRP, (c) Spring TN, TON, and NO_x–N, and (d) Fall TN, TON, and NO_x–N. Relationships for fall were significant ($r = 0.95, p < 0.001$ for TP; $r = 0.96, p < 0.001$ for SRP; $r = 0.77, p < 0.05$ for TN); for late spring, only N was significant ($r = 0.75, p < 0.05$ for TN; $r = 0.73, p < 0.05$ for TON; $r = 0.88, p < 0.05$ for NO_x–N).

Near-street lawns are one potential source of such background nutrients to stormwater, due to their ubiquity in residential watersheds. Lawns can contribute to P losses via erosion and leaching during snowmelt periods and intensive rainfall,[39,54] and potentially to N losses from excess fertilizer application.[55] In addition, lawn fertilizer was found to be the greatest source of new N to some of the study watersheds by Hobbie et al.[3] Our analyses suggest that during warm-season rainfall, lawns and associated soils did not vary much across watersheds as sources of N and P, as an approximation of lawn area (low-density residential area) was not correlated to runoff concentrations of N or P (SLR; Table S3), and was only a minor component (by η^2)

of the top models for TN, TON, and TDP (MLR; Table 3). Lawns tend to border most streets in the study areas, so we expect that near-street lawn cover across sites was less variable than street canopy cover.

For dissolved nutrient forms, and N in particular, atmospheric deposition is another potential source of background nutrients to stormwater. In this study, significant relationships of inorganic N with TIA (NO_x−N and NH_4−N) and with street density (NH_4−N) suggest that vehicle-derived emissions or other sources of atmospheric deposition contributed inorganic N to stormwater (Table S3), consistent with recent studies that identified vehicle emissions as a major input of inorganic N to roadways.[36,56] However, N deposited onto streets likely played a minor role in N loading, as stormwater N yields were dominated by organic forms (76%) and regression analyses showed traffic volume to be a weak predictor of N (Table S3). If atmospheric deposition was the primary source of inorganic N to study watersheds, then the observed negative relationship between watershed vegetation and concentrations of inorganic N may indicate that vegetated landscapes retain more deposited N than less vegetated areas (e.g., through canopy capture, denitrification, or assimilation).[57]

By contrast with traffic volume and residential area, population density was significantly related to dissolved P and N in our analyses (SLR, Table S3; MLR, Table 3). Although dissolved forms were relatively minor components of TP and TN (<25%), these results suggest the presence of additional nutrient sources to stormwater associated with human habitation. Human activities that could contribute nutrients to stormwater include high rates of fertilizer use or pet ownership and associated pet waste deposition in the landscape, both of which could contribute disproportionately to nutrient losses to stormwater. Both fertilizer and pet waste have been identified as substantial new inputs of nutrients to watersheds in the TCMA.[3,58] Further work will be necessary to better understand the relative magnitude of nontree nutrient inputs to the urban landscape.

Street Tree Effects on Nutrient Loading in the Context of Altered Urban Hydrology. The intensity of urban drainage, assessed using street density and several measures of impervious area, strongly influenced runoff volume and nutrient export across sites with loading data (n = 12). Variation in runoff depth (water yield) was significantly and positively related to street density ($r = 0.88$, $p < 0.001$), street area ($r = 0.87$, $p < 0.001$), and total impervious area ($r = 0.81$, $p < 0.05$) in SLR, with similar relationships for runoff coefficient (Table S3). Nutrient yields were largely determined by runoff volume; as a consequence, mean event yields of all forms of N and P were also strongly related to street density (and to TIA) in SLR (Table S3; Figure S2). Street density emerged as the most crucial drainage factor for water and nutrient yields in the MLR analysis, being the lone factor in the top models by AIC_c for all yields (Table 3). The importance of street density for loading suggests that configuration of the most directly connected impervious surfaces (streets) controls runoff volume to a greater extent than total impervious area, as found by previous studies.[53,59−62]

The influence of streets on runoff means that the lawn-street interface may have a disproportionate effect on stormwater nutrient loading: landscape inputs to streets and gutters, such as soil, leaves, and grass clippings, are eventually exported in runoff, as streets offer little opportunity for retention and transformation compared to pervious surfaces. Accordingly, the tree cover directly over the street had the strongest influence on nutrient concentrations, and relationships weakened slightly with measures of tree canopy in larger buffers adjacent to streets (Table S3). This pattern implies that nutrients in litterfall from trees further from streets have more opportunity to be trapped in lawns or removed via management (e.g., raking or mowing) before reaching streets.

Street trees had positive effects on N and P EMCs in this study, and trees have been shown to reduce runoff volume in field observations and model studies elsewhere.[28,29,63] These effects of trees on EMCs and runoff volume should have opposing influences on nutrient loading, and accordingly, neither street canopy nor total vegetation were significant factors in multivariate analyses of nutrient loading. Among the best MLR models by AIC_c and/or Adj. R^2, street canopy was a factor only for water yield (and not for any nutrients), provided little additional variance explained ($\eta^2 = 0.06$), and was not a significant term ($p = 0.14$; Table S4).

However, our ability to determine the combined effects of trees on nutrient loading via effects on EMCs and water runoff volumes was limited by the low sample size in our loading data set ($n = 12$ sites), and especially by the covariance of street canopy cover with street density and stormwater volume. To better assess the influence of tree canopies on stormwater nutrient and water loading, we used nutrient yield models based on MLRs, developed separately to quantify street canopy effects on nutrient concentration versus on water yields (Figure 4; SI). These models demonstrate that street canopy increases nutrient loads to a greater extent at higher values of street density. This effect is also more pronounced for P than for N, due to stronger relationships between concentrations and street canopy for P. A complete explanation for this stronger effect of canopy on P concentrations is not apparent, but may be caused in part by greater importance of noncanopy nutrient sources (e.g., atmospheric deposition, vehicle emissions) for N compared to P.

The models also suggest that a development threshold exists at a street density of ∼10 km/km^2 for TP, and at ∼14 km/km^2 for TN. Below this point, higher street canopy would provide net load reduction via reduced runoff. For example, at a street density of 8 km/km^2, a watershed with a high street canopy fraction (0.45) has a modeled TP EMC (0.45 mg/L) that is roughly double the value (0.22 mg/L) for a low-canopy case (fraction = 0.05), but has a runoff yield that is roughly one-third of that predicted for the low-canopy case (0.11 cm vs 0.30 cm). As a result, modeled event TP yield was 0.48 kg/km^2 for the high-canopy case, roughly 28% lower than for the low-canopy case (0.66 kg/km^2). The opposite pattern (i.e., higher loading for increased canopy cover) is present at higher street density. These results require further investigation, but suggest that the minor volume reduction potentially provided by high levels of street canopy does not substantially offset the enhanced nutrient loading associated with street trees in watersheds with high street density.

Implications for Management. The strong positive relationships between tree canopy cover and stormwater concentrations of N and P, observed across a wide range of scales (3 orders of magnitude of drainage area) and ages of development (approximately 20 to 100 years old) in this study, imply that substantial decreases in nutrient loading to urban lakes and streams could be accomplished through management strategies targeting trees and leaf litter. Such strategies could include enhanced municipal street sweeping operations[34,64,65] and yard waste removal,[66] or strategic placement of trees away from roadways to minimize nutrient transport into streets. Enhanced municipal sweeping, for example, could include more frequent sweeping directed at high-canopy areas during leaf-out

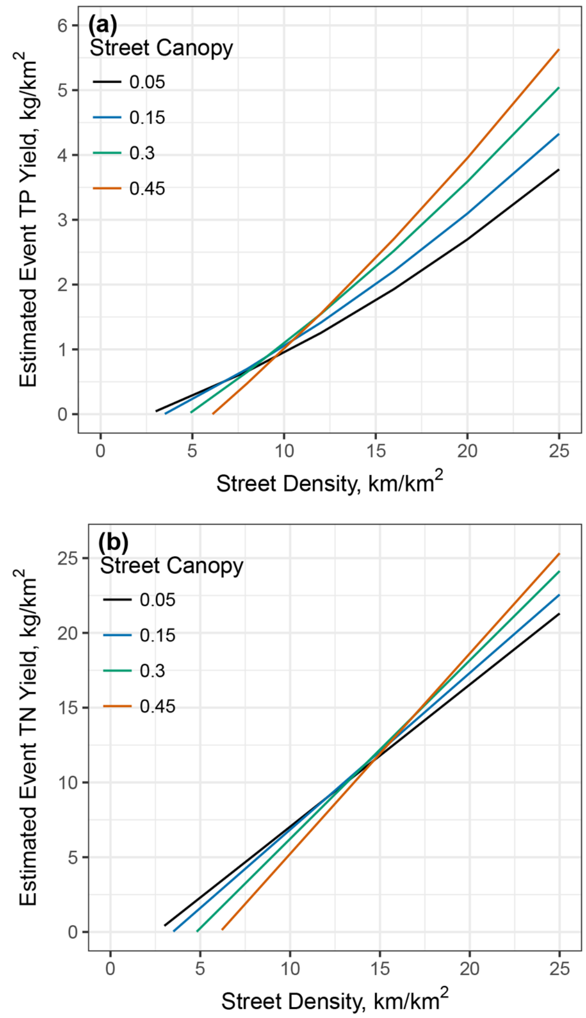


Figure 4. Estimated mean event yields (kg/km^2) of (a) TP and (b) TN, as a function of street density (km/km^2) for fixed levels of street canopy cover. Yields were estimated from the product of event mean concentration (mg/L) and event mean water yield (cm) across a gradient of street density with four levels of street canopy that spanned the ranges observed in this study (Tables S4 and S5).

and leaf-drop periods (the timing of which may vary year to year), with densely developed watersheds in particular having more to gain from management of trees and litter inputs to streets because of their extensive street and impervious cover. Street sweeping that targets litter removal during fall may also be important to prevent snowmelt export of N and P from overwinter leaf decomposition.[50] Adaptive sweeping practices are currently uncommon, but will be necessary to prevent negative water quality effects of increasing tree canopy cover in many cities.

Trees and vegetation do not represent "new" sources of nutrients to urban watersheds, but provide a mechanism of nutrient transport from landscape to street, and thus to urban lakes and streams. Therefore, any improvements in street sweeping practices must be implemented alongside efforts to manage urban watersheds to address eutrophication and other impacts of urbanization on aquatic ecosystems. In particular, continued efforts at the watershed scale to reduce or control nutrient inputs to the landscape are also needed in order to improve urban water quality.[1,11,67,68] Reductions in impervious cover (e.g., via street narrowing or installation of pervious pavement), as well as traditional management such as capture and infiltration of stormwater runoff (especially in more distributed forms as part of green infrastructure[12,14]), are critical for reducing water and nutrient runoff and mitigating downstream impacts of altered flow regimes.[10,69,70]

Ultimately, decision-making related to urban forests must consider the many benefits provided by trees—evaporative and shade cooling, improved air quality, better mental health, reduction of crime, and reduced leaching of nutrients to groundwater, among other benefits[71−75]—along with the potential costs of nutrient transport to stormwater shown in this study. Comprehensive study of the effects of green infrastructure, including trees, on urban ecosystem function should guide management toward the most effective actions to reduce nutrient pollution while allowing expansion of urban tree cover in new residential development, redevelopment in older cities, and as urban forests change following pest and disease outbreaks such as emerald ash borer or oak wilt.

■ ASSOCIATED CONTENT

Ⓢ Supporting Information

The Supporting Information is available free of charge on the ACS Publications website at DOI: 10.1021/acs.est.7b02225.

> Description of derived land cover and drainage metrics used to characterize potential nutrient sources to stormwater, tables describing monitoring data sources and metrics used in analyses, figure of monthly mean nutrient concentrations (mg/L), table of simple linear regression (SLR) results, figure showing event water (cm) and nutrient (kg/km^2) yields vs street density, description of multiple linear regression (MLR) analysis, table of coefficients and statistical parameters for best MLR model for concentration of each nutrient and water yield, figures showing fits of these best models vs observations, and description of model constructed for yields of TP and TN as a function of street canopy and street density (PDF)

■ AUTHOR INFORMATION

Corresponding Author

*Phone: 612-716-6012; e-mail: janke024@umn.edu (B.D.J.).

ORCID

Benjamin D. Janke: 0000-0003-1501-4782

Notes

The authors declare no competing financial interest.

■ ACKNOWLEDGMENTS

This study could not have been possible without the sustained efforts of committed people, agencies and residents of the cities involved in this study. We especially acknowledge Joe Knight (UMN), Britta Belden and Bob Fossum (CRWD), Mike Perniel (MPRB), Stephanie Johnson and Jen Keville (MWMO), John Loomis (SWWD), and Erik Anderson (WCD) for assistance in data acquisition and for their knowledge of the data sets and watersheds included in this study. We acknowledge Michelle Rorer and Sandra Brovold for analyzing water samples at UMN. We gratefully acknowledge financial support from CRWD, SWWD, the University of Minnesota Water Resources Center (Project ID: 2012MN314B), and the University of Minnesota Institute on the Environment (Project IDs: DG-0008-11 and DG-0007-14).

REFERENCES

(1) Bernhardt, E. S.; Band, L. E.; Walsh, C. J.; Berke, P. E. Understanding, managing, and minimizing urban impacts on surface water nitrogen loading. *Ann. N. Y. Acad. Sci.* **2008**, *1134*, 61–96.

(2) Dubrovsky, N. M.; Burow, K. R.; Clark, G. M.; Gronberg, J. M.; Pa, H.; Hitt, K. J.; Mueller, D. K.; Munn, M. D.; Nolan, B. T.; Puckett, L. J. *The Quality of our Nation's Waters—Nutrients in the Nation's Streams and Groundwater, 1992–2004*; 2010.

(3) Hobbie, S. E.; Finlay, J. C.; Janke, B. D.; Nidzgorski, D. A.; Millet, D. B.; Baker, L. A. Contrasting nitrogen and phosphorus budgets in urban watersheds and implications for managing urban water pollution. *Proc. Natl. Acad. Sci. U. S. A.* **2017**, *114* (20), 4177–4182.

(4) Carle, M. V.; Halpin, P. N.; Stow, C. A. Patterns of Watershed Urbanization and Impacts on Water Quality. *J. Am. Water Resour. Assoc.* **2005**, *41* (3), 693–708.

(5) Walsh, C. J.; Roy, A. H.; Feminella, J. W.; Cottingham, P. D.; Groffman, P. M.; Morgan, R. P., II The urban stream syndrome: current knowledge and the search for a cure. *J. North Am. Benthol. Soc.* **2005**, *24* (3), 706–723.

(6) Elmore, A. J.; Kaushal, S. S. Disappearing headwaters: Patterns of stream burial due to urbanization. *Front. Ecol. Environ.* **2008**, *6* (6), 308–312.

(7) Steele, M. K.; Heffernan, J. B. Morphological characteristics of urban water bodies: mechanisms of change and implications for ecosystem function. *Ecol. Appl.* **2014**, *24* (5), 1070–1084.

(8) Carpenter, S.; Caraco, N.; Correll, D. L.; Howarth, R. W.; Sharpley, A. N.; Smith, V. H. Nonpoint pollution of surface waters with phosphorus and nitrogen. *Ecol. Appl.* **1998**, *8* (3), 559–568.

(9) National Research Council. *Urban Stormwater Management in the United States*; The National Academies Press: Washington, DC, 2009.

(10) Walsh, C. J.; Booth, D. B.; Burns, M. J.; Fletcher, T. D.; Hale, R. L.; Hoang, L. N.; Livingston, G.; Rippy, M. A.; Roy, A. H.; Scoggins, M.; Wallace, A. Principles for urban stormwater management to protect stream ecosystems. *J. Freshw. Sci.* **2016**, *35* (1), 398–411.

(11) Carey, R. O.; Hochmuth, G. J.; Martinez, C. J.; Boyer, T. H.; Dukes, M. D.; Toor, G. S.; Cisar, J. L. Evaluating nutrient impacts in urban watersheds: Challenges and research opportunities. *Environ. Pollut.* **2013**, *173*, 138–149.

(12) Loperfido, J. V.; Noe, G. B.; Jarnagin, S. T.; Hogan, D. M. Effects of distributed and centralized stormwater best management practices and land cover on urban stream hydrology at the catchment scale. *J. Hydrol.* **2014**, *519* (PC), 2584–2595.

(13) Burns, M. J.; Fletcher, T. D.; Walsh, C. J.; Ladson, A. R.; Hatt, B. E. Hydrologic shortcomings of conventional urban stormwater management and opportunities for reform. *Landsc. Urban Plan.* **2012**, *105* (3), 230–240.

(14) Pennino, M. J.; McDonald, R. I.; Jaffe, P. R. Watershed-scale impacts of stormwater green infrastructure on hydrology, nutrient fluxes, and combined sewer overflows in the mid-Atlantic region. *Sci. Total Environ.* **2016**, *565*, 1044–1053.

(15) Sansalone, J.; Raje, S.; Kertesz, R.; Maccarone, K.; Seltzer, K.; Siminari, M.; Simms, P.; Wood, B. Retrofitting impervious urban infrastructure with green technology for rainfall-runoff restoration, indirect reuse and pollution load reduction. *Environ. Pollut.* **2013**, *183*, 204–212.

(16) Tzoulas, K.; Korpela, K.; Venn, S.; Yli-Pelkonen, V.; Kaźmierczak, A.; Niemela, J.; James, P. Promoting ecosystem and human health in urban areas using Green Infrastructure: A literature review. *Landsc. Urban Plan.* **2007**, *81* (3), 167–178.

(17) Gaffin, S. R.; Rosenzweig, C.; Kong, A. Y. Y. Adapting to climate change through urban green infrastructure. *Nat. Clim. Change* **2012**, *2* (10), 704–704.

(18) Pataki, D. E.; Carreiro, M. M.; Cherrier, J.; Grulke, N. E.; Jennings, V.; Pincetl, S.; Pouyat, R. V.; Whitlow, T. H.; Zipperer, W. C. Coupling biogeochemical cycles in urban environments: Ecosystem services, green solutions, and misconceptions. *Front. Ecol. Environ.* **2011**, *9* (1), 27–36.

(19) Ellis, C. D.; Lee, S. W.; Kweon, B. S. Retail land use, neighborhood satisfaction and the urban forest: An investigation into the moderating and mediating effects of trees and shrubs. *Landsc. Urban Plan.* **2006**, *74* (1), 70–78.

(20) Sander, H.; Polasky, S.; Haight, R. G. The value of urban tree cover: A hedonic property price model in Ramsey and Dakota Counties, Minnesota, USA. *Ecol. Econ.* **2010**, *69* (8), 1646–1656.

(21) Peters, E. B.; McFadden, J. P. Influence of seasonality and vegetation type on suburban microclimates. *Urban Ecosyst.* **2010**, *13* (4), 443–460.

(22) Pandit, R.; Laband, D. N. A Hedonic Analysis of the Impact of Tree Shade on,Summertime Residential Energy Consumption. *Arborculture Urban For.* **2011**, *37* (1), 13–18.

(23) Pincetl, S. Implementing municipal tree planting: Los Angeles million-tree initiative. *Environ. Manage.* **2010**, *45* (2), 227–238.

(24) McPhearson, P. T.; Feller, M.; Felson, A.; Karty, R.; Lu, J. W. T.; Palmer, M. I.; Wenskus, T. Assessing the Effects of the Urban Forest Restoration Effort of MillionTreesNYC on the Structure and Functioning of New York City Ecosystems. *Cities Environ. CATE* **2010**, *3* (1), 1–21.

(25) Xiao, Q.; McPherson, E. G. Performance of engineered soil and trees in a parking lot bioswale. *Urban Water J.* **2011**, *8* (4), 241–253.

(26) Armson, D.; Stringer, P.; Ennos, A. R. The effect of street trees and amenity grass on urban surface water runoff in Manchester, UK. *Urban For. Urban Green.* **2013**, *12* (3), 282–286.

(27) Denman, E. C.; May, P. B.; Moore, G. M. The Potential Role of Urban Forests in Removing Nutrients from Stormwater. *J. Environ. Qual.* **2016**, *45* (1), 207.

(28) Sanders, R. A. Urban vegetation impacts on the hydrology of Dayton, Ohio. *Urban Ecol.* **1986**, *9* (3–4), 361–376.

(29) Wang, J.; Endreny, T. A.; Nowak, D. J. Mechanistic simulation of tree effects in an urban water balance model. *J. Am. Water Resour. Assoc.* **2008**, *44* (1), 75–85.

(30) Kuehler, E.; Hathaway, J.; Tirpak, A. Quantifying the Benefits of Urban Forest Systems as a Component of the Green Infrastructure Stormwater Treatment Network. *Ecohydrology* **2017**, *10*, e1813.

(31) Berland, A.; Shiflett, S. A.; Shuster, W. D.; Garmestani, A. S.; Goddard, H. C.; Herrmann, D. L.; Hopton, M. E. The role of trees in urban stormwater management. *Landsc. Urban Plan.* **2017**, *162*, 167–177.

(32) Waschbusch, R. J.; Selbig, W. R.; Bannerman, R. T. *Sources of phosphorus in stormwater and street dirt from two urban residential basins in Madison, Wisconsin, 1994–95. USGS Water Resources Investigations Report 99–4021*; Middleton, WI, 1999.

(33) Easton, Z. M.; Petrovic, A. M. Determining Phosphorus Loading Rates Based on Land Use in an Urban Watershed. *Fate Nutr. Pestic. Urban Environ.* **2008**, *997* (997), 19–42.

(34) Selbig, W. R. Evaluation of leaf removal as a means to reduce nutrient concentrations and loads in urban stormwater. *Sci. Total Environ.* **2016**, *571*, 124–133.

(35) Hobbie, S. E.; Baker, L. A.; Buyarski, C.; Nidzgorski, D.; Finlay, J. C. Decomposition of tree leaf litter on pavement: Implications for urban water quality. *Urban Ecosyst.* **2014**, *17* (2), 369–385.

(36) Bettez, N. D.; Marino, R.; Howarth, R. W.; Davidson, E. A. Roads as nitrogen deposition hot spots. *Biogeochemistry* **2013**, *114* (1–3), 149–163.

(37) Rao, P.; Hutyra, L. R.; Raciti, S. M.; Templer, P. H. Atmospheric nitrogen inputs and losses along an urbanization gradient from Boston to Harvard Forest, MA. *Biogeochemistry* **2014**, *121* (1), 229–245.

(38) Morton, T. G.; Gold, a. J.; Sullivan, W. M. Influence of Overwatering and Fertilization on Nitrogen Losses from Home Lawns. *J. Environ. Qual.* **1988**, *17* (1), 124–130.

(39) Bierman, P. M.; Horgan, B. P.; Rosen, C. J.; Hollman, A. B.; Pagliari, P. H. Phosphorus Runoff from Turfgrass as Affected by Phosphorus Fertilization and Clipping Management. *J. Environ. Qual.* **2010**, *39* (1), 282–292.

(40) Janke, B. D.; Finlay, J. C.; Hobbie, S. E.; Baker, L. A.; Sterner, R. W.; Nidzgorski, D.; Wilson, B. N. Contrasting influences of stormflow and baseflow pathways on nitrogen and phosphorus export from an urban watershed. *Biogeochemistry* **2014**, *121* (1), 209–228.

(41) Minnesota Department of Natural Resources. Minneapolis/St. Paul Climate Data: Normals and Averages www.dnr.state.mn.us/climate/twin_cities/normals.html (accessed Nov 10, 2016).

(42) Janke, B. D. *Nutrient Load Estimation and Analysis of Water Quality Monitoring Data from the South Washington Watershed District, 2000–2014*; Woodbury, MN, 2015, https://www.swwdmn.org/pdf/UMNfinalmonitoringreport.pdf.

(43) MCES. *Metropolitan Council Environmental Services Quality Assurance Program Plan: Stream Monitoring.* https://metrocouncil.org/Wastewater-Water/Publications-And-Resources/WATER-QUALITY-MONITOR-ASSESS/Stream-Monitoring-QAPP_Revised_0111_Web_Reduced-pd.aspx; St. Paul, MN, 2011.

(44) Maestre, A.; Pitt, R. *The National Stormwater Quality Database, Version 1.1: A Compilation and Analysis of NPDES Stormwater Monitoring Information*; Center for Watershed Protection, Ellicott City, MD, 2005.

(45) Brezonik, P. L.; Stadelmann, T. H. Analysis and predictive models of stormwater runoff volumes, loads, and pollutant concentrations from watersheds in the Twin Cities metropolitan area, Minnesota, USA. *Water Res.* **2002**, *36* (7), 1743–1757.

(46) Payne, G. A.; Ayers, M. A.; Brown, R. G. *Quality of Runoff From Small Watersheds in the Twin Cities Metropolitan Area, Minnesota—Hydrologic Data for 1980. Open-File Report 82–504.*; St. Paul, MN, 1982.

(47) Fletcher, T. D.; Andrieu, H.; Hamel, P. Understanding, management and modelling of urban hydrology and its consequences for receiving waters: A state of the art. *Adv. Water Resour.* **2013**, *51*, 261–279.

(48) Mejía, A. I.; Moglen, G. E. Impact of the spatial distribution of imperviousness on the hydrologic response of an urbanizing basin. *Hydrol. Process.* **2010**, *24* (23), 3359–3373.

(49) Burnham, K. P.; Anderson, D. R. *Model Selection and Multimodel Inference: A Practical Information–Theoretic Approach*, 2nd ed.; Springer: New York, 2002; Vol. *172*.

(50) Bratt, A. R.; Finlay, J. C.; Hobbie, S. E.; Janke, B. D.; Worm, A. C.; Kemmitt, K. L. Contribution of leaf litter to nutrient export during winter months in an urban residential watershed. *Environ. Sci. Technol.* **2017**, *51* (6), 3138–3147.

(51) Uselman, S. M.; Qualls, R. G.; Lilienfein, J. Quality of soluble organic C, N, and P produced by different types and species of litter: Root litter versus leaf litter. *Soil Biol. Biochem.* **2012**, *54*, 57–67.

(52) Dorney, J. R. Leachable and total phosphorous in urban street tree leaves. *Water. Air. Soil Pollut.* **1986**, *28* (3), 439–443.

(53) Beck, S. M.; McHale, M. R.; Hess, G. R. Beyond Impervious: Urban Land-Cover Pattern Variation and Implications for Watershed Management. *Environ. Manage.* **2016**, *58* (1), 15–30.

(54) Soldat, D. J.; Petrovic, A. M. The fate and transport of phosphorus in turfgrass ecosystems. *Crop Sci.* **2008**, *48* (6), 2051–2065.

(55) Carey, R. O.; Hochmuth, G. J.; Martinez, C. J.; Boyer, T. H.; Nair, V. D.; Dukes, M. D.; Toor, G. S.; Shober, A. L.; Cisar, J. L.; Trenholm, L. E.; et al. A review of turfgrass fertilizer management practices: Implications for urban water quality. *Horttechnology* **2012**, *22* (3), 280–291.

(56) Davidson, E. A.; Savage, K. E.; Bettez, N. D.; Marino, R.; Howarth, R. W. Nitrogen in runoff from residential roads in a coastal area. *Water, Air, Soil Pollut.* **2010**, *210* (1–4), 3–13.

(57) Raciti, S. M.; Burgin, A. J.; Groffman, P. M.; Lewis, D. N.; Fahey, T. J. Denitrification in Suburban Lawn Soils. *J. Environ. Qual.* **2011**, *40* (6), 1932–1940.

(58) Fissore, C.; Hobbie, S. E.; King, J. Y.; McFadden, J. P.; Nelson, K. C.; Baker, L. A. The residential landscape: Fluxes of elements and the role of household decisions. *Urban Ecosyst.* **2012**, *15* (1), 1–18.

(59) Roy, A. H.; Shuster, W. D. Assessing impervious surface connectivity and applications for watershed management. *J. Am. Water Resour. Assoc.* **2009**, *45* (1), 198–209.

(60) Han, W. S.; Burian, S. J. Determining effective impervious area for urban hydrologic modeling. *J. Hydrol. Eng.* **2009**, *14* (2), 111–120.

(61) Ebrahimian, A.; Wilson, B. N.; Gulliver, J. S. Improved methods to estimate the effective impervious area in urban catchments using rainfall-runoff data. *J. Hydrol.* **2016**, *536*, 109–118.

(62) Hatt, B. E.; Fletcher, T. D.; Walsh, C. J.; Taylor, S. L. The influence of urban density and drainage infrastructure on the concentrations and loads of pollutants in small streams. *Environ. Manage.* **2004**, *34* (1), 112–124.

(63) Xiao, Q.; Mcpherson, E. G. Rainfall interception by Santa Monica's municipal urban forest. *Urban Ecosyst.* **2002**, *6*, 291–302.

(64) Kalinosky, P. M. *Quantifying Solids and Nutrient Recovered Through Street Sweeeping in a Suburban Watershed*; University of Minnesota, 2015.

(65) Selbig, W. R.; Bannerman, R. T. Evaluation of Street Sweeping as a Stormwater-Quality-Management Tool in Three Residential Basins in Madison, Wisconsin. *USGS Sci. Investig. Rep. 2007* **2007**.

(66) Templer, P. H.; Toll, J. W.; Hutyra, L. R.; Raciti, S. M. Nitrogen and carbon export from urban areas through removal and export of litterfall. *Environ. Pollut.* **2015**, *197*, 256–261.

(67) Kaushal, S. S.; McDowell, W. H.; Wollheim, W. M. Tracking evolution of urban biogeochemical cycles: past, present, and future. *Biogeochemistry* **2014**, *121* (1), 1–21.

(68) Collins, K. A.; Lawrence, T. J.; Stander, E. K.; Jontos, R. J.; Kaushal, S. S.; Newcomer, T. A.; Grimm, N. B.; Cole Ekberg, M. L. Opportunities and challenges for managing nitrogen in urban stormwater: A review and synthesis. *Ecol. Eng.* **2010**, *36* (11), 1507–1519.

(69) Hamel, P.; Daly, E.; Fletcher, T. D. Source-control stormwater management for mitigating the impacts of urbanisation on baseflow: A review. *J. Hydrol.* **2013**, *485*, 201–211.

(70) Barbosa, A. E.; Fernandes, J. N.; David, L. M. Key issues for sustainable urban stormwater management. *Water Res.* **2012**, *46* (20), 6787–6798.

(71) Mcpherson, G.; Simpson, J. R.; Peper, P. J.; Maco, S. E.; Xiao, Q. Municipal Forest Benefits and Costs in Five US Cities. *J. For.* **2005**, *103*, 411–416.

(72) Chen, W. Y.; Jim, C. Y. Ecology, Planning, and Management of Urban Forests. In Wendy, Y.; Chen, C. In *Ecology, Planning, and Management of Urban Forests: International Perspectives*; **2008**; pp 53–83,10.1007/978-0-387-71425-7_5

(73) Bolund, P.; Hunhammar, S. Ecosystem services in urban areas. *Ecol. Econ.* **1999**, *29* (2), 293–301.

(74) Salmond, J. A.; Tadaki, M.; Vardoulakis, S.; Arbuthnott, K.; Coutts, A.; Demuzere, M.; Dirks, K. N.; Heaviside, C.; Lim, S.; Macintyre, H.; et al. Health and climate related ecosystem services provided by street trees in the urban environment. *Environ. Health* **2016**, *15* (S1), 36.

(75) Nidzgorski, D. A.; Hobbie, S. E. Urban trees reduce nutrient leaching to groundwater. *Ecol. Appl.* **2016**, *26* (5), 1566–1580.