Quantifying Solids and Nutrient Recovered Through Street Sweeping in a Suburban Watershed

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Abstract

Solids that collect on street surfaces are comprised of varying proportions of inorganic particles ranging in size from silt and clays to gravels, vegetative and other organic material, trash, and a host of pollutants deposited from surface runoff and atmospheric sources (ex. car exhaust). This material has alternatively been called ‘street dust’ ‘street dirt’, ‘street dirt’, ‘road sediments’, ‘street particulate matter’ or ‘SPaM’, ‘urban particulate matter’, or simply referred to as ‘gross solids’. Whatever name it goes by, it is a significant source of pollution to urban stormwater and one mean of limiting this source is street sweeping.

The coarse organic component of street particulate matter (leaves, grass clippings, and other vegetative matter) is not well characterized in existing street sweeping literature. Coarse organic debris that enters storm sewers can accumulate in catch basins and pipes, or be transported into streams, lakes, and rivers, releasing nutrients along the way as it decomposes. The primary objectives of the study were to quantify the influence of tree canopy (a source of organic debris), season, and street sweeping frequency on the quantity of solids and nutrients recovered from streets through street sweeping.

We measured the total solids and nutrient loads (TP, TN, TOC) recovered in 392 street sweeping operations over a 2-year period in residential areas of Prior Lake, MN. Coarse organic material was separated from finer, soil-like material through dry sieving followed by density separation (floating the material retained on the sieve in a water bath). Chemical analysis (total phosphorus, TP, total nitrogen, TN, total organic carbon, TOC, % moisture, and % organic matter, %OM) was carried out on each fraction.

Coarse organic material made up 15% of the total dry weight of swept material collected during the study, but 36% of the TP and 71% of the TN. Percent overhead tree canopy cover was a significant predictor of average recoverable loads of coarse organic material and associated nutrients in all months of the year. Sweeping frequency was a significant predictor of total recoverable loads in several months of the year. Seasonal influences were apparent in both fractions of sweepings. The loading intensity (kg/curb-meter) of fines was greatest in the early spring immediately following snow melt and the loading intensity of coarse organic matter was greatest in October during fall leaf litter drop. Fresh coarse organics recovered during May had a significantly higher leaching potential than coarse organics collected at other times of the year.

Regression analysis was used to develop predictive metrics for planning sweeping operations. The regressions predict the average expected solids and nutrient recovery by month, sweeping frequency, and tree canopy cover. Metrics for tracking total phosphorus (TP) and total nitrogen (TN) recovery based on the mass of sweepings collected were also developed based on study findings.

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1.1 Summary

Coarse organic matter (leaves, grass clippings) that finds its way onto streets contributes nutrients to stormwater runoff, and eventually makes its way into storm sewers, unless removed by street sweeping. Once in storm sewers, this material can accumulate in catch basins and pipes, or be transported into streams, lakes, and rivers, releasing nutrients along the way as it decomposes. This study was designed to quantify the influence of tree canopy (a source of organic debris), season, and street sweeping frequency on the quantity of solids and nutrients (total phosphorus, total nitrogen and total organic carbon) recovered from streets through street sweeping.

We measured the total solids and nutrient loads (TP, TN, TOC) recovered in 392 street sweeping operations over a 2-year period in residential areas of Prior Lake, MN. Coarse organic material was separated from finer, soil-like material through dry sieving followed by density separation (floating the material retained on the sieve in a water bath). Chemical analysis (total phosphorus, TP, total nitrogen, TN, total organic carbon, TOC, % moisture, and % organic matter, %OM) was carried out on each fraction. Coarse organic material made up 15% of the total dry weight of swept material collected during the study, but 36% of the TP and 71% of the TN. Percent overhead tree canopy cover was a significant predictor of average recoverable loads of coarse organic material and associated nutrients in all months of the year. Sweeping frequency was a significant

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1.2 Introduction

Street particulate matter (PM), the heterogeneous material that collects on street surfaces, is a source of both suspended solids and dissolved pollutants in urban stormwater. Because streets are connected to stormwater conveyance systems and ultimately to natural surface waters, a reasonable understanding of the character and typical yield of gross solids that collect on streets is necessary for design of adequate stormwater infrastructure and maintenance practices. A number of factors can influence the character and quantity of particulate matter that collects on a given street: pavement type and condition, traffic volume, maintenance practices, precipitation, and land use type among others. One factor that has not been well investigated is the influence of tree canopy cover on street PM. It seems intuitive that spring and fall loading of leaf and other types of plant litter to streets, and consequently to total solids and nutrient loads, would be greater when streets are located in areas with dense vegetation. Yet, due either to limited collection times that excluded fall leaf litterfall or to fractionation schemes that excluded the majority of plant material; previous studies have not quantified the influence of tree canopy on solids and nutrient loads to street.

The Prior Lake Street Sweeping Experiment was undertaken to quantify the influence of three factors - tree canopy, sweeping frequency, and season - on the composition and quantity of street PM recovered through street sweeping, i.e. sweeper waste. Due to limits in the pick-up efficiency of street sweepers, sweeper waste is not the equivalent of street particulate matter, but rather a subset of it. Confusing the matter, naming conventions for these materials are inconsistent. The term ‘street particulate matter’ (street PM) is variously used in the literature to refer to material collected directly from streets by hand-sweeping, dry vacuuming, wet vacuuming, washing, or a combination thereof. The term ‘sweeper waste’ refers to material recovered from streets through street sweeping. Much of the work relevant to street sweeping research has focused not on sweeper waste, but on street particulate matter. In the literature review that follows, studies characterizing both sweeper waste and street PM are discussed side-by-side.

1.3 Street Particulate Matter and Sweeper Waste Characterization Studies

Previous studies have shown that factors influencing the composition and accumulation of street PM or sweeper waste include land use type, roadway type, season, position along the roadway, sweeping frequency, and antecedent dry period. Relevant findings of these studies are described in this section. Some background information on the character of street PM is also included for reference. Additional information on street sweeping research can be found in Appendix A.

Sartor and Boyd (1972) conducted one of the first comprehensive studies characterizing the composition and loading density of street PM. Street PM was collected in 12 urban centers across the county during 1970 and 1971. Street PM was sampled using both wet sampling (simulated rainfall, flushing) and dry sampling (contemporary vacuum street sweeper, hand sweeping). Samples representing different land use/density classifications were collected from each urban center in a single month between the months of December – July. Two months were sampled In San Jose and Phoenix.

Sartor and Boyd found that street PM was composed mainly of inorganic material such as sand and silt and that the finest fraction (particles < 43 µm) contained a disproportionate amount of the overall pollution load. This fraction was typically about 6% of the total solids mass, but contained one-fourth the total chemical oxygen demand (COD), one-third to one-half of the nutrients, and significant percentages of heavy metals that were present. They found that the loading density (mass per linear distance of curb or per area of street) of total solids on the street varied considerably from site to site, but a few factors - land use type, roadway type, and roadway condition - had quantifiable influences on loading density. Average total solids loading intensities were greater for industrial land use types (range 900-4,000 lb/curb-mile, or 0.25-1.1 kg/curb-meter), than for commercial and residential land use types (range 300-1300 lb/curb-mile, or 0.08-0.37 kg/curb-meter). Asphalt roads had an average 80% greater total solids loading than those paved with concrete, and roadways rated as being in “fair-to-poor” condition had average loading densities 2.5 times greater on average than those rated as being in “good-to-excellent” condition.

Over the years, a modest body of work has evolved on the topic of street PM. Some of this work supports general findings of Sartor and Boyd. For example, the finding that metal pollutants tend to be concentrated in the finest fraction of street PM has been confirmed in several studies (Pitt and Amy, 1973), (Durand et al., 2003), (Deletic and Orr, 2005), (Rochfort et al., 2009). Attempts to quantify influences on street PM accumulation and composition are summarized below. Information on sampling methods for a select set of street sweeping studies is provided in Appendix B.

> <u>Land Use</u> - Seattle Public Utilities (2009) collected both street PM and sweeper waste at three sites and found no statistically significant difference in the average dry mass yield (lb/acre/yr), total phosphorus (TP, mg/kg) content, or total Kjeldahl nitrogen (TKN, mg/kg) content of street PM or sweeper waste collected in residential and industrial land use areas. In a Florida-based study, street sweepings (and other types of urban PM) were collected from 3 land use categories in 11 MS4[1] (Berretta et al., 2011). The median TP concentration (mg/kg) of sweepings collected from commercial areas (381.2) was found to be slightly higher than those collected in residential land use (374.9) or highways (349.7), but in pairwise comparisons of sample groups, the only statistically significant difference that could be attributed to land use was a higher TKN content in residential areas (compared to commercial or highway land use). The presence of denser tree planting in residential areas was offered as a possible explanation for this difference.
>
> More recently, Sorenson (2013) found that the median yield of street PM (lb/curb-mile) in residential neighborhoods was 29% greater than the yield in

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[1] "Municipal Separate Storm Sewer System"

commercial neighborhoods in Cambridge, MA (samples collected over a two-year period across all seasons). Differences in the character of street PM samples from these land use areas were also reported. Compared to street PM sampled in commercial land use areas, the median organic content was about 2.5 times greater, and the total phosphorus mass in the medium size particle fraction was 11.5 time greater in street PM samples from residential areas. Denser tree canopy cover in residential neighborhoods is a potential explanation for both of these observations. Additional observations support this hypothesis - the ratio of coarse (>2mm) to fine (<0.125 mm) particulate mass and the rate of accumulation of coarse and medium (0.125-2 mm) particulates was higher in street PM samples from residential land use areas – but difference in tree canopy cover between the land use areas were not described in the study.

Roadway Type - Arterial roadways had higher total solids loading than residential streets for street PM samples taken from Minneapolis, MN prior to spring street cleaning ([X]-Absolute Value, 1996). The particle size distribution of street PM taken from these roadway types also varied with relatively equal mass fractions in fine (<425 μm), medium (<850 μm), and coarse (>850 μm) size ranges for arterial roadway, but a majority of street PM was in the coarse category for residential roadways.

Positions Along the Roadway - A majority of street PM typically collects within 1 ft (0.3 m) of the curb (Pitt and Amy, 1973), but the character of street PM may vary with season (discussed below) and with position along the roadway. In Aberdeen, Scotland, median particle diameter of samples collected near the center of the roadway was smaller (d_{50} = 55 μm) than for samples collected within 0.5 m of the curb ($d_{50} \approx 400$ μm) (Deletic and Orr, 2005). This study also measured differences in pollutant concentrations at four positions across the roadway and found that metals concentration were most often highest in the middle of the lane (2.5 m from the curb).

Season - The distribution of street PM may be influenced by winter road maintenance practices, spring weather, and vehicular action. Selbig and Bannerman (2007) measured higher street dirt yield in the spring (lb/curb-mile, hand vacuum collection), compared to summer and fall and documented an overall migration of street PM from the center lane (crown and driving lane) of the street in April to the curb lane (outer 3 ft) by June. In Aberdeen, Scotland, street PM loading was nearly three times the yearly average during the winter road maintenance ('salting'); metals concentrations in street PM were highest during the summer months (Deletic and Orr, 2005). Seasonal patterns in total street PM and constituent phosphorus yields were noted by Sorenseon (2013). Yields were greatest in during spring cleaning followed by fall with yields significantly reduced in spring and summer.

Antecedent Dry Period and Washoff/Washon Factors – The mass accumulation of pollutants on roadways depends on both the accumulation rate of pollutants during dry periods and the susceptibility of pollutants to washoff during wet weather. Given differences in sorption properties, solubility, and other physical and chemical characteristics, accumulation and washoff rates may vary among pollutant types (Kim et al., 2006; Wang et al., 2011). There may also be a net deposition of pollutants (deposition in excess of wash off) on roadways under wet weather conditions (Sutherland and Jelen, 1996; Sutherland and Jelen, 1997). The composition of street PM depends on both time elapsed and weather conditions since the last sweeping or significant washoff event.

Vegetation - Although there are no studies in the existing literature specifically addressing the topic, the influence of leaf litter and organic matter on the nutrient composition of street PM is often noted (Sartor and Boyd, 1972; Waschbusch et al. 1999; Seattle Public Utilities, 2009; Law et al. 2008; Sansalone and Rooney 2007; Minton and Sutherland 2010; Berretta et al., 2011). Several studies include observations or measurements that highlight the significance of vegetation as a source of street PM. High nutrient contents were noted when leaves were included in the analyzed portion of street PM samples (Waschbusch et al. 1999; Law et al., 2008), or in sediments associated with leaf fall timing (Seattle Public Utilities 2009). Waschbusch (1999) measured the nutrient contribution of leaves separated by hand from a limited number of street PM samples and found that while leaves made up < 10% of the total mass of the samples on average, they contributed approximately 30% of the total phosphorus. Leaves were the only fraction analyzed that had a total phosphorus contribution by percent that was significantly higher than its total mass contribution.

Leaves and organic debris were included in the analyzed portion of sweeping in Massachusetts (Sorenson, 2012). Although the mass contribution of organic debris was not quantified separately from fine (<0.125 mm), medium (0.125 mm–2 mm), and coarse (>2 mm) fractions of sweepings; organic debris was common in the coarse fraction. The median concentration of phosphorus in the coarse fraction of sweeping (800 mg/kg residential, 400 mg/kg commercial land use) was greater than or equivalent to the concentration in the medium fraction (500 mg/kg residential, 400 mg/kg commercial), but less than the concentration in the median concentration in the fine fraction (900 mg/kg residential, 800 mg/kg commercial).

1.4 Experimental Design

The Prior Lake Street Sweeping Experiment was conducted within the city limits of Prior Lake, Minnesota, in collaboration with the City of Prior Lake's Public Works Department. Sweeping was conducted during the entire snow-free season from August 10, 2010 to July 31, 2012. Prior to field work, public works staff completed a preliminary assessment of tree canopy cover using aerial photographs to divide the city into discrete zones classified as having 'high', 'medium', or 'low' tree canopy cover.

The City of Prior Lake also designed street sweeping routes for the study; performed all street sweeping; weighed sweeper loads; and collected sweeper waste samples for laboratory analysis.

A total of nine street sweeping routes, designed to be comparable in length, were designed by the City of Prior Lake (see for Appendix C details). Three sweeping routes were assigned in each tree canopy zone. Sweeping frequencies of 1x, 2x, and 4x per four-week sweeping rotation were assigned one each to high, medium and low tree canopy area routes resulting in a 3 x 3 (frequency x cover)experimental design. A naming convention for the routes using the letters H, M, L to represent canopy type and 1, 2 or 4 to represent sweeping frequency was adopted for convenience (example H4 = high canopy, swept weekly). This naming convention was kept even though high-resolution tree canopy data were later used to quantify a unique percent tree canopy cover for each route (method described below). Comparisons among seasons were possible given the duration of the experiment and the frequency of sweeping (all routes were swept at least once per month during the snow-free season in each year of the study).

Sweeping was performed largely in residential areas, but the low canopy routes L2 and L4 contained some light commercial/industrial areas. Most sweeping routes were composed of 2-3 discrete stretches of road in a given neighborhood that were categorized as having similar tree canopy cover (qualitatively). Only one route (L4) was characterized by contiguous segments of roadway.

1.5 Methods

Field, laboratory, and spatial analysis methods are summarized in sections 1.5.1 - 1.5.3. Additional details including quality assurance and quality control have been reported in Kalinosky, et. al., 2014: http://larrybakerlab.cfans.umn.edu/home/research-projects/quantifying-nutrient-removal-by-street-sweeping/

1.5.1 Field Methods

All street sweeping was conducted using a Tymco model 600 regenerative air street sweeper. For each sweeping run, drivers filed a report detailing the date, time, distance, and gross vehicle weight of the sweeper. GPS vehicle tracking data were used to validate swept distance and fuel use (Appendix D). Sweeper loads were sampled immediately after each sweeping event. It was expected that vehicle motion during sweeping operations would result in some amount of settling and compaction of material collected in the hopper. For this reason, sweeper samples were collected after loads were dumped to take advantage of re-mixing. To insure collection of a representative sample, drivers were instructed to visually inspect the dumped load before sample collection to estimate the portions of soil-like material and plant debris, and to check the degree of consolidation of sediments from the bottom of the hopper.

Vehicle operators were instructed to sample sediment fractions at proportions relative to their presence in the total load. Large pieces of trash and woody debris were avoided, but smaller pieces, which were easily picked up, were not separated from the sample. Vehicle operators wore nitrile gloves to prevent contamination of swept material and to protect operator's hands during sample collection. A volume of approximately ½ to ¾ gallons (2-3 L) of sweeper waste was collected in 1-gallon sized plastic freezer bags. Samples were frozen on site after collection to preserve them for laboratory analysis.

Under ideal conditions, average sweeping intervals for each route corresponded to the interval assigned to each route at the beginning of the study, but occasional rain events or other logistical issues resulted in minor irregularities in the sweeping schedule (Appendix D, Appendix E). Since routes were only swept when streets were free of snow and ice, the greatest irregularities in the sweeping schedule were seen from December through February when road conditions were highly variable from year-to-year. Because sweeping intervals were irregular during winter months, data from these months were excluded from statistical analysis.

1.5.2 Laboratory Methods

The initial processing of all sweeper waste samples was conducted at the University of Minnesota Department of Ecology, Evolution and Behavior. Frozen sweeper samples were thawed under refrigeration and thawed samples were separated into five fractions during processing: garbage, fines (< 2mm fraction), rocks (inorganics ≥ 2mm), coarse organics (organics ≥ 2mm), and soluble nutrients leached during isolation of the coarse organic fraction. The mass, moisture content (determined by oven drying at 65°C), and organic content (%OM) of each of the solid fractions was determined for all sweeper samples. Chemical analyses of total phosphorus (TP), total nitrogen (TN) and total organic carbon (TOC) were performed on the fine, coarse organic, and soluble fractions. It was assumed that garbage and rocks did not contribute significantly to nutrient loads, so only the mass of these fractions was tracked.

Coarse material retained on the 2mm sieve went through a second fractionation using buoyancy to separate the coarse organic material from any adhered soils. Coarse material was added to 3 liters of deionized water in a clean 5-liter plastic bucket. Suspended organics were gently agitated for about 1 minute until adhered soil particles appeared to be dislodged. Vegetative material that floated during the process was classified as coarse organic matter (COM). 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 (<2mm) and the remaining rock fraction (>2mm). The coarse organic matter was then oven dried for nutrient analyses and to determine its dry weight.

Subsamples of dried fines and COM (litter) were ground and shipped to the University of Nebraska Ecosystems Analysis Laboratory for TN and TOC analysis. All other chemical analysis of sweeper waste was performed at the University of Minnesota Department of Ecology, Evolution and Behavior. Laboratory methods for all chemical analysis are summarized in Table 1.

Table 1. Summary of chemical analysis methods.

Component	Fraction	Method
Organic Content	Fines Coarse Organics	Loss on ignition (600 °C, 6hr)
TP	Fines Coarse Organics	Molybdate blue/ascorbic acid colorimetric method, samples ground and ashed prior to sulfuric acid digest.
	Leached	Molybdate blue/ascorbic acid colorimetric method, Persulfate digest.
TN, TOC	Fines Coarse Organics	Carlo Erba 1500 element analyzer.
	Leached	TOC/TN Analyzer, catalytic thermal decomposition· chemiluminescence method

1.5.3 Spatial Analysis of Tree Canopy

Tree canopy cover directly over the street and at variable distances from the curb was quantified through spatial analysis (GIS) for each sweeping route. Tree canopy data were developed by the University of Vermont Spatial Laboratory using object-based image analysis that combines satellite imagery and LiDAR data to develop fine-scale land cover maps (O'Neil-Dunne et al., 2014). Sweeping routes were first digitized using road polygon data provided by the City of Prior Lake. Buffer polygons were created from sweeping route polygons using standard geoprocessing tools. Buffer distances were chosen somewhat arbitrarily, but were intended to represent over the street – 0 meters; near street – 1.5 and 3.0 meters (0, 5, and 10 ft); depth of front yard – 6.1 and 15.2 meters (street to house, 20 and 50 ft); and lot depth – 30.4 and 76.2 meters (street to back of property, 100 and 250 ft) distances. Sweeping route polygons and buffered polygons were then overlaid onto tree canopy cover data. The reported over-street percent tree canopy cover (Section 1.6.1) is equal to the sum of 1 x 1 m tree canopy cells divided by the total area (m^2) of the each route polygon. Percent canopy covers were also calculated for buffered route polygons to compare canopy covers at within various distances from the curb.

1.6 Results and Discussion

1.6.1 Tree Canopy Cover Patterns

Spatial analysis of tree canopy revealed a consistent pattern among the sweeping routes with the percent canopy cover increasing sharply as buffer distance increased from 0 to about 15 meters (50 ft) and leveling off at greater distances (Figure 1). The 15.2 meter (50 ft) buffer roughly represented the average depth of the front yards in the City of Prior Lake.

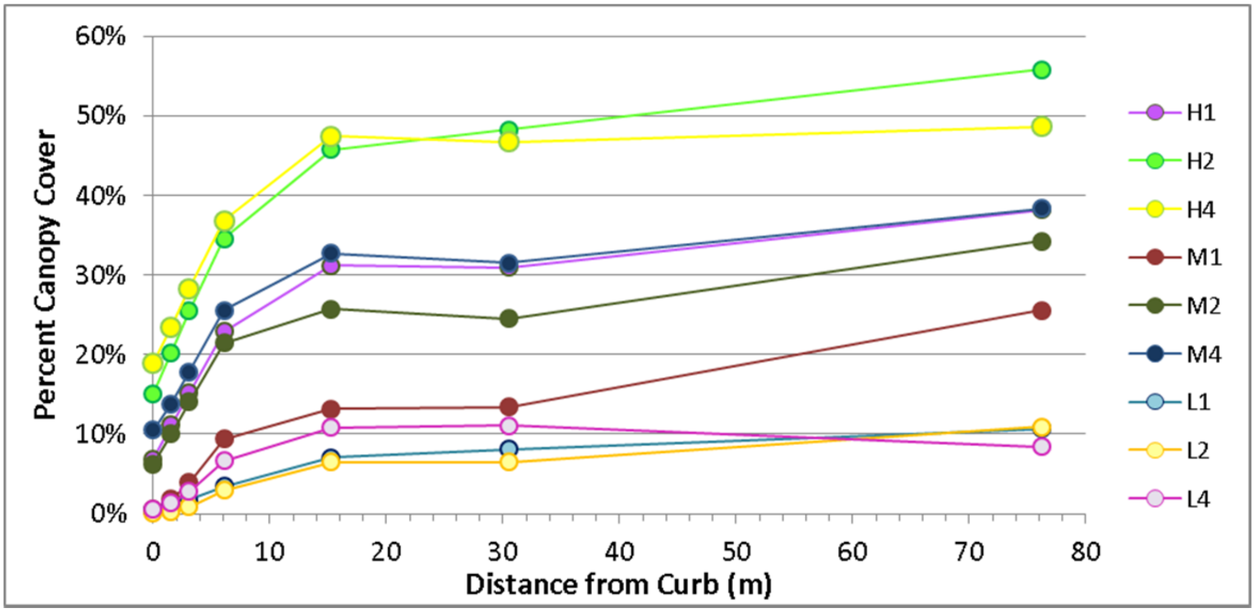


Figure 1. Average percent tree canopy cover at different buffer distances from the curb for the nine sweeping routes in Prior Lake. (Route naming convention = canopy class + sweeping frequency. For example, 'H1' = high canopy swept 1x per month).

The canopy cover pattern shared by the nine sweeping routes is likely characteristic of tree canopy distribution in outer ring suburban single family residential developments, where lot sizes are relatively large and sidewalks and alleyways are rare. In general, many factors will influence canopy cover patterns including land use and roadway type; development type and age; regional tree species and planting practices; and storm damage and disease. For example, in older urban residential areas with boulevard trees, canopy may be densest over/near streets. Whatever the pattern, it is expected that trees nearest the street will have the greatest influence on solids loading.

Correlations between percent tree canopy cover and variables describing the compositions of sweeper waste were tested at each of the buffer distances to determine the best buffer distance to predict nutrient removal from tree canopy cover (Appendix F). While definite patterns emerged, it became clear that homogeneity in canopy patterns among the routes limited the ability to identify the spatial extent of canopy influence. Differences in canopy cover were better resolved as buffer distance from the curb was increased. At smaller buffer distances (0, 1.5 meters) edge effects in the analysis (the result of averaging methods used to approximate raster data values at polygon boundaries) would have a greater influence on the overall percent canopy cover estimate and may have limited the ability to resolve differences in canopy cover among similarly canopied routes. At greater buffer distances, the percent canopy covers increased for all routes and diverged somewhat, reducing clustering in the data (Figure 1). Where correlations existed, they tended to increase in strength (increased R^2) as buffer distance from the curb increased (Appendix F); however, the extent to which the pattern in correlation coefficients is an echo of tree canopy cover distribution (rather than the spatial extent of tree canopy cover influence) cannot be determined. Additional study is need to determine whether differences in tree canopy distribution patterns influences solids and nutrient loading to streets.

This question presented a dilemma for the analysis strategy. Clearly, differences in the average canopy cover values for the nine study route were better resolved at the larger buffer distances, but trees located at these distances (ex. backyards) were not expected to greatly influence PM loading to streets. As a compromise, most findings presented are based on analyses which used the canopy cover within 20ft (6.1 m) of the curb, a front yard-scale distance at which differences in average tree canopy covers are well resolved for the nine study routes. Some results are also presented using over-street canopy cover for comparison. The question of the appropriate measure of tree canopy cover is taken up again in the discussion section and in Chapter 2.

1.6.2 Summary of Recovered Solids

In general, both tree canopy cover and sweeping frequency had a positive influence on total solids recovered (Table 2). On a per sweep basis, tree canopy had a positive influence on the total solids recovered while sweeping frequency had a negative influence (Table 3). These findings are intuitive – areas with dense tree canopy have a greater street PM yield on average than areas with sparse tree canopy cover. Increasing the total number of sweepings increased the total amount of solids recovered, but sweeping streets before the maximum street PM build-up has been reached will result in lower yield per sweep. It should be noted that the 28 day sweeping interval does not represent the total street PM input, but the per sweep yield of recovered solids was greatest for this sweeping interval.

Table 2. Average dry solids collected per year by route (kg/curb-meter/year)

Increasing Frequency ↓

Assigned Sweeping Interval	Low Canopy	Medium Canopy	High Canopy
28 days	0.49	0.62[§]	1.15[†]
14 days	0.79	1.20	1.42
7 days	1.50	2.12	2.04

Table 3. Average dry solids collected per sweep by route (kg/curb-meter)

Assigned Sweeping Interval	Low Canopy	Medium Canopy	High Canopy
28 days	0.055	0.062[§]	0.121[†]
14 days	0.044	0.065	0.086
7 days	0.041	0.055	0.053

[§] Route originally classified as 'medium' canopy, but quantified canopy cover was closer to 'low' canopy routes.

[†] Route originally classified as 'high' canopy, but quantified canopy cover was closer to 'medium' canopy routes.

The pattern was largely the same for recovered nutrients (Figure 2, Figure 3). Overall there was a fairly strong linear relationship between overhead canopy and the annual yield of recovered nutrients (kg/curb-meter/yr), and sweeping frequency also had a positive influence on annual nutrient recovery. On a per sweep basis, overhead canopy had a positive influence on the yield of recovered nutrients (kg/curb-meter), while sweeping frequency had a negative influence (Table 4).

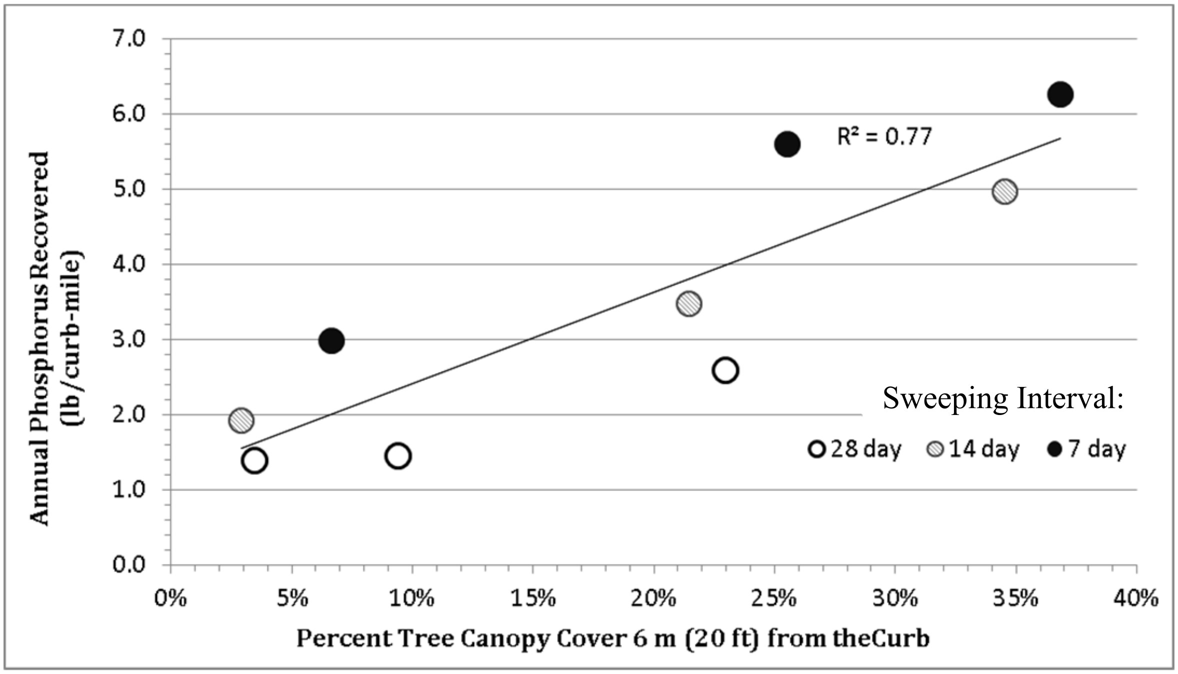


Figure 2. Average total phosphorus recovered per year vs. percent tree canopy cover for the nine street sweeping routes.

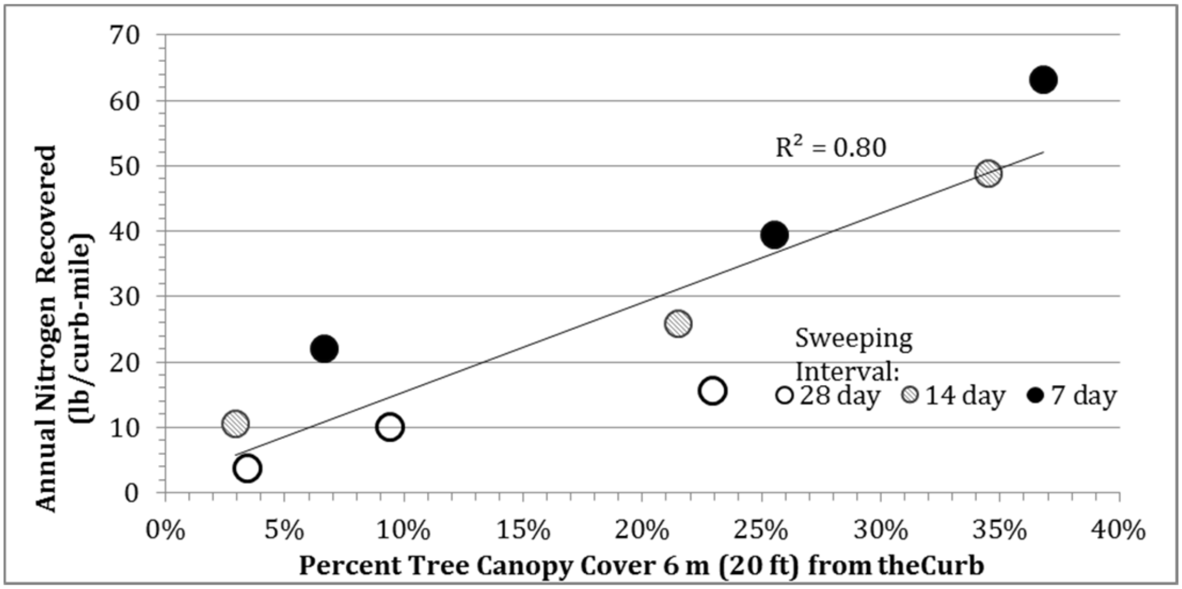


Figure 3. Average total nitrogen recovered per year vs. percent tree canopy cover for the nine street sweeping routes.

Table 4. Average nutrients recovered per sweep for each sweeping route (kg/curb-meter).

Increasing Frequency

Assigned Sweeping Interval	**Low Canopy**	**Medium Canopy**	**High Canopy**
	Phosphorus		
28 days	4.23E-02	4.23E-05	8.46E-05
14 days	2.54E-05	5.36E-05	7.89E-05
7 days	2.25E-05	4.23E-05	4.51E-05
	Nitrogen		
28 days	5.92E-05	1.47E-04	3.33E-04
14 days	7.33E-05	2.06E-04	3.61E-04
7 days	5.92E-05	1.86E-04	2.37E-04

Seasonal patterns in solids recovery were consistent between years 1 (August 10, 2010 – July 31, 2011) and year 2 (August 1, 2011-July 31, 2012) (Figure 4, Figure 5). Total recovered loads were highest in the early spring, tapered off throughout the summer months, and increased again in the autumn. Higher inter-year variability during the February-April period reflects the influence of winter weather and winter road maintenance practices. Due to winter conditions, a regular sweeping schedule could not be established until April in year 1, but milder weather in year 2 allowed regular sweeping to be established in March (Appendix E). This explains why, although the total mass of solids collected in March increased in year 2 compared to year 1 (Figure 4), the mass collected per sweep decreased (Figure 5). (The initial high spring loading intensity was averaged with loading intensities of subsequent, regular sweepings.) Similarly, the relatively high yield of recovered solids in August of year 1 (Figure 5) may be an artifact of start-up operations since regular sweeping was not conducted in all study areas until the start of the experiment. Supporting this, several material loads recovered during the initial weeks of the study had total dry weights that fell within the upper 25th percentile for the entire study.

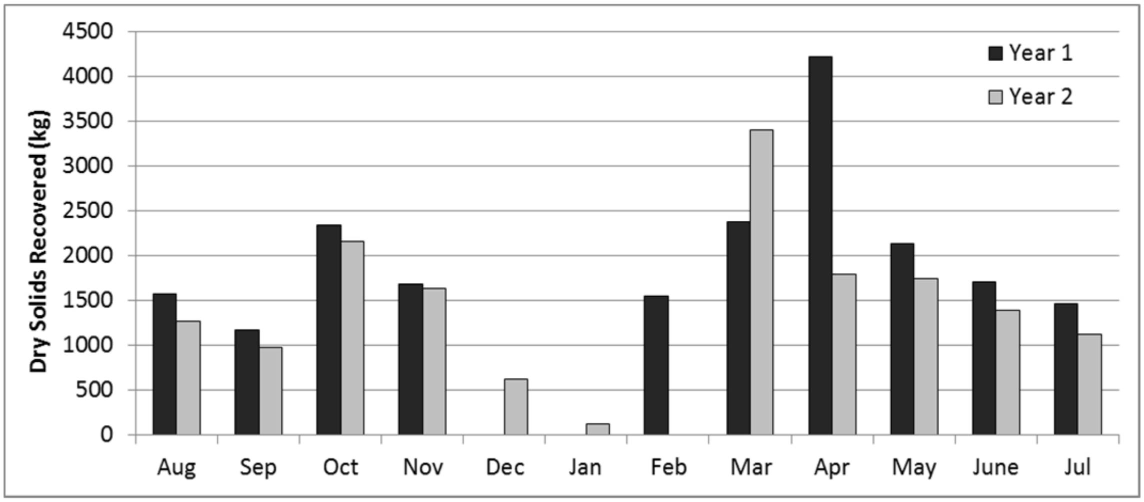


Figure 4. Total dry solids recovered by month and year (all routes combined).

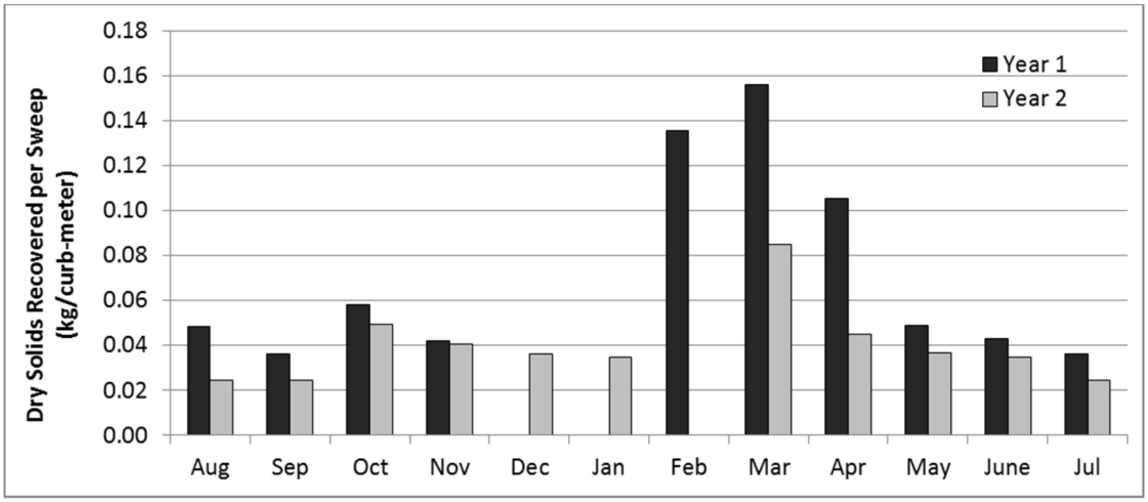


Figure 5. Average dry solids recovered per sweep by month and year (all routes combined).

1.6.3 Influence of Tree Canopy and Sweeping Frequency on the Composition of Recovered Solids

Pearson correlations were used to inspect the relationship between overhead tree canopy and the composition of sweeper waste (Table 5). To distinguish the influence of tree canopy from other influences on sweeper waste, correlations were tested using route average values for compositional variables (nutrient and OM concentrations, and mass ratio of sweeping fractions) and percent overhead tree canopy within specified distances from the curb. Strong positive correlations existed between overhead tree canopy and compositional variables for sweeper waste as a whole and for the fine fraction of sweepings. The phosphorus concentration in the fine fraction, which was only weakly correlated, was a noted exception.

Because the coarse organic fraction is comprised of plant material present in sweeper waste samples, tree canopy cover was expected to influence the *quantity* of coarse organics recovered and in-turn to influence the nutrient concentration of sweeper waste, but to have little influence on nutrient concentrations in the coarse organic fraction itself. Nonetheless, mild negative correlations were seen. The coarse organic fraction included all solids > 2mm diameter than could be recovered by float separation, including grass clippings and organic litter from weeds and brush. No formal observations of the distribution of plant species represented in coarse organics were recorded during the study, but it is reasonable that the dry mass fraction of components within the coarse organic would vary somewhat with tree canopy. Differences in the typical nutrient concentrations of species present in the coarse organic fraction along with their relative mass proportions may explain the moderate correlations (positive and negative) between tree canopy cover and nutrient concentration in the coarse organic fraction of the sweeper waste. Likewise, the leaching rate of nutrients (mg/kg) from material retained on the 2 mm sieve (a mix of coarse organics, adhered soil, and rocks) was not expected to show a strong correlation to percent tree canopy cover.

Table 5. Correlations between percent tree canopy and average nutrient concentrations in sweeper waste for the nine sweeping routes.

Composition Variables	**Pearson Correlation, R**[*]	
	% Canopy Over street	**% Canopy within 20 ft of the curb.**
Dry mass ratio of Coarse: Fine particles	**0.73**	**0.75**
TP, TN, TOC concentrations in sweeper waste[§] (mg/kg)	**0.80, 0.94, 0.96**	**0.78, 0.93, 0.94**
TP, TN, TOC concentration in fine fraction (mg/kg)	0.30, **0.75, 0.76**	0.33, **0.81, 0.84**
TP, TN, TOC concentration in coarse fraction (mg/kg)	-0.40, **-0.54, 0.52**	-0.42, -0.45, **0.61**
TP, TN, TOC leaching rate of 'dirty litter'[§§] (mg/kg)	-0.03, 0.09, 0.16	0.08, 0.11, 0.15
% OM in sweeper waste	**0.87**	**0.93**
% OM in fine fraction	**0.78**	**0.85**
% OM in coarse fraction	0.44	**0.52**

[*] Significant correlations shown in bold. R-values > 0.58 are significant at α=0.05, values > 0.48 at α=0.10.

[§] Sweeper waste includes minor mass fractions of garbage, rocks and soluble nutrients leached during fractionation.

[§§] organic material + adhered soil particles retained on the 2 mm sieve (fresh organics prior to float separation).

In contrast to tree canopy, only a few compositional variables showed a moderate correlation to the average observed sweeping interval (days) for each route, and most coefficients were negative (Table 6). This was not entirely surprising. If the rates of accumulation and washoff were identical for all components of street PM throughout the year, no relationship between sweeper waste composition (variables in Table 5) and sweeping interval would be expected (disregarding decomposition or other chemical transformation). In reality, there are a number of mechanisms at play which may result in differential accumulation/loss of the various components of street PM. Examples include, but are not limited to, the following:

- Application of non-skid materials over the winter increases the accumulation of inorganics/ fines.
- Tracking of street PM from one location to another on vehicle tires may preference fines.
- Fragmentation of coarse organic material left on the street may result in a transfer of material from the coarse to fine fraction over time.
- Materials with relatively low density, such as grass clippings or pollen, can be transported at lower runoff intensities than denser inorganics.
- Leaching rates of nutrients from coarse organics may increase when organic material is fragmented by vehicles, but decrease with repeated exposure to runoff.
- Decomposition of coarse organics and other biochemical transformations that occur in street PM accumulations on street surfaces may result in the import or export of mass from/to the surrounding environment.
- The quantity and character of vegetative inputs to streets varies with season (section 1.6.5).

While all of these factors are expected to influence the composition of street PM over time, it may be that differences in the composition of solids on the street which can be attributed to these factors are difficult to detect at the time scale of experimental sweeping frequencies (7, 14, or 28 day interval). This is one possible explanation for the weak relationships seen between sweeping frequency and the composition of sweeper waste (Table 6).

Table 6. Correlations between average sweeping interval (days) and average compositional variables during periods of regular sweeping (April-November) for the nine sweeping routes.

Average Sweeping Interval (days) vs.	**Compositional Variable**	**Pearson Correlation, R**[*]
	Dry mass ratio of Coarse: Fine particles	-0.22
	TP, TN, TOC concentrations in sweeper waste, (mg/kg)	-0.21, -0.32, -0.32
	TP, TN, TOC concentration in fine fraction, (mg/kg)	0.18, -0.25, -0.18
	TP, TN, TOC concentration in coarse fraction, (mg/kg)	-0.47, -0.18, 0.15
	TP, TN, TOC leaching rate of 'dirty litter', (mg/kg)	**-0.53**, -0.26, **-0.63**
	% OM in sweeper waste	-0.37
	% OM in fine fraction	-0.30
	% OM in coarse fraction	0.37

[*] Significant correlations shown in bold. R-values > 0.58 are significant at α=0.05, values > 0.48 at α=0.10.

On the whole, the prevalence of negative values among the correlation coefficients likely indicates that nutrients are lost over time from material that remains on the streets. On the time scale of the investigation, this pattern was strongest for the leaching rate of fresh (unwashed) coarse organics ('dirty litter').

1.6.4 Influence of Tree Canopy and Sweeping Frequency on the Quantity of Recovered Solids

As described in the section 1.6.2, both tree canopy cover and sweeping frequency had a positive influence on total quantity of material recovered. It is difficult to discuss the influence of these two factors separately since the mass of street PM available for removal at any given time is a function of both the net accumulation rate of solids and the total time of accumulation. Presumably, tree canopy cover influences the first of these, while sweeping frequency determines the latter.

Given the dependence of recoverable solids yield on both tree canopy cover and sweeping frequency, multiple linear regressions were used to describe the relationship between these variables and both the average per sweep yield of recoverable solids (kg/curb-meter, Table 7) and the average annual recoverable yield of solids for each route (kg/curb-meter/yr, Table 8). All regressions were significant at the $\alpha=0.05$ significance level except the regression describing per sweep recoverable fines. In general, a majority of the variation in average recoverable yields (both per sweep or annual) was explained by the tree canopy and average sweeping interval variables (R^2 value > 0.50).

Table 7. Multiple linear regressions relating the average per sweep recovered yield of solids for each route to the average tree canopy cover (within 6.1 m (20 ft) from the curb) and average sweeping frequency (all sweepings included).

Solids	**Solids (kg/curb-meter) = β_o + β_1(Canopy Cover[§]) + β_2(Average Sweeping Interval[§])**				
	β_o	**β_1(canopy cover)**	**β_2 (sweeping interval)**	**R^2**	**p-value**
Sweeper Waste	2.6	**135.1***	**1.5**	**0.63**	**0.0206**
Fines	*10.2*	*52.2*	*1.0*	*0.55*	*0.0902*
Coarse Organics	-5.7	**57.3**	0.2	**0.79**	**0.0038**
Total P	-5.6E-03	**1.4E-02**	**1.1E-03**	**0.86**	**0.0027**
Fine P	2.3E-03	**4.6E-02**	**8.5E-04**	**0.81**	**0.0072**
Coarse P	-7.9E-03	**9.3E-02**	2.8E-04	**0.89**	**0.0013**
Leached P	-2.8E-04	**4.2E-03**	1.8E-05	**0.75**	**0.0157**
Total N	-6.5E-02	**0.87**	**2.8E-03**	**0.88**	**0.0017**
Fine N	-1.1E-02	**0.19**	**1.1E-03**	**0.73**	**0.0187**
Coarse N	-5.4E-02	**0.67**	**2.3E-03**	**0.90**	**0.0009**
Leached N	5.6E-04	**8.2E-03**	3.4E-05	**0.72**	**0.0210**

*Values for coefficients that are shown in bold are significant at $\alpha = 0.05$.

[§] Canopy cover as a decimal fraction; sweeping interval in days.

Table 8. Multiple linear regressions relating the annual recovered yield of solids (kg/curb-meter/yr) for each route to the tree canopy cover (within 6.1 m (20 ft) from the curb) and average sweeping frequency (all sweepings included).

Solids	**Solids (kg/curb-meter/yr) = β_o + β_1(Canopy Cover§) + β_2(Average Sweeping Interval§)**				
	β_o	**β_1(canopy cover)**	**β_2 (sweeping interval)**	**R^2**	**p-value**
Sweeper Waste	**1533***	**2448**	**-28**	**0.88**	**0.0019**
Fines	**1277**	687	**-22**	**0.72**	**0.0223**
Coarse Organics	79.5	**1191**	-3.7	**0.94**	**0.0002**
Total P	**0.87**	**2.8**	**-0.03**	**0.95**	**0.0002**
Fine P	**0.70**	0.75	**-0.01**	**0.77**	**0.0123**
Coarse P	0.17	**1.99**	-0.01	**0.92**	**0.0004**
Leached P	0.01	**0.08**	2.48E-04	**0.95**	**0.0002**
Total N	**2.54**	**17.81**	**-0.08**	**0.94**	**0.0002**
Fine N	**0.91**	**3.44**	**-0.02**	**0.88**	**0.0017**
Coarse N	1.55	**14.26**	-0.06	**0.93**	**0.0003**
Leached N	**0.05**	**0.12**	**-0.001**	**0.89**	**0.0013**

*Values for coefficients that are shown in bold are significant at α =0.05.

§Canopy cover as a decimal fraction; sweeping interval in days.

Tree canopy cover was a significant predictor (α=0.05) for all recovered loads except recoverable fines (per sweep and annual recovered loads) and fine phosphorus (annual recovered). The average sweeping interval was a significant predictor of recoverable yields for most constituents except for components associated with the coarse organic fraction of sweeper waste (per sweep average yields of coarse organics, coarse P, leached P, and leached N; average annual yields for coarse organics, coarse P, and leached P). The main point of interest in the analysis is that tree canopy was not a significant predictor of recoverable fines and sweeping interval was not a significant predictor of recoverable coarse organics. This only holds, however, when regression analysis is based on route average values for recovered loads and sweeping intervals. Within particular seasonal windows (Table 10), sweeping frequency was a significant predictor of recoverable coarse organics and likewise tree canopy of recoverable fines. These dynamics are discussed in greater detail in section 1.6.6.

Overall, regressions describing annual recovered yields were stronger than those describing average (per sweep) recoverable yields (exception fine phosphorus). A possible explanation for the discrepancy is that, in all cases, the route assigned a sweeping frequency of once per week (7-day sweeping interval) had the highest percent canopy cover within each canopy classification (low, medium, high, see Figure 1). Similarly, the M2 and H2 routes had higher tree canopy covers than the M1 and H1 routes respectively. Whether higher canopy routes were intentionally assigned higher sweeping frequencies (a factor that would decrease per sweep yield) is unknown, but the effect of increased canopy cover on per sweep yields may be masked somewhat in the analysis due to the coincidence of higher frequency with higher tree canopy covers.

1.6.5 Influence of Season on the Composition Recovered Solids

Season influenced variables describing both the composition and the quantity of recovered solids. In keeping with the earlier sections, the discussion here begins with a look at the influence of season on sweeper waste composition (variables listed in Table 5). There are a number of ways to interpret 'seasonal' including weather patterns, calendar months, phenological markers, or road maintenance cycles. Because no formal observations of season other than date were recorded during the study, the analysis of seasonal influence is organized around calendar month. To consider the influence of season apart from tree canopy cover and sweeping frequency, results in this section are presented using monthly average values for variables of interests where all routes have been averaged together.

Both the phosphorus and nitrogen concentrations of sweeper waste varied throughout the year (Figure 6 and Figure 7) and seasonal patterns in concentration were similar for the two fractions. Phosphorus concentrations were typically 2-3 times greater in the coarse organic fraction than in the fine fraction; and nitrogen concentrations were from 5 to 52 times greater in the coarse fraction than in the fine fractions. Although nutrient concentrations were lower on average in the fine fraction, the magnitude of change across seasons was greater in the fine fraction than in the coarse organic fraction. Average phosphorus concentrations increased about 2-fold from a low of 900 mg/kg in

February to a high of 1980mg/kg in October in the coarse fraction and increased nearly 3-fold from 340 mg/kg in January to 900 mg/kg in October in the fine fraction (Figure 6). Average nitrogen concentrations in the coarse organic fraction were highest in May (21700 mg/kg), a 2.4 fold increase over the low value in February (924 mg/kg); and average nitrogen concentrations in fine fraction in were highest in October (2500 mg/kg), a 14.7 fold increase over concentrations in February (180 mg/kg).

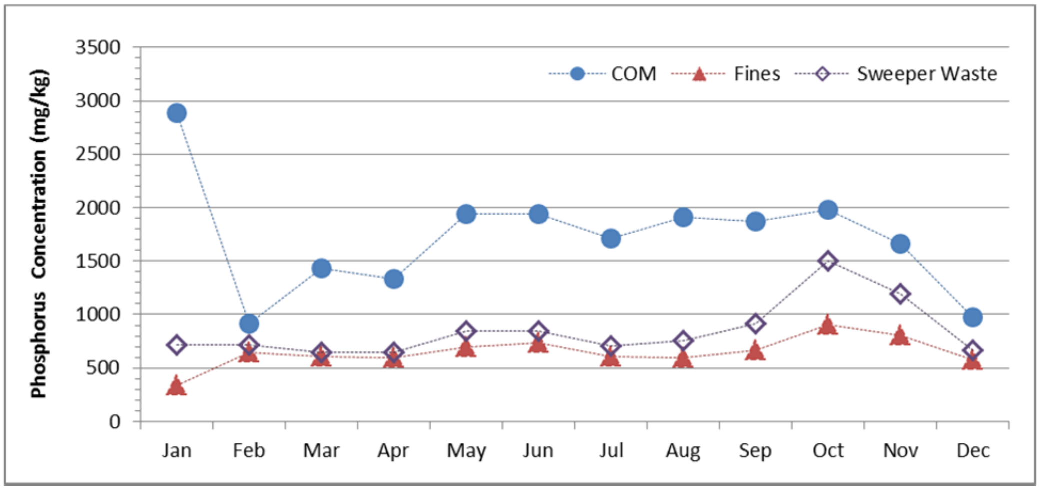


Figure 6. Average phosphorus concentration in sweeper waste and in the fine and coarse organic fractions by month (all sweeping routes combined).

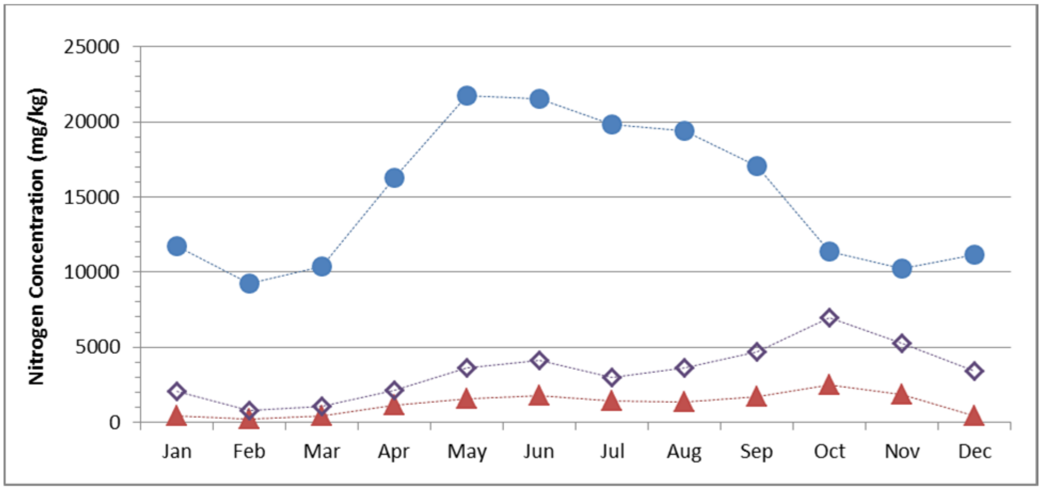


Figure 7. Average nitrogen concentrations in sweeper waste and in the fine and coarse organic fractions by month (all sweeping routes combined).

Variations in nutrient concentrations in the coarse organic fraction are likely due to a few distinct causes. The first is that the concentrations of nutrients in plant tissues vary, for example trees retranslocate nutrient from leaf tissue before leaves drop in the fall, resulting in about a 50% decline in leaf nitrogen and phosphorus concentrations. Secondly, for any given plant species, there may be more than one type of litter drop over the growing season (ex. flowers, pollen, seeds, fruits, or leaves). Lastly, given that growth cycle vary among plant species, the mix of species present in the coarse organic fraction may shift from month to month.

In contrast, changes in nutrient concentration in fine fraction are probably due to a transfer of mass from the coarse organic fraction to the fine fraction, in part by mechanical breakdown of nutrient-rich coarse organic matter into finer particles. Nutrient concentrations in the fine fraction were greatest in October, which corresponds to the period when coarse organic loads were greatest (see Figure 8 and Figure 10). Other factors which may contribute to seasonal variations in nutrient concentrations in the fine fraction include precipitation patterns (greater leaching of nutrients when runoff volume and intensity are greater); road maintenance and construction activity (potential sources of dust and street PM); and season lawn care practices which may affect organic inputs to streets.

Although average nutrient concentrations were consistently greater in the coarse organic fraction than in the fine fractions, the majority of sweeper waste (dry mass) was composed of fine PM during most of the year (Figure 8). Coarse organics made up less than 20% of the total dry mass recovered in all months except October and November (all routes combined). Nonetheless, coarse organic matter comprised the majority of the phosphorus collected during the fall and a majority of the nitrogen throughout the year.

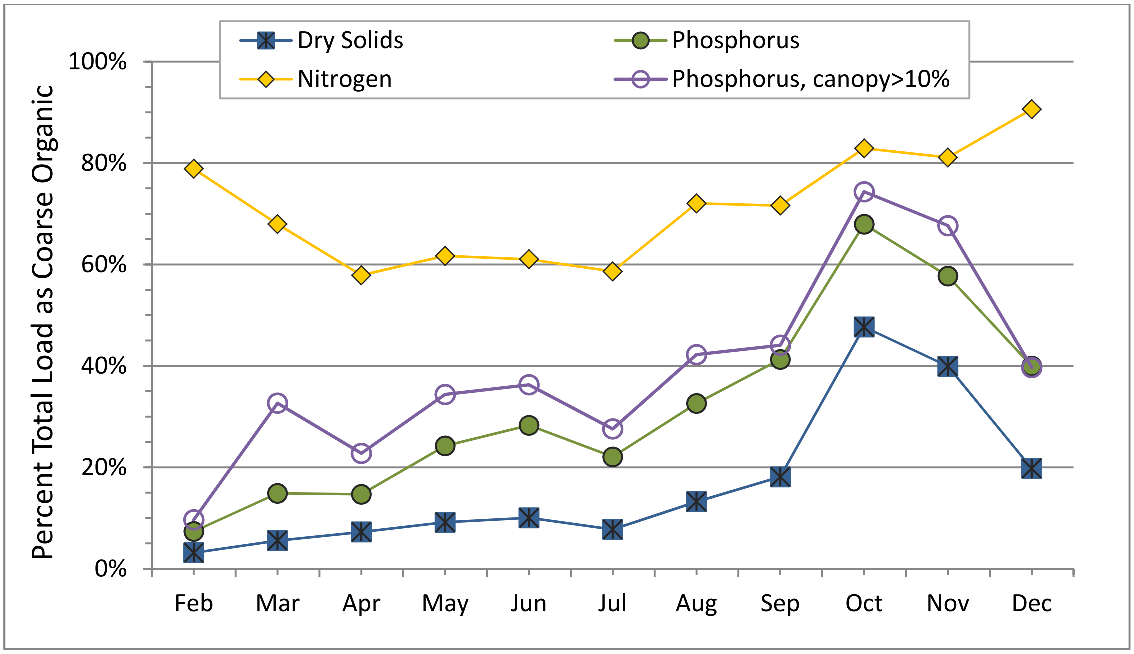


Figure 8. Average composition of sweeper waste by month showing the percent total load of dry solids, total phosphorus and total nitrogen recovered as coarse organics.

One component of sweepings that showed a very strong seasonal influence was the leaching rate of 'dirty litter'. Recall that 'dirty litter' refers to the fresh/thawed coarse organics retained on a 2 mm sieve to which fine particles may have been adhered. The method used to separate material retained on the 2 mm sieve ('dirty litter' and rocks) also functioned as an informal leaching experiment. Solids were inundated with water and gently agitated before coarse organics were filtered out. Wash water was sampled within 5-10 minutes of inundation. The average leaching rates of nutrients from material retained on the 2 mm sieve (which includes adhered soil) is shown by month in Figure 9.

Leaching rates were highest in May for both phosphorus (18.4 mg P/kg) and nitrogen (79.8 mg N/kg) and declined over the summer and fall months to low values in December (1.1 mg/kg phosphorus, 2.5 mg/kg nitrogen). Average leaching rates were lowest for both phosphorus and nitrogen in December, however, in pairwise comparisons, differences in average leaching rates for the months August-March were not significantly different from one another (α=0.5) for either phosphorus or nitrogen. In general, leaching rates were comparable to values reported leaf litter leaching studies (Table 9).

Table 9. Observed leaching rates of urban tree leaves, various studies (laboratory results).

Study	**Leaching Time**	**Observed Leaching Rates** (dry mass basis)
Cowen and Lee, 1973	1 hr	54 mg P/kg leaf tissue fallen, intact oak leaves 650 mgP/kg cut up oak leaves (collected as fallen, intact)
Dorney, 1986	2 hr	Range: 38.1 – 259.9 mg P/kg leaf tissue (common urban species, Milwaukee, WI).
Wallace et al., 2008	6 hr	Range 10-400 mg P/kg leaf tissue (Australian and European species).
Hobbie, et al., 2013	0.5 hr 24 hr	Range 9 – 26% loss of total phosphorus mass, leaf tissue. Range 27 – 88% loss of total phosphorus mass, leaf tissue. (Common urban tree species, Minneapolis, MN).

The leaching potential of material collected in the spring and early summer (April – July) was clearly greater than that of material collected at other times of the year, but it is difficult to draw additional inferences from the data. It is likely that differences in the type of organic debris collected each month (ex. flowers, bracts, and seed vs. leaf litter) account for differences in observed leaching rates, but no formal observations were taken to support this. Within the dirty litter, the dry mass ratio of adhered soil to coarse organic litter was greatest in February and March when leaching rates were low. No significant relationship was otherwise found between the dry mass ratio of adhered soil to COM and the leaching rate of nutrients from dirty litter. Although some portion of leached nutrients presumably originates in the soil component of ‘dirty litter’, allotment of leached nutrients to adhered soil or COM was not possible given the data collected.

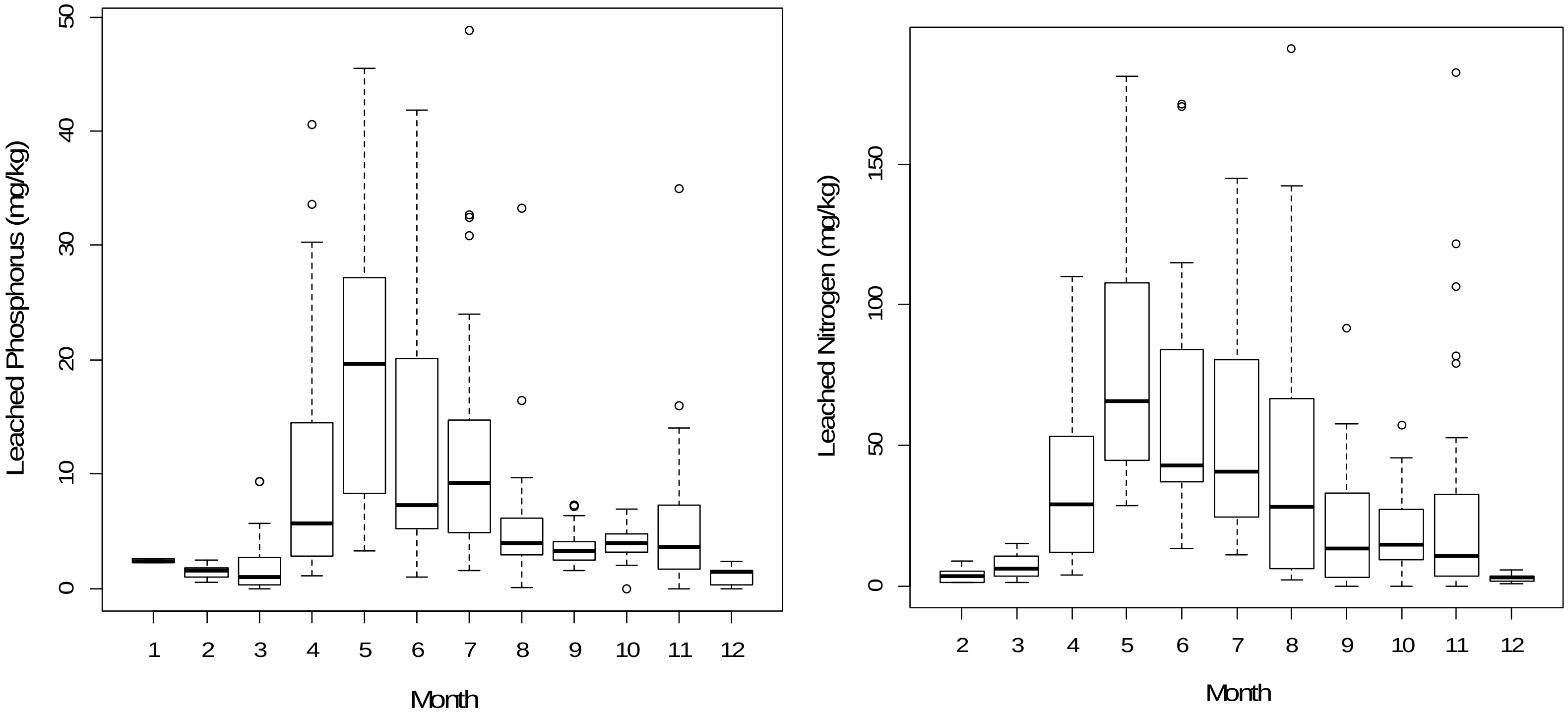


Figure 9. Leaching rates (dry mass basis) of phosphorus and nitrogen from the 'dirty litter' component of sweeper waste (fresh coarse organics + adhered soil). Leaching time 5 - 10 minutes. Box plots show average and 25th and 75th percentiles; bars show 10th and 90th percentiles.

1.6.6 Influence of Season on the Quantity of Recovered Solids

The influence of season on the quantity of solids recovered was very clear (Figure 4, Figure 5); but seasonal patterns varied depending on the fraction of sweeping being considered. Average recovered loads (kg/curb-meter) were greatest in Feb-April for the fine fraction (Figure 10); and greatest in the Oct-Nov for the coarse organic fraction (Figure 11) and for total leached nutrients (leaching rate x dry mass 'dirty litter'). In pairwise comparisons, the average recovered fine sediment loads (kg/curb-meter) did not differ significantly (α=0.05) in the months of May through February. Likewise, average recovered loads did not differ significantly by month from January through September for coarse organics, or from November through August for leached nutrient loads.

Seasonal patterns for nutrient loads associated with the fine and coarse organic fraction were similar to the patterns in recovered solids in each fraction. The influence of winter residuals (largely fines) and seasonal pulses of coarse organic inputs can be seen when total recovered nutrients are plotted by month (Figure 12, Figure 13). Large increases in total nutrient loads are seen in both the early spring (winter residuals) and the fall (leaf litter inputs), with the greatest average nutrient recovery for both nitrogen and phosphorus in October. As mentioned in the section 1.6.2, relatively large difference between average loading rates in the early spring (March-April) between years 1 and 2 are likely the result of difference in the timing of snow melt (and the start of regular sweeping) for year 1 and year 2 while differences in loading rates for late summer

(August-September) between years are likely an effect of extended periods of build-up prior to the start of sweeping in August, 2010.

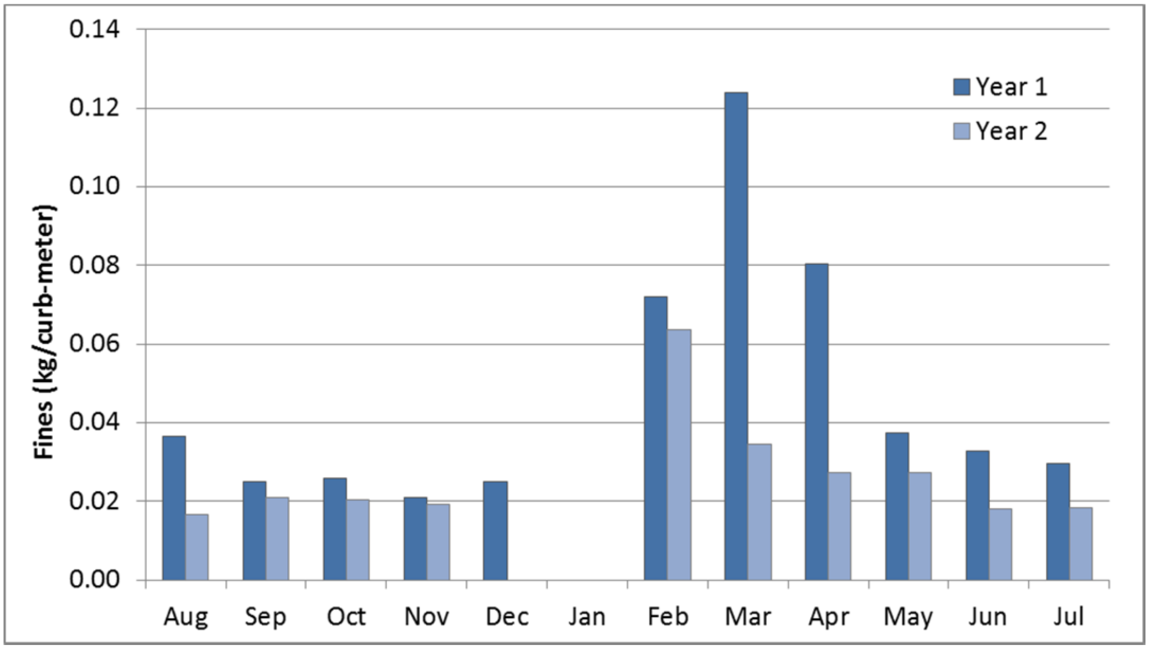


Figure 10. Average recovered load, fine solids (dry weight) by month and year.

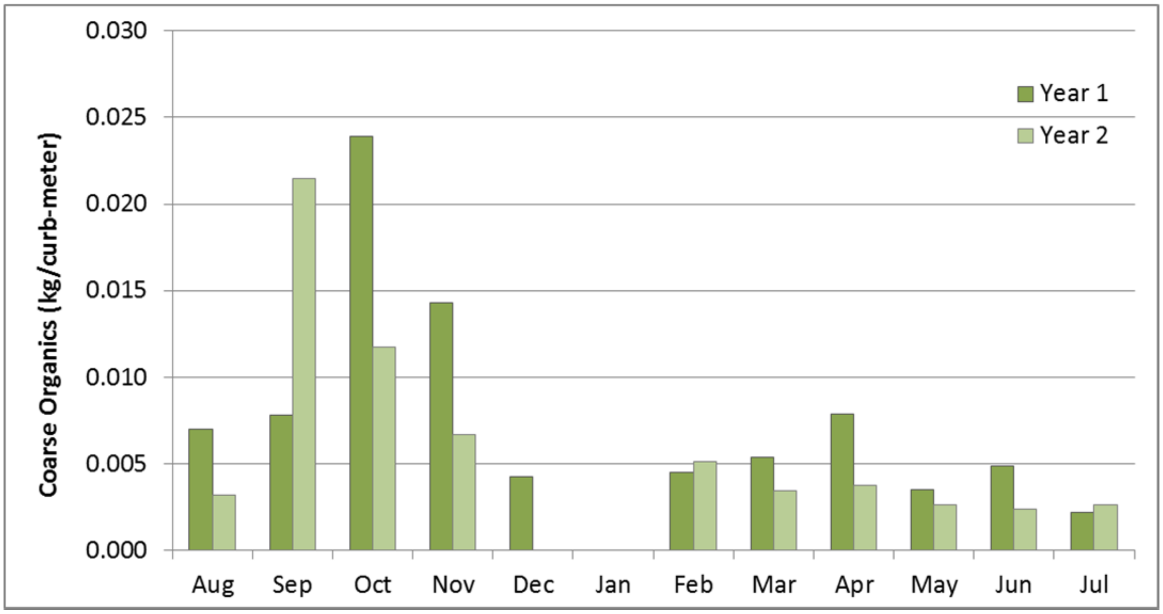


Figure 11. Average recovered load, coarse organic solids (dry weight) by month and year.

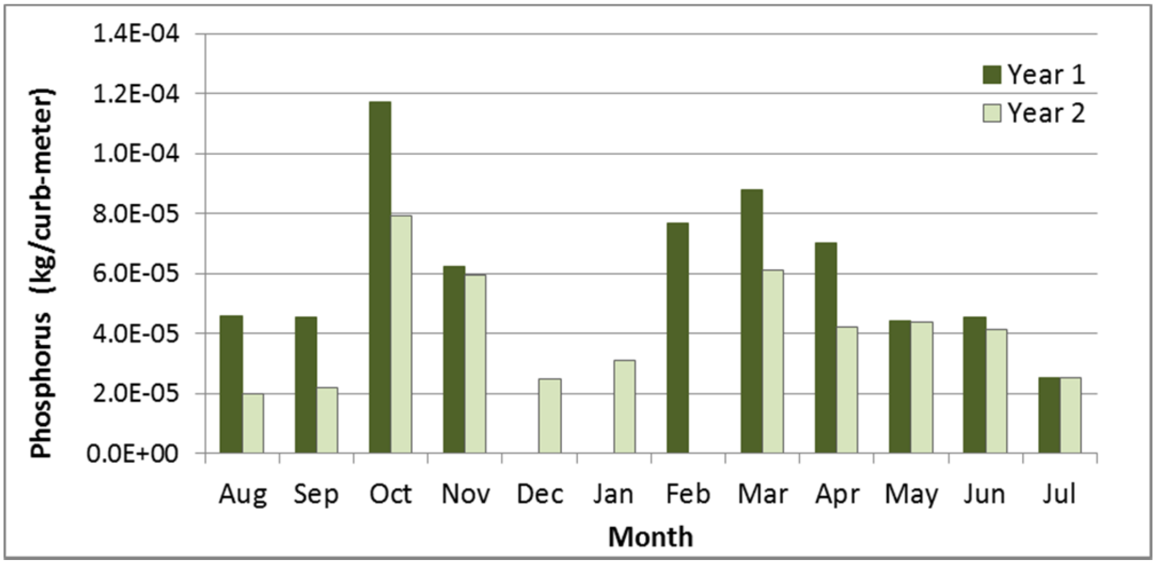


Figure 12. Average recovered load, phosphorus (sweeper waste) by month and year.

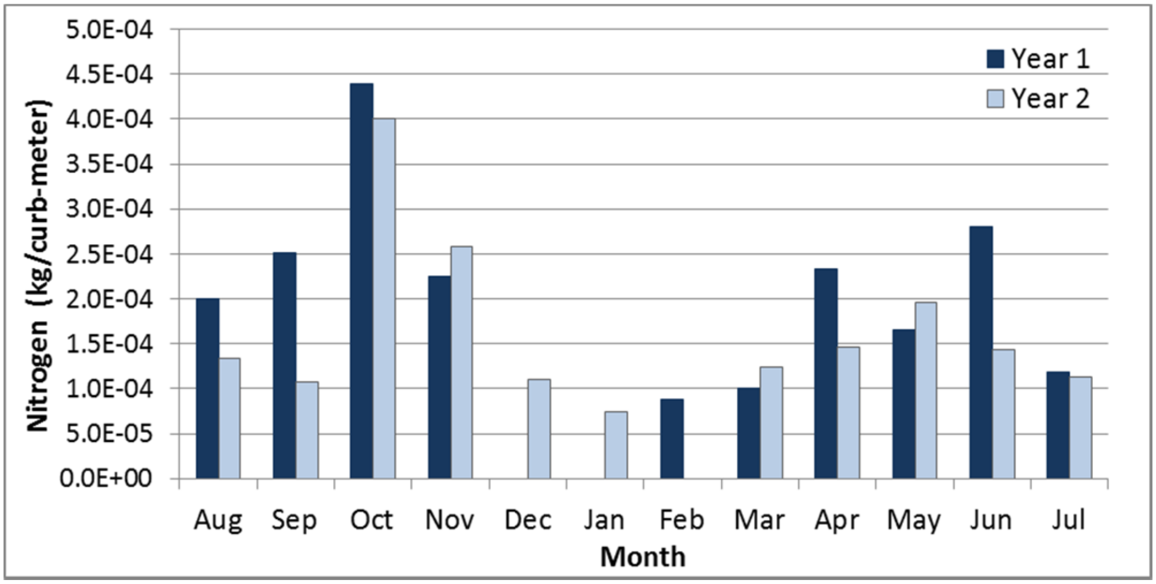


Figure 13. Average recovered load, nitrogen (sweeper waste) by month and year.

To summarize the significance of the three influences being investigated, we used the regression described in Table 7 and Table 8 with subset of the data to look at whether or not tree canopy cover and sweeping frequency were significant predictors of recovered loads within each month from March - November. Results of the analysis are shown in Table 10. In general, tree canopy cover was a significant predictor of recovered load associated with the coarse organic fraction for all or most months, but was significant in predicting recovered loads associated with the fine fraction in fewer months, most notably in October. There was no recovered load type for which sweeping frequency was a significant predictor in all months, but sweeping frequency was a significant predictor for recovered loads associated with the fine fraction in most months. Notable exceptions to this were recovered total nitrogen and fine nitrogen loads, for which sweeping frequency was a significant predictor in September or June only.

Table 10. Summary of tree canopy cover and sweeping interval as predictors of recovered loads by month and recovered load type.

Load Type (lb/curb-mile)	Months for which the given factor is significant ((α=0.05) (March – November)	
	% Canopy within 20 ft of the curb	**Average sweeping interval**
Dry Solids	Oct, Nov	Apr-Jun, Aug, Sep, Nov
Coarse Organic Solids	All	Apr, Sep
Fine Solids	Oct	Apr-Jun, Aug, Oct, Nov
Total P	May, Jun, Aug-Nov	Mar-May, Sep, Nov
Fine P	Mar, Oct	Mar-May, Sep-Nov
Coarse P	All	Sep
Leached P	Mar-May, Oct	Sep
Total N	All	Sep
Fine N	May, Jun, Sep, Oct	Jun
Coarse N	All	Apr, Sep
Leached N	Oct, Nov	None

1.7 Conclusions and Limitations

Study Conclusions

1) The quantity of solids and nutrients that can be recovered from street surfaces increases as over-street or near-street tree canopy cover increases.
2) Nutrient concentrations in sweeper waste (phosphorus, nitrogen) increase with increasing tree canopy cover.
3) The mass fraction of nutrients recovered as coarse organics is greater than the mass fraction of solids collected as coarse organics throughout the year (% nutrient mass contribution greater than % mass contribution). A majority of the nitrogen recovered from streets during the study was recovered as coarse organic and coarse organics accounted for from about 10% to 75% of the total phosphorus recovered depending on the time of year and the route tree canopy cover.
4) The mass of street PM per unit length of street in each sweep that can be recovered through street sweeping tends to decrease as sweeping frequency is increased. Regular sweeping at higher sweeping frequencies may result in greater cumulative removal over time, but individual sweepings are less effective (decreased mass recovered per unit effort) at higher frequencies.
5) Negative correlations between sweeping frequency and the leaching rate of fresh coarse organics ('dirty litter') provide evidence that mass may be lost by solids retained street surfaces through leaching in between sweeping events.
6) Recoverable loads of solids and nutrients are highly dependent on season. Recovered solids loads (kg/curb-meter) were greatest in October during fall leaf

drop, followed by spring cleaning operations (March or April) after spring snow melt. Solids were recovered in the early growing season at greater loading intensities (kg/curb-meter) than those recovered later in the summer.

7) Nutrient concentrations in sweeper waste are dependent on season. The character of solids recovered from street changes throughout the year. Nutrient concentrations in sweeper waste reflect these changes.
8) The leaching rate of fresh coarse organics varies with season. The average leaching rate of both phosphorus and nitrogen from coarse organics recovered during May was about five times greater than the leaching rate for coarse organics collected in August.

Study Limitations

It is possible that seasonal influences on recovered loads would be more well-defined if phenological observations and climate data were taken into account. The timing of events which appear to drive peak loading intensity (ex. spring snow melt, fall leaf drop) might be approximated by calendar month, but in reality, the timing of these events may vary from one year to the next on the order of weeks. It may be possible to get a more accurate estimate of expected monthly average recoverable loads for a particular location though extended monitoring of recovered loads; however, such efforts could be complicated by other factors which influence street PM loading rates and which may change over time such as road condition, traffic volume, and changes in land use or vegetative cover.

No formal survey of tree species in swept neighborhoods, or of plant species found in sweeper waste, was conducted during the study, but differences in dominant vegetation (example conifers vs. deciduous trees) are expected to influence results. The routes that were swept during this study were located in suburban neighborhoods where; while conifers are not uncommon, deciduous trees dominate. In general, results should be interpreted as regional in character. Results for localities with significantly different climate and vegetation cannot be inferred from the study; However, we would expect the general pattern of nutrient dynamics to be similar in other residential watersheds located in temperate climates and dominated by deciduous trees.

On a similar note, a limited range of tree canopy covers (percent cover) were included in this study. It is not unlikely that the linear relationship observed between recovered loads and tree canopy cover would be better approximated by a logarithmic relationship if higher canopies covers were included. This is because although higher canopies would be expected to produce greater coarse organic loading to streets, there is a limit to the storage capacity of street surfaces. Additionally, the role of canopy cover distribution patterns (as opposed to an average percent cover) could not be quantified in the study. Trees nearest the street are expected to have the greatest influence on street PM loads, but in this case, the influence of canopy was better described when the canopy cover within a typical front yard distance was used in the analysis. It is not clear that this would be the case if tree canopy were densest near the street or otherwise distributed differently than in study neighborhoods.

Additional street PM dynamics and variation in composition might be explained if precipitation records, mainly rainfall intensity, were taken in to account in the analysis. Daily precipitation records were available for regional climate stations (Chanhassen, MN; Chaska, MN) however; the analysis described here used route average values (annual averages) to make comparisons. Without rain gage data for each sweeping route, it was not possible to consider differences in annual precipitation among the routes; and other metrics, such as total precipitation depth or number of precipitation events between sweepings, are dependent on the sweeping interval (a factor being investigated). An event-based analysis, which was outside the scope of this study, would be needed to consider the role of precipitation in load recovery.

Chapter 2 Predicting Solids and Nutrient Recovery through Street Sweeping in a Suburban Watershed

2.1 Summary

Regression analysis was used to develop predictive metrics for planning street sweeping operations. Regressions were developed based on findings from a recent street sweeping study in Prior Lake, MN. The regressions predict the average expected solids and nutrient recovery by month, sweeping frequency, and tree canopy cover. Metrics for tracking total phosphorus (TP) and total nitrogen (TN) recovery based on the mass of sweepings collected were also developed based on study findings.

2.2 Introduction

Street cleaning, in one form or another, has been performed to address health, safety, and aesthetic concerns for many centuries, and modern, automated sweepers were originally designed to serve this purpose. In more recent decades, with passage of the Clean Water Act (1972) and a growing awareness of the pollution transported in urban stormwater, more attention has been paid to the potential for street sweeping to be used as a water quality best management practice (BMP). Intuitively, street sweeping makes sense. Solids collected from street surfaces are not available for transport to the stormsewer network. But how can street sweeping research be applied in practice?

The goal of the work described in this paper was to translate sweeping research in practical tools. Along these lines, we saw a need for better quantification of solids loading to streets. Reasonable estimates of the mass of solids and nutrients that can be recovered through sweeping could help managers to optimize sweeping programs. Such estimates may also be useful in stormwater quality modeling, where solids loading to BMPs and surface waters may been underestimated. And lastly, watershed manager are increasingly required to document and refine pollutant reduction strategies. Tools for estimating nutrient recovery might help in documenting watershed management activities.

2.3 Previous Studies

Efforts to quantify the effects of street sweeping on urban stormwater quality include several monitoring studies as well as efforts to incorporate street sweeping as a modeled BMP in stormwater quality software packages. Strategies used to quantify the benefits of sweeping have evolved over the last few decades. A brief summary of these efforts is described in sections 2.3.1 - 2.3.3.

2.3.1 Monitoring Studies

Beginning with the National Urban Runoff Program (NURP, 1983), it has proven difficult to quantify the effects of street sweeping based on stormwater monitoring. This is due in part to inherent variability in the composition of urban stormwater. Monitoring studies have typically evaluated street sweeping using stormwater event mean concentrations (EMCs) from paired catchments (control and treatment) or using serial treatment phases. Street particulate matter ('street PM') loads carried by urban stormwater during and after individual precipitation events are dependent on a wide range of factors including rainfall depth, intensity, and frequency; pavement type and condition; traffic density; and road maintenance practices. Furthermore, stormwater composition is influenced by source areas other than streets such as directly and indirectly connected impervious areas, lawns, and particulates that collect in storm sewers. Due to this inherent variability, the number of stormwater samples needed to demonstrate modest differences in stormwater quality between control and treatment is generally high. In the case of NURP, based on sampling frequency and the accuracy of chemical analysis at the time, average stormwater EMC reductions of less than 50%, which occurred in 30 of 50 test cases, were not considered sufficient to demonstrate a positive effect.

More recent monitoring studies have had similar difficulty quanitfying the effects of street sweeping with high confidence. Approximately 40 paired water quality samples were collected in treatment (swept) and control (not swept) basins during a four year period (2003-2007) in Madison, WI (Selbig and Bannerman, 2007). Analysis of variability in sampled stormwater pollutant concentrations indicated that a minimum of 200 paired samples would have been needed to detect a 25% difference between control and treatment EMCs at 95% confidence (0.5 power) for the 26 constituents sampled. An increase in ammonia-nitrogen of 63% was detected (α=0.1 significance level) in one of the treatment basins, but for most constiuents, sampling was not sufficient to demonstrate any significant change. Given these concerns it is not surprising that attempts to quantify stormwater quality improvements associated with street sweeping have sometimes been abandoned due to insufficient sampling (Law et al. 2008) or cost-prohibitive sampling requirements (Seattle Public Utilities 2009).

Other factors complicating efforts to quantify the effects of street sweeping (or any upstream practice) on stormwater EMCs are limitations of stormwater sampling equipment and bias in sampling methods. The particle size sampled by automated samplers is limited by the diameter of the intake (larger coarse organics such as leaves and grass clipping may not be sampled); the velocity of water in the pipe (large inorganic particulates may settle out before reaching the intake); and the depth within the water column at which the sample is collected (a velocity gradient along the water column will tend to bias sampling toward different particle size classes at different depths). Particles larger than the sampler inlet tube (about 1 cm) would never be collected. Newer sampling technologies and alternative methods can be used to address some of these biases (Clark, et al., 2007; Law, 2008; Selbig and Bannerman, 2011) but such biases are likely inherent in historical data.

Paired and serial basin studies have also been conducted using simulated runoff, or wet sampling, which offers a more controlled setting for collecting samples. Results have been mixed. Vaccuum sweeping twice per week was reported to reduce total copper, lead, and zinc concentration in simulated runoff by 71%, 83%, and 69% percent respectively compared to the control basin in San Diego (San Diego Phase I-II, 2010). Rochort and others (2009) used both wet and dry sampling to compare pollutant concentrations in a paired site study. Wet and dry sampling results did not agree, but sweeping produced a significant reduction in TP (dry sampling), Cr (wet sampling), and Zn (wet sampling) compared to the control site.

2.3.2 Modeling Studies

Stormwater modeling software has also been used to quantify expected water quality benefits of street sweeping. Several continuous stormwater modeling software packages include functions intended to simulate removal of street PM through street sweeping (or mechanisms other than runoff which can be adapted to simulate street sweeping). Examples include P8, SIMPTM, WinSLAMM, HSPF, and SWMM. In general these models require information (either field data for calibration or literature values) about street PM accumulation rates, the chemical composition of the street PM, and the removal or pick-up efficiency of the sweeper. Model predictions depend on calibrated parameters associated with functions describing deposition, washoff, or removal of street PM.

Pollutant removal rates for street sweeping reported in modeling studies vary greatly and depend on the context in which they are applied. For example, weekly sweeping with newer sweeping technologies was predicted to reduce TSS in direct drainage by 22% in the Lower Charles River watershed (Zariello et. al, 2001, EPA SWMM); to reduce pollutant washoff by 49-85% depending on land use in Jackson, MI, and by 80% in residential neighborhoods of Portland, OR (Tetra Tech, 2001, SIMPTM) Sutherland and Jelen, 1997, SIMPTM).

A number of efforts to model the effects of street sweeping were untaken by Sutherland and others in the 1990s using the Simplified Particle Transport Model (SIMPTM) (Sutherland and Jelen, 1996; Sutherland and Jelen, 1997; Sutherland et al., 1998). These efforts produced positive results for street sweeping, but also entailed some problem-solving. For example, Sutherland and Jelen (1996) found that the build-up function in the model significantly underestimated accumulations during wet weather. Initially, an exponential function of the form $B = B_{max}(1-e^{-t/T})$ was used to describe build-up. This function predicts the accumulated load based on the elapsed dry period since precipitation or sweeping and limits build-up to some maximum amount. The model was found to be inadequate during the wet weather season, when storm events often resulted in a net accumulation, or 'wash-on', of street PM. This problem was addressed by adding a wash-on function and allowing wash-on to exceed washoff for rainfall events exceeding a specified threshold intensity.

A related problem has been how to adequately account for residual loads remaining after storm events or sweeping (even when these are less than the initial load). In models that use exponential or Michaelis-Menton type functions to describe accumulations, if the time variable resets to zero after a storm event (triggering an initial period of rapid accumulation), the model may overestimate accumulations when residual loads are significant. Zariello and others (2002) encountered this problem using the EPA Storm Water Management Model (SWMM) to simulate the effects of street sweeping on the Charles River, MA.

The Charles River study also found that pollutant removal rates of modeled sweepers were highly sensitive to pollutant washoff coefficients. Adjusting coefficients such that less load was washed off meant that more of the load was available to sweepers and therefore the overall pollutant removal rate for sweeper increased. Conversely, when more of the load was washed off, less was available to sweepers and pollutant removal rates were lowered. This was addressed by using an increased washoff coefficient for small rain events.

One shortcoming of stormwater models is that they may not have the capacity to adequately predict loading and removal of large particulates and coarse organic material (coarse organics, garbage, or other debris) which may comprise a majority of the mass of gross solids that have collected on street surfaces at certain times of the year (Figure 8). Coarse organic material is not typically included in the default particle files used to simulate the export, deposition, re-suspension and wash-off of solids from impervious surfaces (example Figure 14). Sophisticated models (P8, SWMM, WINSLAMM, others) allow users to define particle size distributions (PSDs) and associated characteristics such as build-up, wash-off, and decay rates.

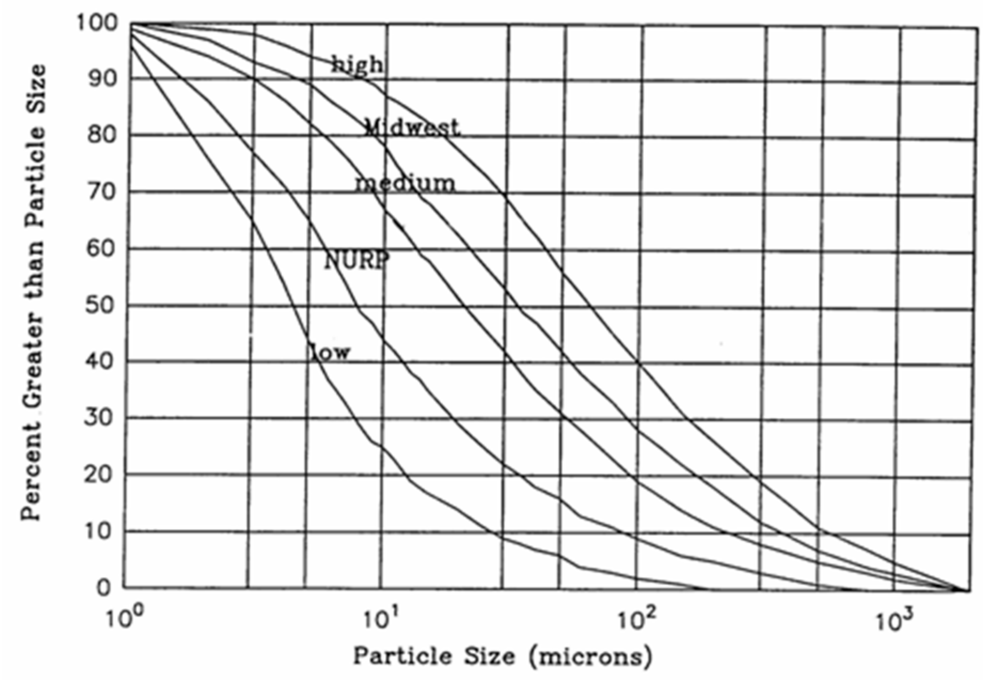


Figure 14. Example of particle size distributions used in stormwater modeling (Pitt and Clark, 2007).

Even when this information can be supplied, other modeling assumptions may be inadequate for describing the transport of vegetation in stormwater. Examples include approximating particles as spheres (Stoke's Law), or assuming a constant particle size distribution for solids exported from source areas. In sections 1.6.5 - 1.6.6, it was shown that both the character and quantity of solids varies with season. Modeling the seasonal variation in coarse organics exported from upland areas would likely require manually editing the source area PSDs and running simulations over seasonal increments, or developing customized routines to add this functionality.

Additionally, the physical characteristics of coarse organic material on street surfaces may depend on time (duration rather than season) and climate conditions. Vegetation on street surface may dehydrate, decompose, or become waterlogged. This complicates modeling the transport of coarse organics. Fresh and dried vegetation may float, but decaying, waterlogged debris may require greater energy for transport. Vegetation that remains on the street surfaces after runoff events can also aggregate forming a mat or 'crust' on pavement or on top of denser sediment accumulations. Some shortcomings in model approximations of solids loading (any solids) and transport are to be expected. Mathematical models cannot generally capture the full suite of variables at play in reality. Nonetheless, coarse organics present some challenges to particle transport modeling that have not typically been addressed in stormwater modeling.

2.3.3 Conceptual Models

Simpler, conceptual models have also been used to estimate effects of street sweeping on downstream water quality. Such models use observed values or literature values for street PM accumulation rates and chemistry along with reported street sweeper efficiencies to estimate potential pollutant reductions that can be achieved through street sweeping. The projected benefits of sweeping depend heavily on model assumptions and the context in which they are applied. The Center for Watershed Protection (CWP) used a conceptual model to compare expected pollutant removal rates (fraction removed ÷ total catchment load) for different sweeper types in two Baltimore area catchments (Law et al., 2008). A 'treatable load' was estimated using street PM accumulation rates observed in study catchments and applying discounts for factors such as parked cars and dust lost which make PM unavailable to sweepers. Street sweeper pick-up efficiencies reported in the literature were applied to this treatable load, and finally the overall reduction in loading was adjusted to take into account pollutant contribution from source areas other than streets. Predicted pollutant removal rates for weekly sweeping with regenerative air technology were modest for TSS (31%) and smaller for TP (8%) and TN (9%). Similar to the Baltimore study, observed street PM accumulation rates and chemistry, and street sweeper efficiencies were applied in estimates of total pollutant recovery for regular sweeping practices in New Bedford, MA (Breault et al., 2005). In this case, pollutant recovery was estimated rather than reductions in downstream pollutant loads.

2.3.4 Focus on Maintenance Practices

Whatever the water quality benefits of sweeping, some portion of this benefit is derived from regular maintenance practices. For stormwater managers, who must often document actions taken to improve water quality for permits and other regulatory requirements, being able to translate maintenance practices into documented pollutant reductions is of great practical use. Furthermore, detailed records of maintenance practices could provide the kind of robust data set that is needed to better define the link between maintenance and water quality (Bateman, 2005).

Most structural water quality BMPs are designed for targeted, or specified minimum pollutant removal efficiencies. While BMPs such as catch basins and sedimentation ponds may achieve design efficiency when first installed, as particulates accumulate, efficiencies are reduced. Regular maintenance of structural BMPs insures that pollutant removal efficiencies are not greatly compromised, and source control BMPs, such as street sweeping, can extend the maintenance lifetime of structural BMPs. With the importance of regular maintenance and good housekeeping practices in mind, a research group at the University of Florida developed a 'Florida-based yard stick' for estimating pollutant recovery through typical stormwater maintenance practices including street sweeping (Beretta et al, 2011). This yardstick is a set of metrics describing the typical chemistry (mg/kg) of PM recovered through street sweeping, catch basin cleaning and a collection of other structural BMPs. The metrics (Appendix H) are based on samples of recovered PM collected from 3 land use areas (each) in 11 MS4 communities around the state of Florida.

The fairly broad geographic basis of the 'Florida based yardstick' helps explain the relatively large coefficients of variation (CVs) seen in the metrics (Appendix H). Presumably, the yardstick could be fine-tuned to smaller geographic areas or to take into account other factors that influence the composition of street PM such as season or tree canopy cover. Along this line of thinking, the sections that follow describe how the relationships outlined in Chapter 1 were used in the development of two tools for use in the greater Minneapolis-St. Paul Regional area: (1) a set of regressions for predicting solids and nutrient recovery potential; and (2) a set of regional metrics for tracking nutrient recovered through street sweeping.

2.4 Study Overview and Background

The Prior Lake street sweeping study was designed to study the influence of sweeping frequency and overhead tree canopy cover on recovered solids and nutrients (TP, TN, and TOC). Over a two-year period, the total mass of solids and nutrients recovered through individual sweeping events was analyzed and recorded for nine sweeping routes. Sweeping frequency was tested at intervals of one week, two weeks, and four weeks and sweeping routes were chosen to test three values of tree canopy cover - 'high', 'medium', and 'low'(3 x 3 factorial design). Given the duration of the experiment (regular sweeping was conducted during the entire snow-free season over a two-year period) it was also possible to assess the influence of season on recovered loads. Relationships between average recovered loads (solids and nutrients) and these three variables are discussed in Chapter 1. Additional details about experimental design and sweeping route characteristics can be found in section 1.4 and Appendix C - Appendix E. Field and laboratory methods are described in section 1.5 and section 1.5.2.

2.5 Development of Regional Regressions for Predicting Solids and Nutrient Recovery

Our approach in developing predictive metrics was to build on the multiple linear regressions (MLRs) described in section 1.6.4. While the regressions describing these relationships demonstrate the significance of tree canopy as a predictor for average or annual load recovery, they are of limited practical use for planning sweeping operations. A more practical tool would take into account the influence of season (see section 1.6.6) and adjust the expected load recovery accordingly. Sections 2.5.1 - 2.5.3 describe the strategies used to develop and validate regressions that do so.

2.5.1 Distribution Characteristics of Response Variables

Linear regressions predict average expected values for the response and are appropriate if there is a central tendency (normal distribution) in the observed data. Analysis of the distribution of recovered loads (kg/curb-km) supports this assumption. Recovered loads for the period March – November appeared to follow log-normal or exponential distributions (Figure 15 - Figure 21). The log-normal distribution hypothesis was tested using the Shapiro-Wilk normality test. Note that the null hypothesis for this test is the normal distribution, so larger p-values indicate a greater likelihood of a normal distribution. Based on p-values for this this test (see figure captions), total solids, total phosphorus, fine fraction phosphorus, and total nitrogen loads recovered were well-approximated by a log-normal distribution for the months March – November (significant at $\alpha = 0.05$). The null hypothesis (normal distribution) was rejected in all other tests; however, p-values were several orders of magnitude larger for each load component when log values were tested.

2.5.1.1 *Sweeper Waste*

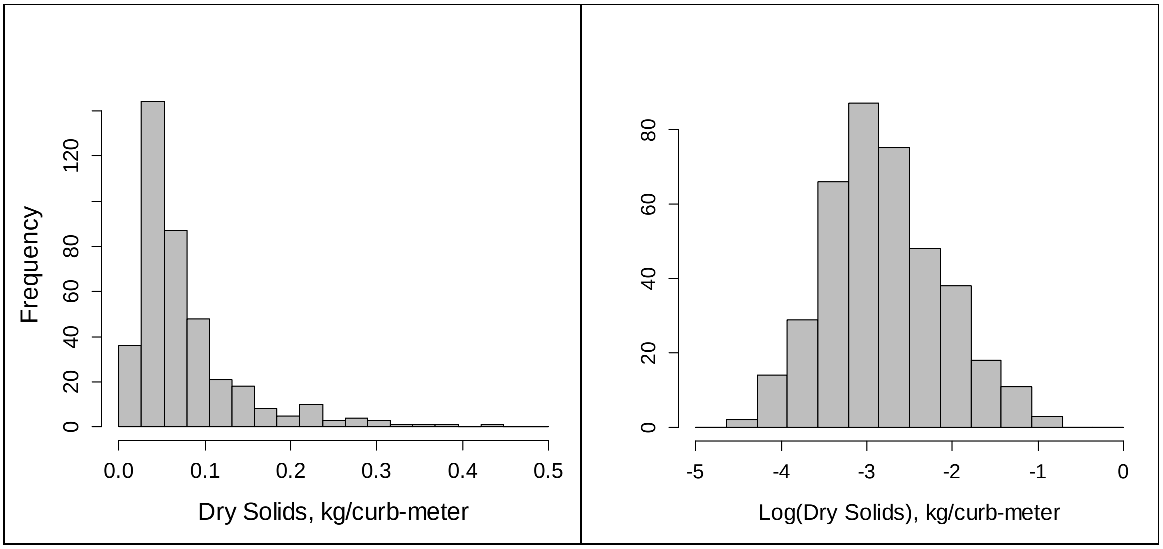


Figure 15. Distribution of recovered total solids loads (sweeper waste) for the months March-November (n=392). Shapiro-Wilk test: $p<2.2e-16$ for dry solids, $p=0.005$ for log(dry solids).

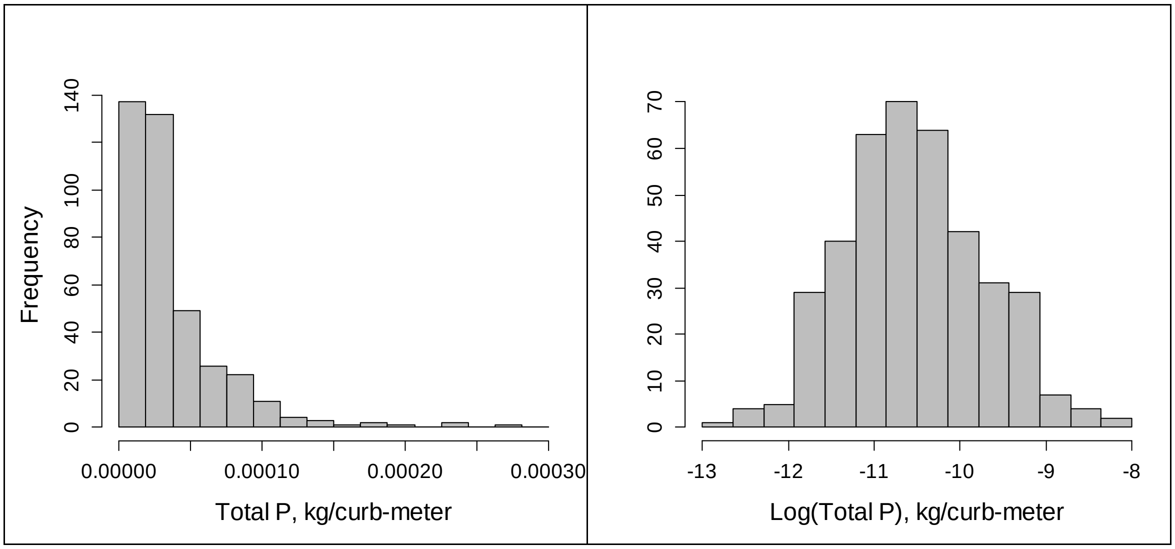


Figure 16. Distribution of recovered phosphorus loads for the months March-November (n=392). Shapiro-Wilk test: $p<2.2e-16$ for total phosphorus, $p=0.32$ for log(total phosphorus).

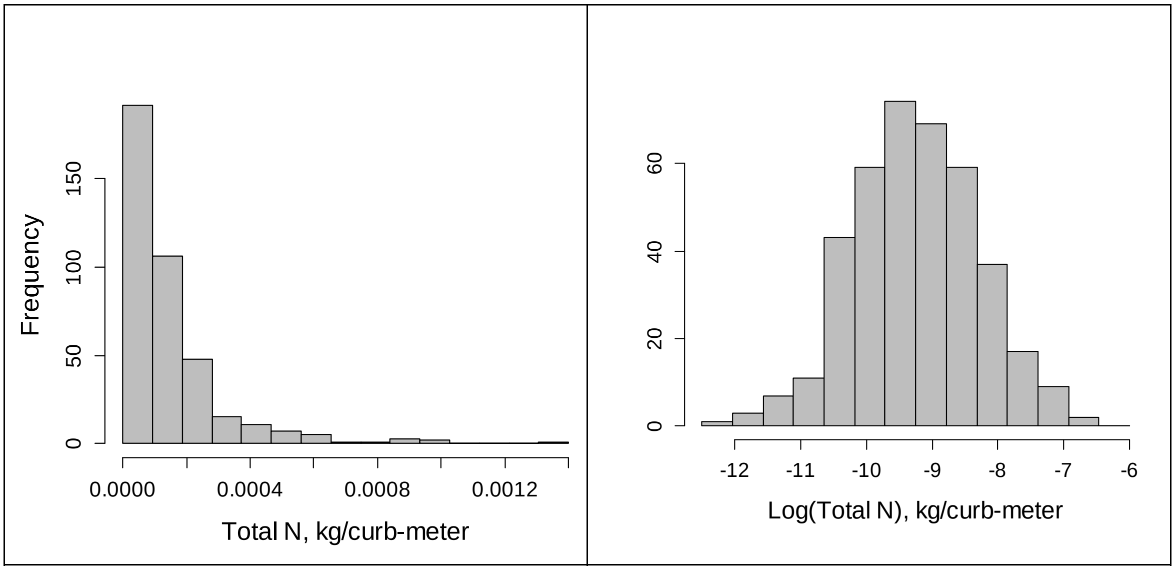


Figure 17. Distribution of recovered nitrogen loads for the months March-November (n=392). Shapiro-Wilk test: $p<2.2e-16$ for total nitrogen, $p=0.94$ for log(total nitrogen).

2.5.1.2 Fine Fraction of Sweeper Waste

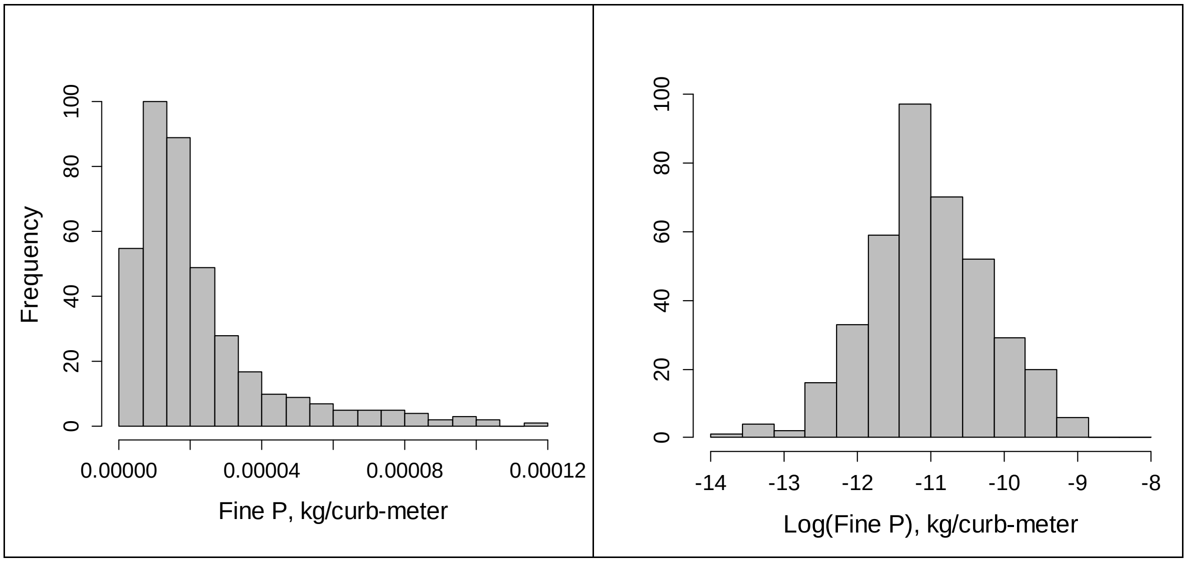


Figure 18. Distribution of fine phosphorus loads for the months March-November (n=392). Shapiro-Wilk test: p<2.2e-16 for fine phosphorus, p=0.16 for log(fine phosphorus).

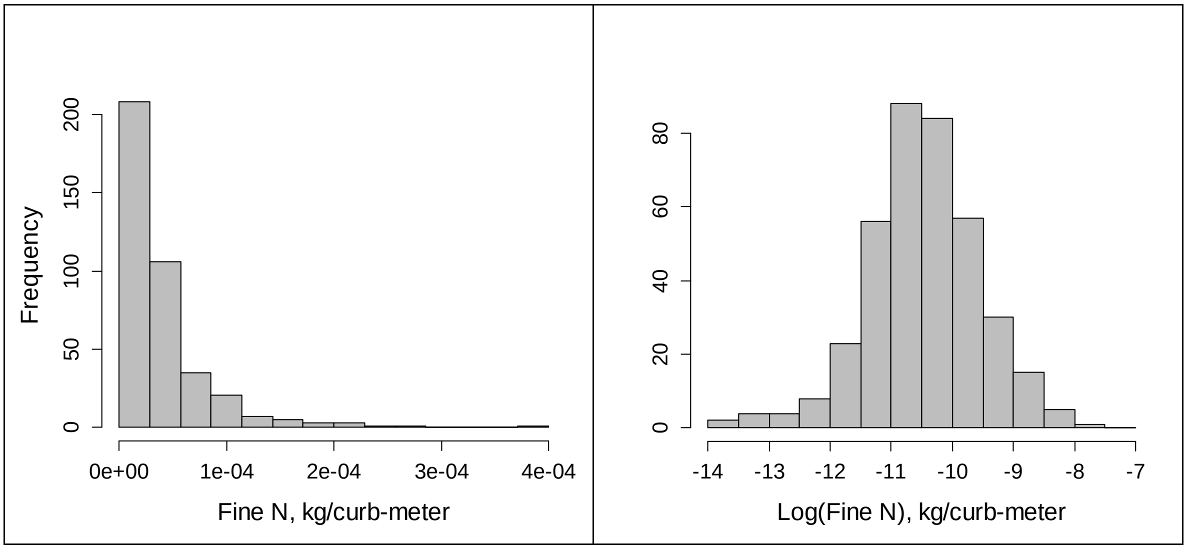


Figure 19. Distribution of recovered fine nitrogen loads for the months March-November (n=379). Shapiro-Wilk test: p<2.2e-16 for fine nitrogen, p=0.003 for log(fine nitrogen).

2.5.1.3 Coarse Fraction of Sweeper Waste

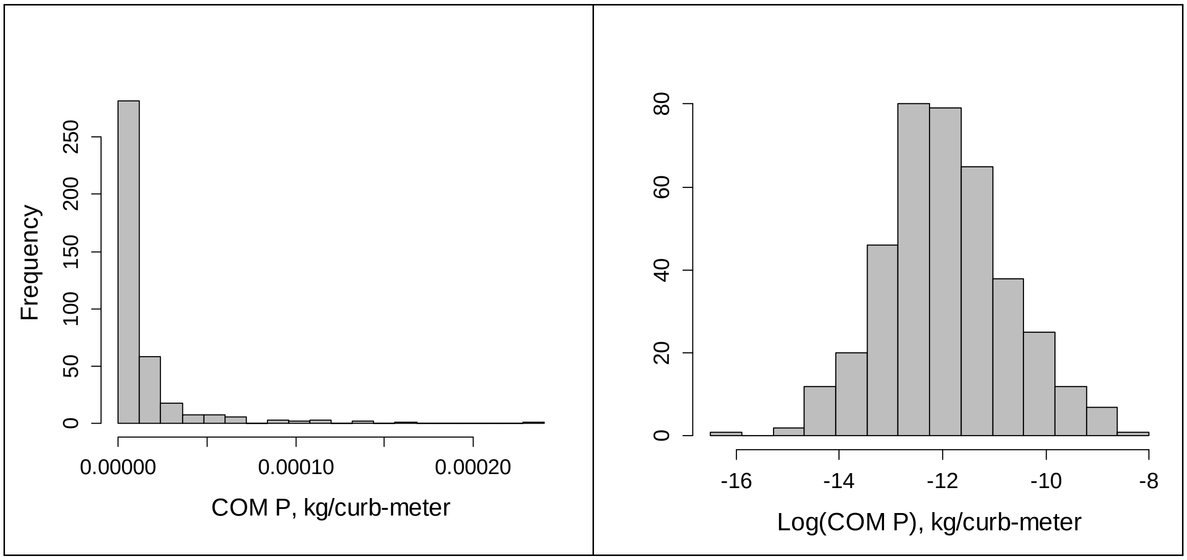


Figure 20. Distribution of recovered coarse phosphorus loads for the months March-November (n=392). Shapiro-Wilk test: $p<2.2e-16$ for coarse phosphorus, $p=0.003$ for log(coarse phosphorus).

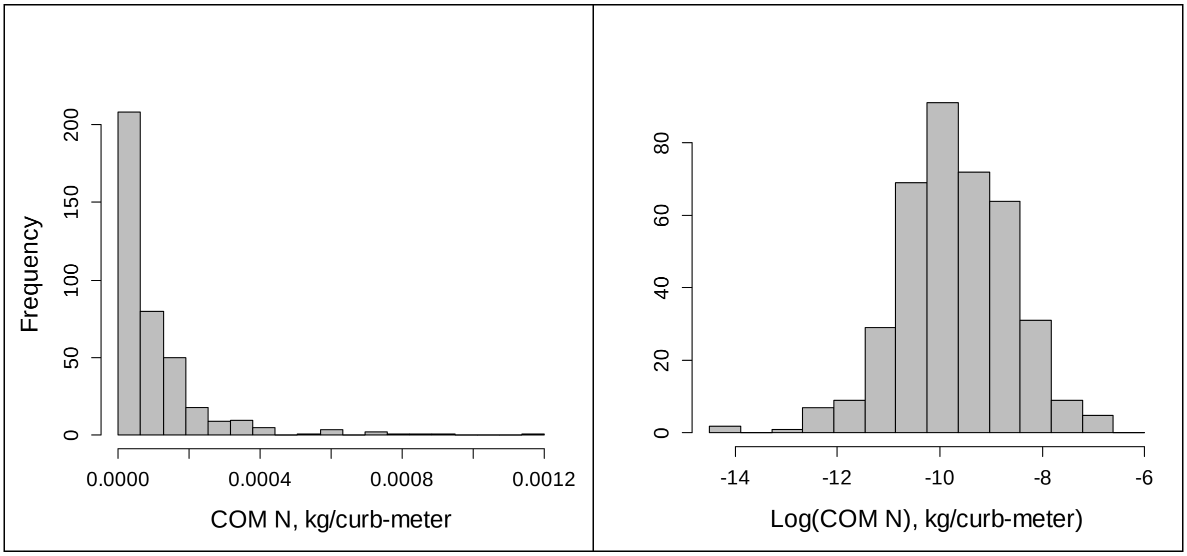


Figure 21. Distribution of recovered coarse nitrogen loads for the months March-November (n=392). Shapiro-Wilk test: $p<2.2e-16$ for coarse nitrogen, $p=0.004$ for log(coarse nitrogen).

As described in Chapter 1, clear seasonal patterns were seen in both the composition of sweeper waste (sections 1.6.5) and the quantity of sweeper waste collected (section 1.6.6). Given this characteristic and the general pattern observed in load distributions, it was hypothesized that recovered loads (kg/curb-meter) would follow a log-normal distribution within season windows. Shapiro-Wilk tests were repeated after the data were subset by month. For sweeper waste, the null hypothesis was accepted for all subsets when the log distribution was tested (Table 11). For the fine and coarse fractions, the null hypothesis was accepted for most constituents across most months (Table 12). Results of these tests support the application of log-transformation in regression analysis.

Table 11. P-values for Shapiro-Wilk normality tests for subsets of total solids and nutrient loads defined by calendar month. Tests for which the null hypothesis was rejected are shown in *grey italic font.*

	Dry Solids (kg/curb-meter)		Total Phosphorus (kg/curb-meter)		Total Nitrogen (kg/curb-meter)	
Month	**Dry Solids**	**Log(Dry Solids)**	**Total P**	**Log (Total P)**	**Total N**	**Log (Total N)**
March	*0.0298*	0.6766	*0.0460*	0.7679	*0.0056*	0.1806
April	*2.78E-05*	0.3031	*7.52E-05*	0.0998	*6.50E-05*	0.4750
May	*2.59E-07*	0.5573	*3.06E-06*	0.1630	*4.12E-04*	0.3968
June	*1.58E-07*	0.1493	*1.14E-05*	0.0687	*7.17E-07*	0.4584
July	*8.25E-04*	0.3575	*4.58E-05*	0.4124	*8.42E-05*	0.6942
August	*5.66E-05*	0.9011	*1.20E-06*	0.0814	*1.28E-04*	0.9229
September	*5.37E-04*	0.5675	*1.45E-05*	0.2334	*1.65E-04*	0.6609
October	*1.8E-04*	0.6250	*1.12E-04*	0.6459	*1.34E-04*	0.2630
November	*1.05E-06*	0.8270	*2.41E-07*	0.5056	*1.44E-07*	0.6704

Table 12. P-values for Shapiro-Wilk normality tests for subsets of sweeper load components defined by calendar month. Tests for which the null hypothesis was rejected are shown in *grey italic font.*

	Log(Fine Solids)	**Log(Coarse Solids)**	**Log(Fine P)**	**Log(Coarse P)**	**Log(Fine N)**	**Log(Coarse N)**
March	0.9955	*0.0117*	0.1900	0.1761	0.1480	*0.0254*
April	0.5666	0.3719	0.1523	0.1627	0.5362	0.2761
May	0.1434	0.1935	*0.0169*	0.5259	0.9680	0.6477
June	0.0506	0.6004	0.5545	0.6283	*0.0421*	0.5692
July	0.0542	0.8305	*0.0143*	0.8969	*0.0220*	0.7802
August	0.4040	0.7119	0.2196	0.1206	0.8594	0.8768
September	0.6474	0.0901	0.7887	0.5764	0.1189	0.4795
October	0.7423	*0.0255*	0.6666	0.1745	0.7012	0.1118
November	0.3825	0.7268	0.9478	0.3915	0.5773	0.4259

2.5.2 Regression Analysis

Sweepings that occurred during the months December through February were not included in the data set used for regression analysis. Data for these months was sparse with observations limited to year 1 or year 2 only for January and February. Furthermore, road maintenance practices (e.g., sanding and salting) which would heavily influence winter street PM loads, could not be evaluated.

As discussed in (section 1.5.3) after the study was underway, spatial analysis was used to quantify tree canopy as a percent canopy cover over the street and within various distances from the curb. Due to the degree of variability in canopy covers, tree canopy was treated as a continuous variable rather than a factor. For example, there was a strong linear relationship between overhead tree canopy cover and the average total solids and nutrient recovered (Section 1.6.4) and the average nutrient content of sweeper waste (Section 1.6.3). Although the correlations described in section 1.6.3 and section 1.6.4 were generally stronger when the canopy cover within 20ft of the curb was used in the analysis, it was not clear that this would be the case in other settings. The effect of different canopy cover distributions on recovered loads could not be tested using the Prior Lake data set (distribution patterns were similar although density varied, see section 1.6.1). For this reason, over-street canopy cover (which has a similar, though somewhat weaker influence on recovered loads in this case) was deemed a more appropriate predictor for recovered loads in other regional settings.

The regression analysis outlined in section 1.6.4 used a compressed data set (route average values) to describe the over-arching relationship between recovered loads and two prediction variables (tree canopy cover and sweeping interval). In order to use month as a prediction variable, the full data set of observed sweeping was used (n = 392). In doing so, the amount of variability in the response variables was greatly increased. As a result, the goodness of fit (R2) for regressions predicting monthly averages (Table 13) was generally much lower than for regressions predicting annual averages for recovered loads (Table 8). The effect of increasing variability in the responses variable can be seen in Table 14 where goodness of fit for different regression strategies is compared.

Despite the reduced goodness of fit, the regressions in Table 13 demonstrate the strength of the prediction variables. In all cases, the regressions, as well as individual coefficients for the intercept (β_o), tree canopy cover (β_2), and sweeping frequency (β_3), were significant at the α= 0.05 significance level. In a majority of cases, month factors were also significant (Table 15). The regression for coarse organic loads is the only case in which fewer than half of the month factors were significant predictors of the average recovered load.

Table 13. Regressions predicting recoverable loads (average) based on the month in which sweeping occurred, over-street tree canopy, and the frequency of sweeping (1, 2, or 4 times per 4-week interval). All coefficients shown were significant at $\alpha = 0.05$.

Log(Load Component, kg/curb-meter) =
$\beta_o + \beta_{month} + \beta_2$(Canopy Cover*) + β_3(Average Sweeping Interval*)

Load Component	β_o	β_{month}	β_2	β_3	R^2	p-value
Dry Solids	1.8E-03	(See Table 15)	9.0E-04	-5.6E-05	0.45	<2.2e-16
Fines	1.7E-03		4.8E-04	-5.0E-05	0.43	
Coarse Organics	7.1E-04		2.8E-03	-7.1E-05	0.60	
Total P	-3.5E-04		1.3E-03	-6.7E-05	0.42	
Fine P	-3.6E-04		7.1E-04	-6.9E-05	0.34	
Coarse P	-1.1E-03		2.6E-03	-6.5E-05	0.56	
Leached P	-2.2E-03		2.5E-03	-6.4E-05	0.33	
Total N	-3.8E-04		2.2E-03	-6.1E-05	0.46	
Fine N	-6.0E-04		1.3E-03	-6.0E-05	0.24	6.1e-16
Coarse N	-5.9E-04		2.5E-03	6.3E-05	0.49	2.2e-16
Leached N	-1.7E-03		1.4E-03	-4.6E-05	0.27	9.3e-13

*Over-street canopy cover as a decimal fraction; sweeping interval in weeks.

Table 14. Comparison of goodness of fit for regressions predicting average annual load recovery (kg/curb-meter) and monthly average load recovery (kg/meter) as increased degrees of variability are included in the response variable.

Load Component (Response Variable)	**R^2**		
	Case A*	**Case B***	**Case C***
Dry Solids	0.63	0.56	0.45
Fines	0.55	0.57	0.43
Coarse Organics	0.79	0.71	0.60
Total P	0.86	0.57	0.42
Fine P	0.81	0.54	0.34
Coarse P	0.89	0.69	0.56
Leached P	0.75	0.48 (n=155)	0.33
Total N	0.88	0.58	0.46
Fine N	0.73	0.41 (n=154)	0.24
Coarse N	0.90	0.61 (n=154)	0.49
Leached N	0.72	0.40 (n= 111)	0.27

* Case A – fit for regression using annual average values for the response variable and tree canopy and sweeping frequency as predictors (from Table 7) .

Case B - fit for regressions using monthly average values for the response variable (average loads by route/month) and month, tree canopy, and sweeping frequency as predictors, n = 156 unless otherwise noted.

Case C – fit for regressions using the full data set with month, tree canopy, and frequency as predictors (as listed in Table 13).

Table 15. Coefficients for $\beta1$ for regressions described in Table 13. Coefficients which were not significant at $\alpha = 0.05$ are shown in *gray italic font*.

Month*	Dry Solids	Fines	Coarse Organics	Total P	Fine P	Coarse P	Leached P	Total N	Fine N	Coarse N	Leached N
April	-1.4E-04	-1.3E-04	*1.6E-05*	-1.1E-04	-1.1E-04	*-2.0E-05*	3.3E-04	1.3E-04	1.7E-04	1.4E-04	3.7E-04
May	-2.7E-04	-2.6E-04	*-2.9E-05*	-1.7E-04	-2.0E-04	*4.8E-05*	4.6E-04	1.5E-04	1.6E-04	1.8E-04	4.3E-04
June	-3.0E-05	-2.9E-04	*-5.2E-05*	-2.1E-04	-2.3E-04	*2.5E-05*	3.1E-04	1.3E-04	1.4E-04	1.6E-04	3.9E-04
July	-3.6E-04	-3.6E-04	-1.5E-04	-3.3E-04	-3.5E-04	-1.1E-04	2.1E-04	*4.2E-06*	*1.6E-05*	*3.7E-05*	*2.6E-04*
August	-3.3E-04	-3.3E-04	*1.3E-05*	-2.7E-04	-3.2E-04	*4.7E-05*	2.1E-04	1.1E-04	*5.0E-05*	1.9E-04	*2.0E-04*
September	-3.8E-04	-4.0E-04	*7.6E-05*	-2.6E-04	-3.7E-04	1.4E-04	2.1E-04	1.3E-04	*4.5E-05*	2.2E-04	6.3E-05
October	-2.3E-04	-3.7E-04	4.6E-04	*-8.2E-06*	-2.7E-04	5.4E-04	5.0E-04	3.7E-04	1.7E-04	2.1E-04	4.3E-04
November	-3.1E-04	-4.2E-04	2.6E-04	-1.5E-04	-3.3E-04	2.9E-04	2.8E-04	1.6E-04	*-2.6E-05*	4.9E-04	*2.1E-04*

* $\beta_{month} = 0$ for March (baseline condition).

Given that month was not always a significant predictor of sweeper waste components loads, the use of recursive partitioning based on anova testing of the response variable was considered as an alternative to MLR analysis. In this type of analysis, a greedy algorithm is applied recursively to find a locally optimal solution to a decision criterion. Regression trees were developed for several recovered load types using the R analysis package ‘rpart’ which uses anova testing as the decision criterion. While fits for regression trees were slightly better than for corresponding MLRs (R^2 typically 0.02 - 0.04 higher), there was no gain in simplicity. Models were less intuitive than MLRs since the analysis resulted in different splitting junctions for each recovered load type whereas MLRs used the same splitting criterion (month) for all types.

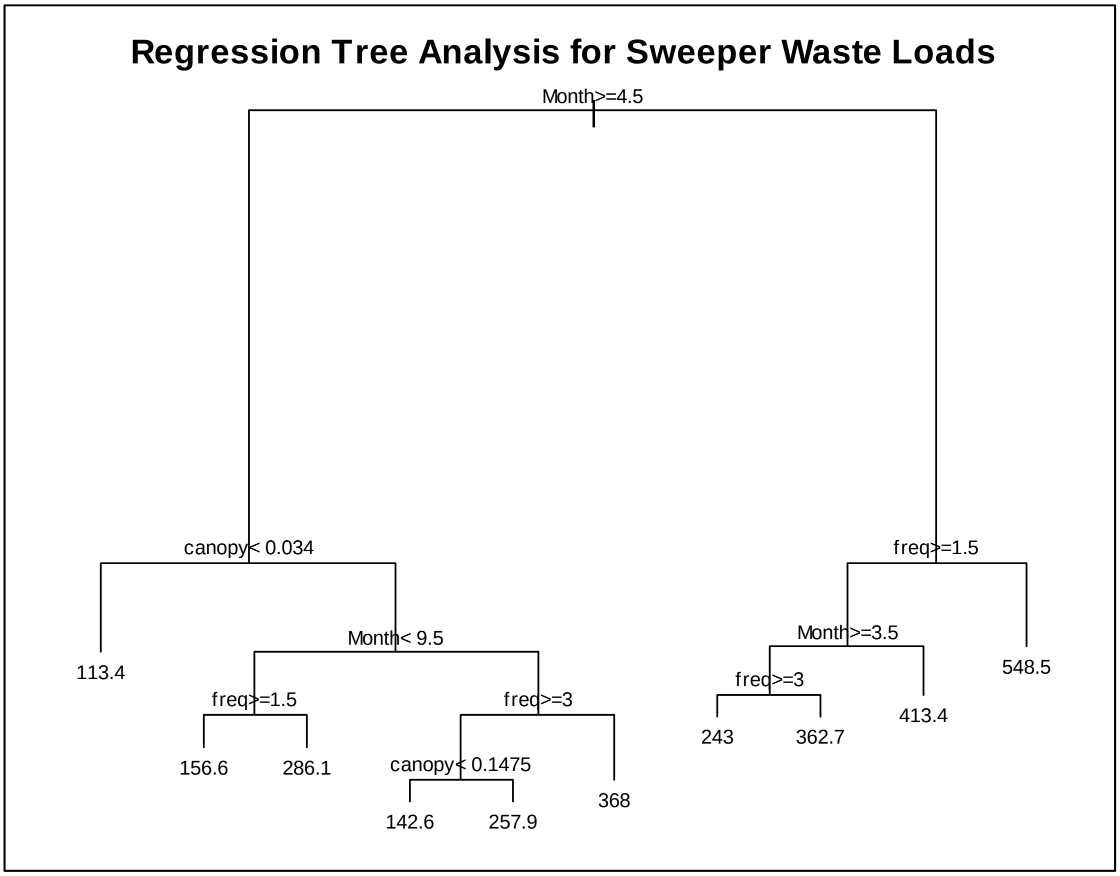


Figure 22. Example of recursive partitioning using anova splitting criterion (means for response variable tested). Sweeper waste samples (lb/curb-mile) meeting the specified criterion at each junction are partitioned to the left side of the junction. In the figure, 'canopy' refers to the tree canopy cover over the street and 'freq' refers to the sweeping frequency (1X, 2X, or 4X per 4-week cycle).

2.5.3 Cross-validation Results

Regression model predictions were validated using a five-fold cross-validation procedure. In this procedure, the data set is randomly divided into five subsets and the model 'trained' using 4 of the five subsets. Recovered loads are then predicted for the 'test' subset. By sequentially exchanging one of the training subsets and the test subset, a prediction for the entire data set can be obtained. A five-fold cross validation was chosen over a simple calibration-validation procedure using half of the data set, so that conditions which were observed infrequently, in particular values for component loads in once per month sweeping zones, would be adequately represented in the model development. The entire cross-validation procedure was repeated with similar results in several trials. The average result from 10 trials for various recovered load types is shown in Table 16. Prediction errors ranged from approximately -10% to -22% for most load types. Prediction errors were greater for recovered leached nutrients (31% for leach phosphorus, 20% for leached nitrogen); however the leached component was a relatively small portion of total nutrient loads (typically less than 2% of the total phosphorus and less than 3% of the total nitrogen).

Table 17 shows average prediction results when regressions were developed using untransformed response variables. Although the magnitude of prediction errors was generally smaller when recovered loads were predicted in the domain corresponding to that of samples loads (untransformed response), recovered loads were over-predicted and goodness of fit (R^2) was generally reduced for these regressions. Log-transformation may offer a more conservative prediction - appropriate for estimating load recovery credits, but with some risk of underestimating operational costs associated with hauling and disposal of sweeping waste. These regressions were incorporated into a spreadsheet calculator tool which is available through the University of Minnesota's Stormwater U program: (http://www.extension.umn.edu/environment/stormwater/pastNov13.html)

Table 16. Five-fold cross-validation results for regression described in Table 13 and Table 15 (response variable log-transformed). Load components that were for which regional metrics were derived have been highlighted in yellow.

Load Component* (dry weight)	**Total Collected (kg)**	**5-fold cross validation result (kg)**	**% Error**
Fresh Solids	360,409	323,823	-10.2%
Dry Solids	**263,609**	**237,650**	**-9.8%**
Fine Solids	187,567	165,842	-11.6%
Coarse Organics	41,627	33,879	-18.6%
Fine +Coarse	229,193	203,941	-11.0%
Fine phosphorus	122.7	102.9	-16.3%
Coarse phosphorus	73.7	57.5	-22.0%
Leached Phosphorus (n=385)	3.2	2.2	-31.2%
Total Phosphorus (n=385)	**199.6**	**170.5**	**-14.6%**
Fine Nitrogen (n=377)	226.8	176.9	-22.1%
Coarse Nitrogen	568.9	464.8	-18.3%
Leached Nitrogen (n=273)	9.6	6.8	-28.8%
Total Nitrogen (n=262)	**805.4**	**674.2**	**-16.3%**

*n = 392 unless otherwise noted.

Table 17. Five-fold cross-validation results for regressions developed using untransformed response variables. Load components that were for which regional metrics were derived have been highlighted in yellow**.**

Load Component* (dry weight)	**Total Collected (kg)**	**5-fold cross validation result (kg)**	**% Error**
Fresh Solids	360,409	372,458	+3.3%
Dry Solids	**263,609**	**270,794**	**+2.7%**
Fine Solids	187,567	190560.7316	+1.6%
Coarse Organics	41,627	44,693	+7.4%
Fine +Coarse (dry wt)	229,193	233,852	+2.0%
Fine phosphorus	122.7	125.6	+2.4%
Coarse phosphorus	73.7	79.0	+7.2%
Leached Phosphorus (n=385)	3.2	3.4	+6.8%
Total Phosphorus (n=385)	**199.6**	**207.3**	**+3.8%**
Fine Nitrogen (n=377)	226.8	235.0	+3.6%
Coarse Nitrogen	568.9	599.4	+5.4%
Leached Nitrogen (n=273)	9.6	10.0	+3.8%
Total Nitrogen (n=262)	**805.4**	**843.6**	**+4.7%**

*n = 392 unless otherwise noted.

2.6 Development of Regional Metrics for Tracking Nutrient Recovery

The MLRs discussion in section 0 and section 2.5.3 predict the average expected recovery based the distance to be swept, the timing of planned sweepings, and the average overhead tree canopy cover along the route. They are intended for use in optimizing the design of sweeping programs. Expected load recovery for different sweeping scenarios (ex. annual vs. monthly sweeping) can be used to predict the cost-effectiveness of changes in sweeping programs. (Information on the cost-efficiency and cost-effectiveness of street sweeping conducted during the pilot study is reported in Kalinosky et al., 2014). Since actual load recovery for any particular sweeping event is expected to differ from predicted load recovery, practitioners may also need a method for tracking nutrient recovery based on the actual mass recovered. Below, we provide nutrient concentration data for sweeper waste that can be multiplied by actual sweeper loads to obtain more precise estimates of sweeper load nutrient content.

Total phosphorus and nitrogen concentrations in sweeper loads (Table 18 -

Table 20) were developed taking into account relationships described in Chapter 1 and section 2.5.1. Key findings that were incorporated into the development of the metrics include the following:

- Season (month) has a marked influence on concentration of nutrients in sweeper waste (1.6.5).
- Sweeping frequency has little influence or no influence on the nutrient concentration in sweeper waste (1.6.3).
- Although season had a significant influence on the nutrient concentrations in coarse organic solids, percent tree canopy was only weakly – moderately correlated to nutrient concentration in coarse organics (1.6.3).
- Most recovered loads types (ex. fines, coarse organics, total phosphorus) can be reasonable described using a log-normally distribution (2.5.1).

The strategy used in the development of metrics is further described below.

Table 18. Potential metrics for tracking nutrient recovery through street sweeping for the Minneapolis-St. Paul regional for recovered sweeper waste.

		Sweeper Waste (contributing fractions)*					
Over-Street Tree Canopy Cover	**Month**	**TP (mg/kg)**			**TN (mg/kg)**		
		Mean	Median	CV	Mean	Median	CV
Low <2%	Mar	686	**639**	0.32	212	**206**	0.15
	Apr	660	**594**	0.28	888	**856**	0.55
	May	742	**696**	0.31	1693	**1736**	0.38
	Jun	770	**731**	0.38	2457	**2264**	0.46
	Jul	651	**637**	0.29	1892	**1821**	0.48
	Aug	654	**656**	0.32	3060	**2878**	0.41
	Sep	745	**739**	0.22	3651	**3175**	0.40
	Oct	1114	**1082**	0.37	4592	**4293**	0.41
	Nov	883	**824**	0.31	2940	**2734**	0.69
Medium 2% - 15%	Mar	612	**639**	0.43	931	**793**	0.33
	Apr	692	**673**	0.26	2252	**2016**	0.68
	May	856	**848**	0.22	3010	**2570**	0.42
	Jun	900	**890**	0.41	5028	**5344**	0.60
	Jul	787	**675**	0.40	2774	**2298**	0.42
	Aug	855	**722**	0.41	4177	**3854**	0.35
	Sep	982	**1033**	0.25	5138	**5151**	0.33
	Oct	1441	**1465**	0.24	6646	**5723**	0.25
	Nov	1331	**1193**	0.22	5857	**5644**	0.24
High >15%	Mar	749	**643**	0.63	627	**793**	0.00
	Apr	663	**673**	0.19	2492	**2390**	0.30
	May	1014	**989**	0.36	5388	**3910**	0.58
	Jun	972	**890**	0.56	6796	**6683**	0.56
	Jul	733	**680**	0.38	2810	**2899**	0.37
	Aug	804	**808**	0.37	4228	**3854**	0.45
	Sep	1040	**1049**	0.31	5499	**5253**	0.34
	Oct	1610	**1635**	0.23	8480	**7727**	0.25
	Nov	1181	**1193**	0.27	5829	**6372**	0.37

Font Key: Values shown in **bold blue font** are the result of averaging low and medium, or all canopy cover results for the given month/load type. Values shown in **bold orange font** are the results of averaging medium and high canopy cover results.

* Does not include mass of Rocks and trash.

Table 19. Potential metrics for tracking nutrient recovery through street sweeping for the Minneapolis-St. Paul regional for recovered fines.

		Fine Fraction					
		TP (mg/kg)			**TN (mg/kg)**		
Over-Street Tree Canopy Cover	**Month**	Mean	Median	CV	Mean	Median	CV
Low <2%	Mar	661	**588**	0.31	190	**160**	0.49
	Apr	624	**561**	0.29	609	**560**	0.52
	May	669	**635**	0.33	1062	**910**	0.50
	Jun	676	**673**	0.37	1284	**1160**	0.57
	Jul	558	**506**	0.31	1047	**1075**	0.47
	Aug	539	**536**	0.31	1222	**1070**	0.45
	Sep	561	**577**	0.33	1382	**1210**	0.65
	Oct	682	**596**	0.46	1685	**1649**	0.51
	Nov	676	**613**	0.34	1150	**1139**	0.75
Medium 2% - 15%	Mar	552	**588**	0.49	545	**440**	0.67
	Apr	612	**561**	0.26	1547	**1170**	0.76
	May	679	**650**	0.24	1624	**1285**	0.61
	Jun	716	**673**	0.44	1869	**1770**	0.69
	Jul	664	**574**	0.43	1549	**1110**	0.59
	Aug	650	**544**	0.52	1369	**1120**	0.49
	Sep	704	**643**	0.41	1731	**1520**	0.49
	Oct	1008	**842**	0.37	2786	**2087**	0.47
	Nov	1013	**941**	0.35	2548	**2030**	0.76
High >15%	Mar	591	**588**	0.78	467	**450**	0.63
	Apr	546	**561**	0.22	1256	**1170**	0.50
	May	757	**721**	0.41	2249	**1770**	0.53
	Jun	841	**722**	0.53	2312	**1815**	0.69
	Jul	584	**574**	0.43	1629	**1110**	0.95
	Aug	594	**564**	0.24	1374	**1221**	0.64
	Sep	762	**643**	0.52	2128	**1750**	0.66
	Oct	1045	**1072**	0.54	3258	**2087**	0.85
	Nov	778	**941**	0.41	2043	**2030**	1.07

Font Key: Values shown in **bold blue font** are the result of averaging low and medium, or all canopy cover results for the given month/load type. Values shown in **bold orange font** are the results of averaging medium and high canopy cover results.

Table 20. Potential metrics for tracking nutrient recovery through street sweeping for the Minneapolis-St. Paul regional for recovered coarse organics.

		Coarse Organic Fraction					
Over-Street Tree Canopy Cover	**Month**	**TP (mg/kg)**			**TN (mg/kg)**		
		Mean	Median*	CV	Mean	Median*	CV
Low <2%	Mar	1631	**921**	0.62	10188	**9715**	0.21
	Apr	1586	**1388**	0.38	17545	**15698**	0.32
	May	2004	**2033**	0.23	23476	**22194**	0.23
	Jun	1916	**1875**	0.26	22326	**21941**	0.23
	Jul	1795	**1719**	0.15	22128	**19794**	0.17
	Aug	1839	**1677**	0.58	20248	**19076**	0.23
	Sep	1921	**1835**	0.34	18990	**16790**	0.22
	Oct	2149	**1911**	0.40	11845	**11261**	0.23
	Nov	1699	**1658**	0.25	10699	**9983**	0.20
Medium 2% - 15%	Mar	1271	**921**	0.37	10423	**9715**	0.25
	Apr	1306	**1388**	0.29	16012	**15698**	0.24
	May	1972	**2033**	0.25	21557	**22194**	0.18
	Jun	2111	**1875**	0.21	22084	**21941**	0.15
	Jul	1697	**1719**	0.22	19118	**19794**	0.15
	Aug	1930	**1677**	0.37	19776	**19076**	0.12
	Sep	1894	**1835**	0.23	16217	**16790**	0.14
	Oct	1857	**1911**	0.26	10846	**11261**	0.09
	Nov	1710	**1658**	0.18	10204	**9983**	0.06
High >15%	Mar	1398	**921**	0.35	10495	**9715**	0.30
	Apr	1074	**1388**	0.27	14877	**15698**	0.25
	May	1854	**2033**	0.29	19835	**22194**	0.24
	Jun	1811	**1875**	0.26	19769	**21941**	0.17
	Jul	1598	**1719**	0.28	18054	**19794**	0.17
	Aug	2025	**1677**	0.57	17529	**19076**	0.22
	Sep	1770	**1835**	0.16	15214	**16790**	0.13
	Oct	1924	**1911**	0.19	11562	**11261**	0.12
	Nov	1562	**1658**	0.22	9652	**9983**	0.16

* Median values for coarse organic phosphorus and coarse organic nitrogen are monthly medians for all sweepings (no tree canopy dependence per section 1.6.3).

Since metrics for tracking nutrient recovery are based on nutrient concentrations in sweeper waste (rather than expected recovered mass), the distribution of TP and TN concentrations in sweeper waste and component fractions were inspected to determine the appropriate statistic to represent typical nutrient concentrations (example Figure 23, Figure 24). Fine fraction nutrients (TP and TN) and total sweeper waste TP were reasonably approximated by a log-normal distribution, but total sweeper waste TN and coarse fraction nutrients (TP, TN) were not; nor were they described by a normal distribution. All nutrient concentration distributions included some extreme values on the high end, giving them a characteristic skewness. Based on these observations and assessment, it was decided that a median value would best represent a 'typical concentration' within any category and would be the appropriate concentration to multiply by sweeper load mass in nutrient recovery estimates. Using an average value would likely overestimate concentrations since the average value would be influenced by extreme high values.

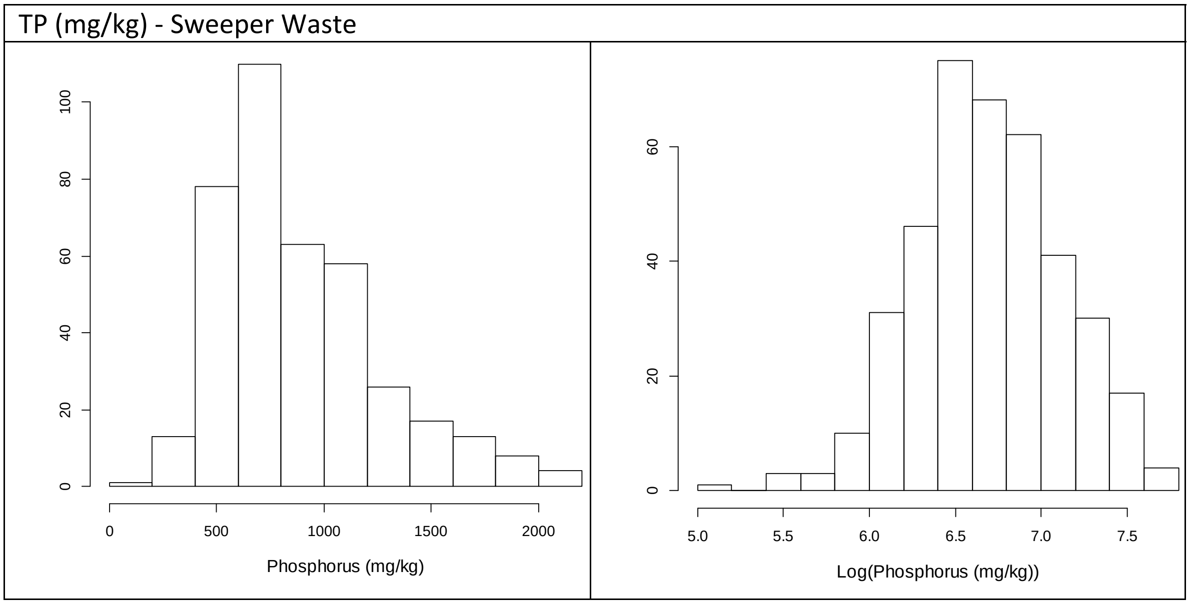
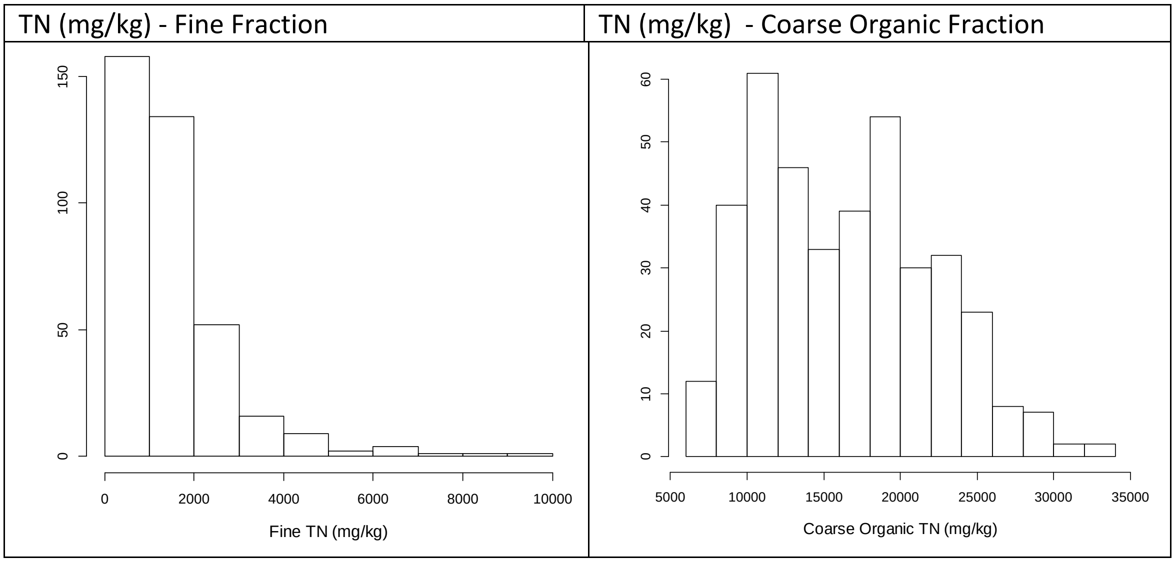


Figure 23. Distribution of TP concentration (mg/kg) in total sweeper waste for the months March-November (n=391). Shapiro-Wilk test: p=5.0e-12 for TP-mg/kg , p=0.07 for log(TP – mg/kg).


TN (mg/kg) - Fine Fraction

TN (mg/kg) - Coarse Organic Fraction

Figure 24. Distribution of TN concentration (mg/kg) in the fine and coarse fraction of sweeper waste for the months March-November (n=262, n= 391).

Basic statistical summaries (mean, median, standard deviation, CV) were computed for total phosphorus and total nitrogen concentrations in sweeper waste (contributing fractions, no rocks or trash, see section 1.5.2), the fine fraction of sweepings, and the coarse organic fraction of sweepings. Summaries were produced for the full set of sweeping evaluated in section 0 (March – Nov sweepings) and for subsets of the data based on month, and month + tree canopy classification. Sub-setting strategies were validated by applying the computed median TP and TN concentrations to the observed recovered dry mass of sweepings (or fraction thereof) for each sweeping event and comparing predicted and observed values.

Three strategies were tested:

1) metrics based on the entire sweeping season (median TP and TN concentrations for all 375 sweeping in Mar-Nov)
2) metrics based on monthly subset of the data (median TP and TN concentration for all sweeping within a given month).
3) metrics based on tree canopy cover class further subdivided into months.

When the simple, sweeping-season based metrics (number 1 above) were tested, overall predictions were reasonable, ranging from -1% for recovered coarse organic phosphorus to +23% for recovered coarse organic nitrogen (Table 21). But within monthly windows, predictions were less robust. Recovered nutrient loads tended to be over-predicted in the spring and under-predicted in fall. While this might not be a problem if sweeping is performed regularly throughout the year, it does present concerns if the metrics are applied to sporadic sweeping event. For example, annual nutrient recovery would be significantly overestimated if sweeping is conducted in the spring only.

Table 21. Percent difference between estimated and observed recovered nutrient loads within monthly windows. Estimates based on observed median TP and TN concentrations of sweeper waste and sweeper waste fractions for the entire sweeping season (Mar-Nov).

Month	**Sweeper Waste***		**Fines**		**Coarse Organics**	
	TP (mg/kg)	**TN (mg/kg)**	**TP (mg/kg)**	**TN (mg/kg)**	**TP (mg/kg)**	**TN (mg/kg)**
Mar	22%	**251%**	4%	**243%**	20%	**54%**
April	23%	**73%**	3%	**27%**	**57%**	14%
May	-7%	2%	-11%	-19%	-11%	-23%
June	-7%	-11%	-8%	**-31%**	-19%	**-27%**
July	12%	24%	4%	-7%	0%	-16%
August	5%	8%	6%	10%	4%	-8%
September	-13%	-19%	-7%	-24%	-8%	-1%
October	**-47%**	**-41%**	**-36%**	**-47%**	-13%	**46%**
November	**-34%**	-22%	**-29%**	**-27%**	14%	**75%**
Grand Total	**-11%**	**6%**	**-8%**	**-2%**	**-1%**	**23%**

*Based on mass of contributing fraction only (no rocks or trash).
Key: Brown=under-predicted by >10%, Orange =over-predicted by >10%, **Bold Red** = prediction >(+/- 25%).

Predictions within monthly windows were significantly improved when metrics based on monthly medians were applied (Table 22), but when the same metrics were evaluated within canopy cover class windows (Table) it was clear that metrics could be further refined to take advantage of observed relationships between canopy cover and nutrient concentrations (1.6.3).

Table 22. Percent difference between estimated and observed recovered nutrient loads within monthly windows. Estimates based on observed median TP and TN concentrations of sweeper waste and sweeper waste fraction for each month of the sweeping season (Mar-Nov).

Month	**Sweeper Waste***		**Fines**		**Coarse Organics**	
	TP (mg/kg)	**TN (mg/kg)**	**TP (mg/kg)**	**TN (mg/kg)**	**TP (mg/kg)**	**TN (mg/kg)**
Monthly Median						
Grand Total	-6%	-16.9%	-7.0%	-1.1%	-11.3%	2.5%
Monthly Average						
Mar	4%	**-41%**	2%	-1%	10%	-3%
April	4%	-14%	1%	22%	15%	13%
May	1%	-10%	1%	0%	6%	2%
June	2%	7%	9%	-9%	-1%	-4%
July	2%	-18%	2%	-2%	6%	2%
August	2%	4%	2%	15%	18%	9%
September	-1%	1%	1%	0%	6%	3%
October	-9%	-9%	-5%	0%	9%	2%
November	-8%	-12%	-7%	9%	9%	9%
Grand Total	**-2%**	**-8%**	**1%**	**3%**	**8%**	**4%**

*Based on mass of contributing fraction only (no rocks or trash).

Key: Brown=under-predicted by >10%, Orange=over-predicted by >10%, **Bold Red** = prediction >(+/- 25%).

Table 23. Percent difference between estimated and observed recovered nutrient loads within tree canopy cover windows. Estimates based on observed median concentration in each month of the year (see section 2.6).

	Sweeper Waste*		Fines		Coarse Organics	
Month	**TP (mg/kg)**	**TN (mg/kg)**	**TP (mg/kg)**	**TN (mg/kg)**	**TP (mg/kg)**	**TN (mg/kg)**
Monthly Median						
Grand Total	-6%	-16.9%	-7.0%	-1.1%	-11.3%	2.5%
Monthly Average						
0.1%	17%	**53%**	8%	-14%	**51%**	-3%
0.4%	-13%	**96%**	**-28%**	-4%	**89%**	12%
0.5%	19%	**44%**	11%	-8%	**51%**	-7%
0.6%	-6%	-10%	-13%	-1%	-13%	-7%
6.2%	-11%	-21%	-16%	-5%	**-28%**	0%
6.9%	5%	-7%	6%	-4%	-5%	2%
10.5%	-9%	**-27%**	-10%	2%	-25%	2%
15.1%	-22%	**-34%**	**-33%**	11%	**-40%**	14%
19.0%	-8%	**-32%**	7%	-6%	-19%	0%
Grand Total	**-6%**	**-17%**	**-7%**	**-1%**	**-11%**	**3%**

*Based on mass of contributing fraction only (no rocks or trash).
Key: Brown=under-predicted by >10%, Orange=over-predicted by >10%, **Bold Red**= prediction >(+/-25%).

In order to take advantage of tree canopy cover information, and at the same time avoid being overly specific, tree canopy was reclassified in ‘high’, ‘medium’, and ‘low’, cover class categories this time using the results of spatial analysis. Based on the clustering of tree canopy cover values shown in Figure 1, the H2 and H4 were classified as ‘high’ canopy (>15% canopy over the street); routes M2, M4, and H1 were classified as ‘medium’ canopy (2% - 15% canopy cover over the street); and routes L1, L2, L4, and M1 were classified as ‘low’ canopy cover (<2% canopy over the street). Within each tree canopy category, median nutrient concentrations were calculated for each month. Recovered nutrient predictions within monthly windows that were produced using this strategy (Table 24) were comparable to predictions based on simply monthly metrics.

There was also some improvement to predictions within canopy cover classification (Table 21, Table 26).

Table 24. Percent difference between estimated and observed recovered nutrient loads within monthly windows. Estimates based on observed median TP and TN concentrations of sweeper waste and sweeper waste fraction for each month of the sweeping season (Mar-Nov) for 3 canopy cover classes.

	Sweeper Waste*		Fines		Coarse Organics	
Month	**TP (mg/kg)**	**TN (mg/kg)**	**TP (mg/kg)**	**TN (mg/kg)**	**TP (mg/kg)**	**TN (mg/kg)**
Monthly Median Concentrations by Tree Canopy Type						
Mar	-2%	**-46%**	-17%	**-36%**	-8%	-9%
April	0%	-21%	-7%	**26%**	-3%	9%
May	-1%	**-26%**	-4%	4%	-15%	5%
June	0%	18%	**-27%**	-12%	-9%	-2%
July	-6%	-22%	-6%	-1%	-17%	2%
August	-4%	-2%	-6%	1%	1%	7%
September	3%	-3%	-6%	-2%	-8%	1%
October	-2%	-10%	-10%	-4%	-14%	0%
November	-8%	1%	-4%	9%	3%	6%
Grand Total	**-2.3%**	**-9.6%**	**-10.3%**	**-0.7%**	**-8.4%**	**2.6%**

*Based on mass of contributing fraction only (no rocks or trash).

Key: Brown=under-predicted by >10%, Orange=over-predicted by >10%, **Bold** = prediction >(+/- 25%).

Table 25. Percent difference between estimated and observed recovered nutrient loads within tree canopy cover windows. Estimates based on observed median TP and TN concentrations of sweeper waste and sweeper waste fraction for each month of the sweeping season (Mar-Nov) for 3 canopy cover classes.

Over Street Tree Canopy	**Sweeper Waste***		**Fines**		**Coarse Organics**	
	TP (mg/kg)	**TN (mg/kg)**	**TP (mg/kg)**	**TN (mg/kg)**	**TP (mg/kg)**	**TN (mg/kg)**
Monthly Median Concentrations by Tree Canopy Type						
0.1%	3%	1%	-7%	-14%	15%	-3%
0.4%	-23%	24%	**-36%**	-4%	**43%**	12%
0.5%	7%	-4%	-5%	-8%	15%	-7%
0.6%	-15%	**-41%**	-25%	0%	**-34%**	-7%
6.2%	-6%	-12%	-13%	-6%	-19%	0%
6.9%	12%	6%	11%	-3%	8%	2%
10.5%	-3%	-17%	-7%	2%	**-15%**	2%
15.1%	-13%	-11%	**-30%**	12%	**-26%**	14%
19.0%	4%	-8%	2%	-5%	-3%	0%
Grand Total	-2.3%	-9.6%	-10.3%	-0.7%	-8.4%	2.6%

*Based on mass of contributing fraction only (no rocks or trash).
Key: Brown=under-predicted by >10%, Orange=over-predicted by >10%, **Bold Red**= prediction >(+/- 25%).

To further test the robustness of the strategy, it was tested using random subsets of the data. The metrics were computed using 1/2 of the data (selected through random number assignment) and then applied to the entire record. The procedure was repeated in two trials. Overall, predicted recovery was comparable to other tests (-13% - +0.5% depending on load type and trial, Appendix I - Table 33 and Table 34). There were still some larger prediction errors within tree canopy cover windows, but prediction were improved compared to simple monthly metrics.

Some adjustments were made to metrics after median concentrations were calculated for the full data set (subset by tree canopy class and month). Because group (categories) now had few samples, the influence of extreme values was more apparent.

In section 1.6.3 it was shown that nutrient concentration in sweepings tend to increase with increasing canopy cover. To retain the general character of this finding, some values were ‘smoothed’ to restore this pattern. When the median value computed for a higher canopy cover was less than the value computed for the next lowest canopy cover, the two values were averages and used as the metric for both canopy cover classes. Instances of averaging are color coded in Table 18. Additionally, nutrient concentrations for coarse organics are based on monthly medians (no tree canopy taken into account). The tree canopy variable offered no advantage in defining expected coarse organic nutrient concentrations and was therefore dropped from these metrics (see section 1.6.3). The predictions shown in Table 23 and reflect these adjustments Table 24. Note that while the median value listed for some items in Table 18 is not the median for the specified group, but instead the median of neighboring groups (through averaging), values for the average and coefficient of variation within each group were provided to give some additional dimension to group statistics.

2.7 Findings and Limitations

Key Findings

- Recovered loads are well approximated by log-normal distributions within seasonal windows.
- Regression analysis shows that for regular sweeping, tree canopy cover, sweeping frequency and season are significant predictors of recoverable loads.
- Regressions developed to predict recoverable nutrients under-predicted recovered loads when the response was log-transformed and over-predicted recovered loads when the response was untransformed.
- Although errors were somewhat greater in magnitude when the response was log-transformed, this approach is thought to be more appropriate for general application given observed distribution characteristics.
- Recovered nutrient loads were estimating by applying the observed median nutrient (TP, TN) concentration of sweeper waste within monthly windows for three canopy cover types (0-2%, 2-15%, and >15% canopy cover over the street) to the observed recovered dry mass of solids. Estimates were within +/- 10% overall of the observed recovered nutrient mass. Estimates were less accurate within subsets of the data (month, tree canopy cover).
- The same method was applied to estimated recovered nutrients in the fine and coarse organic fraction of sweepings. Results were similar to those for sweeper waste. In both cases, estimates within canopy cover categories were less robust than estimates within month categories.

Study Limitations

The regressions developed to predict potential solids and nutrient recovery through street sweeping should be applied with caution. Regressions are not intended to predict recoverable loads for singular sweeping events. Predictions represent the average expected recoverable loads and may be used for comparison and planning and are not necessarily appropriate for tracking nutrient recovery. Additionally, the regression do not describe load reductions to downstream waters; however, load recovery predictions might be used in conjunction with other modeling packages to estimate downstream reductions that could be achieved through street sweeping.

The results of this study are regional in character and should be extrapolated to other cities only with caution. The pattern and character of leaf inputs to streets would be different for cities located in regions where autumn leaf fall is less pronounced, or where the dominant tree species are conifers. Furthermore, results of this study likely underestimate recoverable loads for streets with very dense canopy covers - for example, older neighborhoods with large boulevard trees.

Results may also depend on street sweeper make, model, and operational speed. In this study, all loads were recovered using a regenerative air sweeper at speed of about 4-5 mph. High efficiency sweepers are expected to recover street PM with similar efficiency, but recovery may be lower for older technologies.

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Appendix A. Literature Review

A Brief History of Street Sweeping Research

Prior to the 1970's, the main goal of stormwater management was to drain urban watersheds quickly. Early sewer systems in US cities were most often built as combined systems which carried sewage and surface runoff to a receiving surface water body with little or no treatment (Tarr 1996). As populations grew, increasing amounts of treatment were added to these systems to insure sanitary conditions in public drinking water supplies. The cost of this additional treatment drove a movement to separate municipal and storm sewers (Burian et al. 1999). Ironically, diversion of stormwater from treatment with sanitary waste may have unmasked the pollution loads present in urban stormwater. The US Public Health Department became concerned about pollutants identified in urban runoff in the 1960s, but the original 1972 Clean Water Act focused mainly on point sources of pollution (such as municipal and industrial wastewater discharges).

Pioneering research into storm sewerage, including using street sweeping as a pollution control measure, was completed during this era (Heaney and Sullivan 1971, Sartor and Boyd 1972, Pitt and Amy 1973, Shapiro and Hans-Olaf 1974). Initial conclusions regarding the value of street sweeping as a water quality tool were not always positive, but amendments to the Clean Water Act in 1987 and development of the EPA's Stormwater Program, have prompted a re-evaluation of these conclusion and a renewed interest in street sweeping as a pollution control measure.

Early Street Sweeping Studies and NURP

Early street sweeping studies were concerned largely with characterizing street sediments and evaluating the performance of street sweepers. An extensive study by Sartor and Boyd (1972) characterized the accumulation and composition of street sediments in 12 urban centers around the country and found street sediments were composed largely of inorganic material such as sand and silt, 78% of which could be found within 6 inches of the curb. The fine fraction (< 43 µm) of these sediments contained a great portion of the overall pollution load. While this fraction was typically small, about 6% of the total solids, it contained one-fourth the total chemical oxygen demand (COD), one-third to one-half of the nutrients, and significant percentages of various heavy metals. Although sweepers were generally very effective at removing larger debris and sediments from roads (79% effective overall), removal efficiencies for the finest fractions were only 15-20%. The combined findings indicated that street sweeping, which removed less than 50% of the total sediment load on the street, would be relatively ineffective as a water quality management tool.

Sartor and Boyd did not monitor stormwater quality in their study, but the need to link source control practices to stormwater quality improvements would become the proving ground for street sweeping during the EPA-sponsored National Urban Runoff

Program (NURP), conducted from 1979 to 1983. The NURP program provided technical support and management assistance for 28 projects across the United States, which investigated urban hydrology and water quality. Among these studies, street sweeping was evaluated at 17 sites in 5 cities across the United States. To show definitively the effectiveness of street sweeping in reducing stormwater pollutant loads, all NURP studies used a paired or serial basin approach in which swept (treatment) and unswept (control) basins or treatment phases were compared. The criterion for a positive result were documented reduction of 50% stormwater event mean concentrations (EMCs, EMC = flow-weighted mean concentration throughout a runoff event), with 90% statistical confidence. The final NURP report was not was promising for street sweeping. For the five major pollutants monitored [lead (Pb), total Kjeldahl nitrogen (TKN), total phosphorus (TP), chemical oxygen demand (COD), and total suspended solids (TSS)], sweeping never resulted in the EMC reduction criteria set by the EPA at any of the 17 study sites (EPA 1983).

The final recommendation was that street sweeping was generally ineffective as a water quality improvement tool. The lackluster conclusions of NURP appear to have derailed interest in street sweeping as a BMP for about the next decade. Literature on street sweeping from 1985-1995 is sparse. The intuitive appeal of street sweeping as a source reduction tool was, however, hard to ignore. The development of higher efficiency sweepers, better stormwater modeling software, and critical analysis of NURP methods would all contribute to a renewed interest in street sweeping as the enactment of NPDES permitting (1990, 2003) increased regulation on stormwater quality.

Street Sweeper Performance and Efficiency Studies

Street sweeper testing methods and data collected on sweeper efficiency by Sartor and Boyd provided a foundation for future sweeper performance testing (Burton and Pitt 2002). A variety of parameters influence street sweeper efficiency: the mass, particle size distribution and uniformity of the sediment load; the type and condition of pavement; pick-up broom type, diameter, angle and rotational speed; and the influence of other operational parameters including forward speed and number of passes. Sweeper pick-up performance and efficiency testing is a sub-class of street sweeping study which, although important to best practices, is not a focus in the current study. Sweeper studies rate sweeper pick-up performance by total solids removed and percent removal by particle size classes, for various loading conditions, and under various operational parameters (Sutherland and Jelen 1997, Breault et al. 2005, Selbig and Bannerman 2007). Work in this area has addressed potential standardization of testing protocols for sweeper performance evaluation (Sutherland 2008) and development of resources for guiding street sweeper purchasing and program implementation (CT DEEP 2007, Kuehl et al. 2008, others). Evaluations largely agree that because regenerative air and vacuum type sweepers remove fine particles with greater efficiency than mechanical sweepers, these types are preferred when sweeping for water quality. Mechanical broom sweepers are preferred for removal of large debris and highly compacted material. High- efficiency sweepers combine various sweeper technologies with dust control systems and improve sweeper efficiency in removal of fine particles, but tend to cost considerably more than other sweeper types (Sutherland 2011).

Continued Work on Street Sediment Characterization

Data on street sediment characterization are used in stormwater modeling, sweeper efficiency modeling, and for determining the proper use and disposal of street sweepings. Chemical analysis of street sediments, most often analysis of metals and organic contaminants, has been performed in numerous studies (Pitt and Amy 1973, Wilber and Hunter 1979, Townsend et al. 2002, Zarriello et al. 2002, others). Fine sediments have frequently been found to contain a significant proportion of metal pollutant loads (Pitt and Amy 1973, Durand et al. 2003, Deletic and Orr 2005, Rochfort et al. 2009). Fewer studies have looked at the relationship between particle size and nutrient concentrations in street sediments and results are quite variable. Total phosphorus by percent has been reported highest in fine sediments (< 104 μm)(Sartor and Boyd 1972), silt and clay sized particles (Breault et al. 2005), and larger particles > 250 μm (Waschbusch et al. 1999).

Street sediment composition has been shown be to be influenced by season (Deletic and Orr 2005), land use area (Seattle Public Utilities 2009, Berretta et al. 2011), and street type ([X]-Absolute Value 1996). The distribution of sediments across the street can be affected by winter road applications and spring snow melt (Selbig and Bannerman 2007), and the particle size distribution and pollutant concentration of sediment samples can be influenced by distance from the curb (Deletic and Orr 2005).

Although exceptions occur on a regional basis or for particular pollutants, concentrations of metals and organic pollutants in street sweepings have generally been found to be below soil contamination standards (Townsend et al. 2002, Durand et al. 2003, [X]-Absolute Value 1996, Land Technologies 1997). A sampling of best management practices for street sweepings indicates that screened sweeping material does not typically qualify as hazardous waste (CT DEEP 2007, Minnesota Pollution Control Agency (MPCA) 2010). Appropriate uses for street sweepings include construction fill, landfill cover, winter non-skid material, aggregate in asphalt and concrete, and compost (vegetative fraction) (Land Technologies 1997, Minnesota Pollution Control Agency 2010, Clark et al. 2007, MWH Americas 2002).

Modeling Studies and Renewed Interest in Street Sweeping as a Water Quality Management Tool

Early street sweeping studies established mathematic models describing accumulation, wash-off, transport, and removal of street sediments, which were used to model theoretical stormwater load reductions from street sweeping. Due to the low efficiency of mechanical broom sweepers, particularly in the smaller particle size ranges, NURP era models showed that streets must be swept at a frequency about equal to or greater than inter-event dry period to have any effect on reducing the total solids load on the streets (Sartor and Gaboury 1984). The post-NURP decade brought new higher efficiency sweepers and improved stormwater modeling software into the market. These technological improvements prompted a number of papers that re-evaluated the value street of sweeping as a water quality management tool (Sutherland and Jelen 1997, Sutherland and Jelen 1996, Sutherland et al. 1998, Minton et al. 1998).

Among these modeling studies, (Sutherland and Jelen 1997) used the Simplified Particle Transport Model (SIMPTM) to compare the total suspended solids (TSS) removal capacities of the newer, high efficiency sweeping technologies SIMPTM allowed the modeler to set base residual loads and sweeper removal efficiencies for different particle sizes and sweeper types. SIMPTM also had the capacity to continously model accumulation, washoff, and resuspension of particles and associated pollutants on an event-by-event basis. In this study, the model predicted TSS reductions of up to 20-30% for newer mechanical sweepers and up to 80% for the Envirowhirl™ technology. SIMPTM was also used to model targeted total solids reduction in Jackson County, MI (Tetra Tech 2001). Modeled load reductions for TS, COD, TP, Cd, Cr, Pb, Cu, and Zn ranged from 63 -87% for high efficiency sweepers and 49 – 85% for regenerative air sweepers for a sweeping frequency of once to twice monthly with cleaned catch basins.

Modeling using the Storm Water Management Model (SWMM) in the Lower Charles River basin produced less promising pollutant load reductions from sweeping (Zarriello et al. 2002). A conservative assumption that 20% of the surface was unavailable to be swept (parked cars, other) was built into the model. Simulations predicted load reductions of less than 10 percent for total solids and less than 5% for fecal coliform and total phosphorus for a sweeping frequency of seven days or greater. These estimates improved when a lower value of the wash-off coefficient was used to model sediment removal during smaller storms, which resulted in larger residual loads being available for removal through sweeping. The discrepancy highlights the sensitivity of predictions to modeling assumptions and constraints. Improved stormwater quality modeling has been an active areas of research that includes empircal validation of modeling parameters (Breault et al. 2005), accumulation rates (Kim et al. 2006), and optimization of street sweeping practices for water quality improvement (Sutherland 2007b).

End of Pipe Studies – Promise and Pitfalls

Although modeling studies have shown varying degrees of promise for sweeping as a water quality BMP, *measured* reductions in pollutant EMCs or loadings have continued to be the standard by which sweeping is gauged. An extensive study, which had both paired and serial basin aspects, was conducted in Madison, WI, from 2003-2007(Selbig and Bannerman 2007). Street sediment yield and storm EMCs for 26 constituents were monitored during calibration and treatment (sweeping) phases in three residential basins. A fourth basin served as a control for all three swept basin comparisons. Sweeping was conducted from April through September during each year of the study, and was suspended when autumn leaf accumulations made vacuum sampling impractical. For a frequency of once per week, sweeping reduced street sediment yield by an average of 76%, 63%, and 20% respectively for regenerative air, vacuum assist, and high-frequency mechanical broom treatments but data on stormwater quality improvement was less encouraging.

Approximately 40 paired water quality samples were collected during the Madison study. Based on this sampling, the only significant change in stormwater concentrations was an increase in ammonia-nitrogen of 63% in one of the treatment basins (10% significance). Study authors reported that high variability in stormwater composition (as is typical in stormwater monitoring) made statistical comparisons of calibration and treatment phases difficult. Sources of variability in stormwater composition include differences in precipitation patterns, land use, street type, traffic patterns, maintenance practices, and sediment sources other than street dirt (ex. rooftops, lawns, driveways, and sediments transported in the sewer system) which are not controlled through street sweeping. Variability in stormwater loads dictates large sampling requirements to produce statistically relevant results at high levels of confidence, in particular if differences between control and treatment water quality are modest. In the Madison study, for a coefficient of variation of 1.5 between control and test basins, a minimum of 200 paired samples would have been required to detect a 25% difference (at 95% confidence, 0.5 power) between calibration and treatment phase stormwater EMCs (Selbig and Bannerman 2007). For most constiuents, the sampling completed was not sufficient to demonstrate a significant change. Some recent studies have abandoned attempts to quantify stormwater quality improvements associated with street sweeping due to insufficient sampling (Law et al. 2008) or because sufficient sampling was cost-prohibitive (Seattle Public Utilities 2009).

Given the difficulties in proving reductions in EMCs or loading at the end of the pipe, it is not surprising that contemporary studies have questioned the value of NURP criteria and conclusions (Minton et al. 1998, Sutherland 2007b, Kang et al. 2009). Critical review of data analysis methods has shown that many NURP era studies lacked the statistical power required to draw statistically significant conclusions about water quality, making inferences about the influence of street sweeping on water quality only speculative(Kang et al. 2009). Others have argued that NURP criteria were unrealistic. Because EMC reduction of 50% or greater would be difficult to demonstrate at high confidence levels, results should be re-evaluated (Minton et al. 1998). Although there were no instances in which stormwater EMC reductions met the EPA criteria for a postive result, for the five pollutants studied, NURP data showed EMC reductions in 30 of 50 cases evaluated (range approximately 5%-55%). While EMCs increased in 16 cases, 9 of the increases occurred at the same two sites where rainfall intensity may have been an important factor (Minton et al. 1998). Reductions in stormwater EMCs, albeit less than 50%, have been also observed in highway cleaning studies (Sutherland 2007c).

Compounding these problems, the ability of automated samplers to collect representative stormwater samples has been called into question in recent years. In a simulation study, Clark and others showed that automated samplers failed to reliably to capture particles in the 250-500 mm (largest simulated) particle size range (Clark et al. 2007). Sampling is limited by particle diameter and intake velocity at the sampling tube. Large particles may settle out of the water column before reaching the sampler or bypass the system altogether. This problem can be addressed to some degree by supplementing with bedload sampling or by employing a cone sample splitter (Law et al. 2008), but tree leaves and other coarse organic particles which tend to float near the surface may still bypass sampling equipment. Furthermore residual solids loads in unmaintained infrastructure may contribute pollutant loading to stormwater during low flow/base flow periods when stormwater is not being sampled.

Focus on Source Control and Maintenance Practices

The intuitive appeal of street sweeping as a source control measure is difficult to ignore. Material that is removed from the street system is not available for transport via storm sewers to surface waters. Considering the factors that limit the ability of stormwater monitoring studies to demonstrate treatment effects (swept versus control), a focus on measuring recovered solids rather than on stormwater monitoring makes sense. The cost effectiveness of street sweeping found in many studies is also appealing. In an early example, Heaney and Sullivan (1971) created a solids budget for a typical 10-acre area in Chicago that included dustfall loading, sanitary wastes, refuse, and unclassified solids (street sweepings and catch basin sediments) Monthly source loads for each class of solids were estimated based on literature values and public works records. Heaney and Sullivan found that the unit cost of solids removal though street sweeping compared favorably with removal through catch basin cleaning, sewer cleaning, and municipal garbage collection. Likewise, recent studies have found the unit cost of solids removal through street sweeping to compare favorably with catch basin cleaning and other structural BMPs (Seattle Public Utilities 2009, Berretta et al. 2011, Tetra Tech 2001, Sutherland 2007a).

In the big picture, TSS reductions are critical to urban stormwater management and several studies have concluded that sweeping reduces solids loading to streets or to the watershed (Burton and Pitt 2002, Selbig and Bannerman 2007, Seattle Public Utilities 2009, Sutherland and Jelen 1996, Sutherland et al. 1998, Tetra Tech 2001). Yet due to insufficiencies in sampling methods, stormwater TSS loads have frequently been underestimated, leading to inadequate design of downstream structural stormwater control measures (SCMs) (Sutherland 2007b). Sediment recovery from structural SCMs is expensive; moreover, many Municipal Separate Storm Sewer System (MS4) communities have limited space for placement of structural SCMs. This highlights the importance of maintenance practices such as street sweeping and catch basin cleaning in urban watershed management (Bateman 2005, Sansalone and Spitzer 2008).

Given the importance of maintenance practices, MS4 communities would like tools to quantify load reductions achieved through maintenance practices for use in NDPES permits and TMDLs. To establish the link between maintenance practices and water quality improvements, documentation of recovered loads is of key importance (Bateman 2005). Work in street sediment characterization has shown that street sediments have a “typical” composition influenced by geography, land use, and other identifiable parameters. Typical pollutant concentrations could be applied to the dry mass of solids recovered to estimate recovered pollutant loads (Sansalone 2008).

Along this line of thinking, Sansalone and Rooney (2007) conducted a preliminary study to develop a method for incorporating MS4 maintenance practices into load reduction assessments Existing data on solids and pollutant loads recovered through maintenance practices were examined to determine whether the nutrient composition of urban solids could be categorized statisically by BMP type, land use, or other category. Analysis of existing data sets demonstrated that quantification of recovered pollutants loads based on the mass of dry solids recovered was possible, however, disparity in sampling and analysis methods, lack of QA/QC data, and geographic influence apparent among data sets meant that a more robust data set was required for the development of reliable metrics (Sansalone and Rooney 2007).

A follow-up assesment of particulate matter was carried out to develop a “yardstick” for quantifying pollutant load recovery in Florida cities (Berretta et al. 2011).

Street sweepings, catch basin sediments, and particulate matter from a variety of BMPs were collected in hydrologic functional units (HFUs) representing commercial, residential, and highways land use areas in each of 12 MS4s from across the state of Florida. Because nutrient concentrations showed a consistent distribution pattern (log-normal) within land use and BMP categories, investigators concluded that MS4s need only track dry solids recovered through maintenance practices to estimate recovered nutrient loads. The metrics could also be applied to estimate maintenance requirements for target load reductions and the associated cost per pound of nutrient recovery (Berretta et al. 2011).

Nutrient Management and Prior Lake Innovations

Innovations of the Prior Lake study are built on the mass balance approach taken in source control studies with a focus on the influence of tree canopy. Characterization studies focused on priority pollutants have largely overlooked the significance of leaves and other organic litter in street sediment pollutant loads. In some cases, leaves and larger pieces of organic litter were actively separated (by screening) and discarded; only the "fines" passing through the screen were chemically analyzed (Townsend et al. 2002, Rochfort et al. 2009). Similarly, in some studies, street sediment sampling or stormwater quality monitoring were conducted during short periods that did not include autumn leaf fall (Selbig and Bannerman 2007, Vaze and Chiew, 2004). Although the influence of leaf litter and organic matter on nutrient loads in street sediments is often noted (Waschbusch et al. 1999, Seattle Public Utilities 2009, Law et al. 2008, Sansalone and

Rooney 2007, Minton and Sutherland 2010), few studies have attempted to quantify the effect of coarse organic material on nutrient fluxes to storm sewers.

Sartor and Boyd (1972) identified accumulations of decomposing vegetation in catch basins as a potential source of oxygen demand to receiving waters and accumulations on road surface as potential source of pollution from pesticides and fertilizers. Since then, a significant body of work has evolved which provides evidence for the influence of tree canopy and roadside vegetation on nutrient loads in street sediments and runoff.

As a solid source of nutrients, organic matter has been shown to contain a significant proportion of the nutrient load in street sediments. High nutrient contents have been noted in the leaf fraction when leaves were included in the sediment analysis (Waschbusch et al. 1999), or in sediments associated with leaf fall timing (Seattle Public Utilities 2009). Waschbusch et al. found that while leaves made up < 10% of the total mass of street dirt samples on average, they contributed approximately 30% of the total phosphorus. Leaves were the only fraction analyzed that had a total phosphorus contribution by percent that was significantly higher than its total mass contribution, by percent. Furthermore, leaves in each particle size contributed approximately 25% of the total phosphorus in that size fraction. Waschbusch also found a strong, linear correlation between percent tree canopy over streets and both total and dissolved P concentrations in street runoff.

Lawns, yards and the plant-soil complex have been identified as a dominant source of nutrients in stormwater monitoring and modeling studies (Waller 1977, Pitt

1985, Waschbusch et al. 1999, Easton et al. 2007), but leaching studies indicate that fresh leaf litter can also be a significant source of dissolved nutrients during storm events. Leaching rates of nutrients from freshly fallen leaves are species dependent and can be substantial over short periods of time (Cowen and Lee 1973, Dorney 1986, Qiu et al. 2002, Wallace et al. 2008). Cowen and Lee (1973) found that intact oak and poplar leaves leached 5.4 – 21% of their total phosphorus in a 1-hour leaching time. In a similar study of 13 urban tree species, leaves readily leached from 4.5% (Honey Locust) to 17.7% (Silver Maple) of total leaf phosphorus over a 2-hour period (Dorney 1986). Under field conditions, leaf litter leaching rates were observed to be highest during the "first flush" portion of the wet season (McComb et al. 2007) and measurable phosphorus has also been detected in the surface moisture of leaves collected after rain events (Cowen and Lee 1973).

Leaves that remain on street surfaces may be damaged by vehicle traffic or inundated with runoff channeled by curb and gutter lines. Damaged leaf tissue (cut, ground) was shown to leach significantly more phosphorus than intact leaves (Cowen and Lee 1973, Qiu et al. 2002). Consecutive leachings resulted in additional phosphorus extraction (Cowen and Lee 1973, Dorney 1986, Qiu et al. 2002) and increased leaching time was positively correlated to leachate concentration (Cowen and Lee 1973). These findings indicate that mechanical breakdown on street surfaces are likely to increase leaf litter leaching rates.

Summary

Prior research over more than 40 years has shown the following:

(1) Tree leaves and other vegetative debris can make a substantial contribution to nutrients entering streets and storm sewers.

(2) Removal of vegetation debris by street sweeping probably does reduce stormwater nutrient loadings, but better quantification is needed.

(3) Removal of solids by sweeping may also reduce maintenance costs for structural SCMs.

The Prior Lake study is the first study we know of to quantify the influence of tree canopy cover on nutrient loads in street sediments. The scope of data collection allows for identification of seasonal trends in nutrient loads and the development of season specific metrics for estimating potential nutrient load recovery. Obvious extensions of this study are to model pollutant export from streets to stormwater networks; to estimate load reductions to urban watersheds; and to quantify water quality improvements that can be achieved through street sweeping. A robust model of pollutant export from streets would take into account differential sediment transport within urban stormwater systems and in situ biochemical transformation of nutrients associated with different sediment fractions.

Appendix B. Summary of Sample Collection Methods from Select Street Sweeping Studies

Table 26. Summary of sample types and sampling methods from select street sweeping studies.

Study	Sample Type(s)	Description of Sampling Plan	Fractionation Scheme	Comments
Berretta et al., 2011	**Sweeper waste**	Collection in 17 Hydrologic Functional Units (HFUs) located in 14 MS4s in Florida, 3 land use areas each HFU, (153 samples total), (2008-2011)*	None (whole sweepings)	
Breault et al., 2005	**Street PM** – wet sampling	Three sampling events each at two sites, collection during August, 2004.	Five fraction based on 2000, 250, 1250, and 63 μm sieves,	
Deletic and Orr, 2005	**Street PM** - wet sampling	Bi-weekly samples taken at the curb and 0.75 m from curb on alternate weeks, Sept 1998 – Feb 2000. Additional samples taken along transect (5X).	Five fractions based on 500, 250, 125, and 63μm sieves	
Law, et al., 2008	**Street PM** – dry sampling	26 Street PM samples collected, 10 before sweeping, 10 after sweeping, 6 at non-swept site. July 2006 – April 2007.	Nine fractions based on 4000, 2000, 1000, 500, 250, 125, and 63 μm sieves, plus large organics (organics >4000 μm)	Chemical analysis did not include autumn leaf drop.
	Stormwater	Composite stormwater samples form 32 pretreatment and 18 treatment runoff events. Supplemental bedload (10) and 'first flush' (41, grab) samples.	n/a	
Pitt, 1973	**Street PM** – dry sampling	See Sartor and Boyd, 1972 (same samples)	Five fractions based on 495, 495, 295, and 104 μm sieves	
Weston Solutions, 2010	**Sweeper Waste**	Composite grab samples from sweeper waste collected weekly for defined sweeping route. 2008, 2009.	Initial sieving using 4000 μm sieve, addition grain size analysis using laser diffraction	No chemical analysis of fraction > 4000 μm

Study	Sample Type(s)	Description of Sampling Plan	Fractionation Scheme	Comments
	Stormwater	Grab samples were taken at the curb during the 'first flush[§]' period for 10 storm events.	n/a	
Sartor and Boyd, 1972	**Street PM** – dry sampling	80 samples collected at several sites in 12 urban centers across the US, Dec – July, 1970, 1971.	Three fraction based on 246, and 43 μm sieves	
Seattle Public Utilities, 2009	**Street PM** – dry sampling	Bi-weekly samples collected 1-2 days prior to street sweeping, June 2006 – June 2007.	15 particle size classes ranging from <75 μm to > 75 mm.	
	Sweeper Waste	Monthly composite samples from sweeper waste dumpster bin at 3 study sites, June 2006 – June 2007.		
Selbig and Bannerman, 2007	**Street PM** – dry sampling	60 – 112 composite samples at each of 3 sweeping sites and 1 control site. Samples collected April-September in 2002-2006.	Eight fraction based on 2000, 1,000, 500, 250, 125, and 63 μm sieves Plus 'Detritus" (organicx >2000μ m)	No chemical analysis of street PM. Detritus mass not reported.
	Stormwater	84 – 111 composite samples at each of 2 sweeping and 1 control site. Samples collected April-September in 2002-2006.	Ten fractions based on 500, 250, 125, 63, 32, 14, 8, 5, 2, μm sieves.	
Waschbusch et al., 1999	**Street PM** – Dry sampling	5-6 composite samples at each of 6 sites collected 04/1994 – 10/1995.	Five fraction based on 250, 63, 25 μm sieves plus 'Leaves' (separated by hand)	
	Stormwater	25 runoff events monitored at several source areas each. Flow composite samples also collected at stormsewer outfall. May-Nov, 1994; June-Nov, 1995.	n/a	
X-Absolute Value, 1996	**Street PM**	Samples collected from 4 roadway types, collection method and sample numbers not available.	'small, medium, large'	Analysis of metals only.

*Approximate study start/end dates, sampling dates not given.

[§] Defined by the author as samples taken within 1 hr of the onset of flow in the gutter.

Appendix C. Street Sweeping Route Distribution and Details

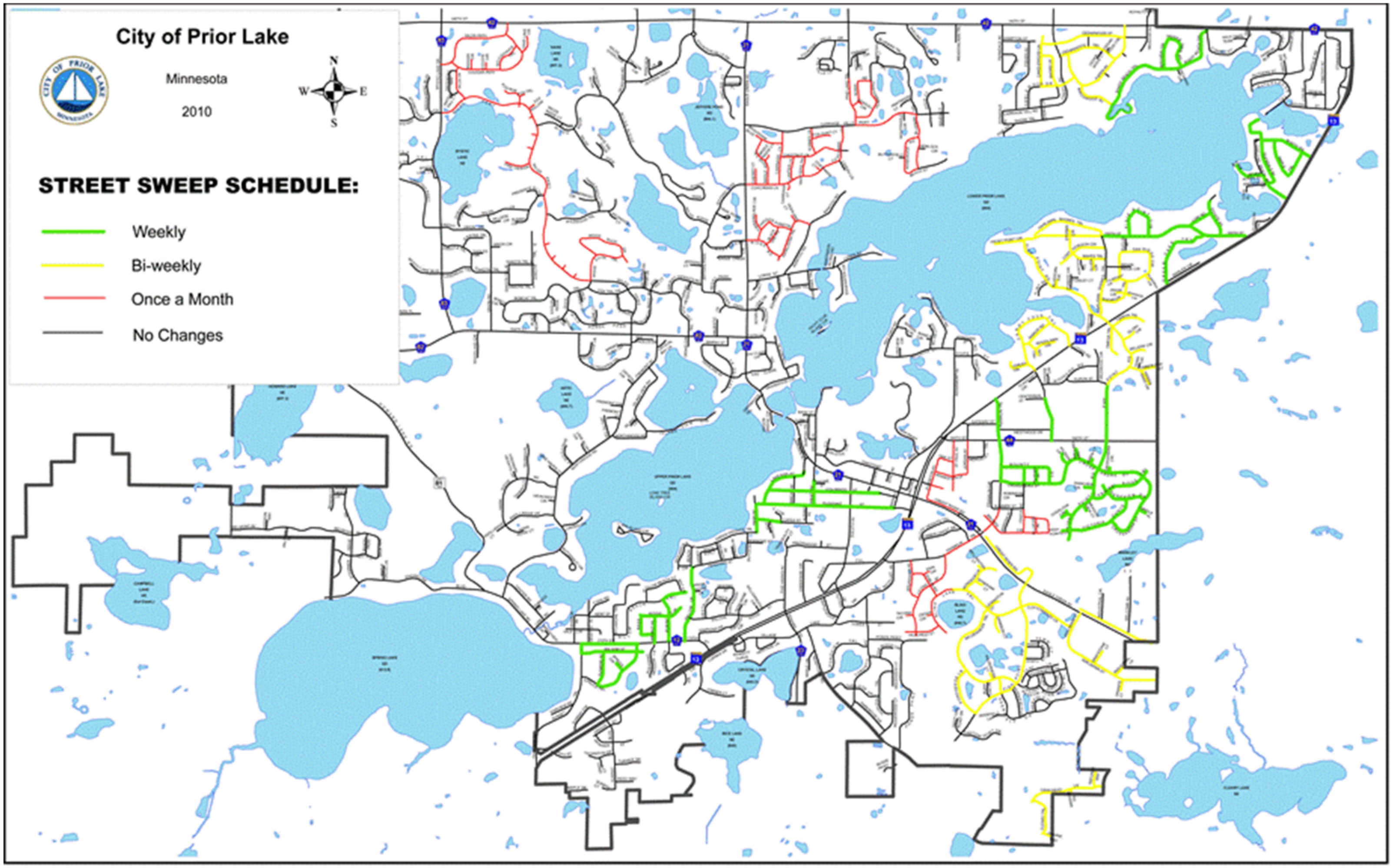

Figure 25. Distribution of sweeping routes (sweeping frequency categories) in Prior Lake, MN.

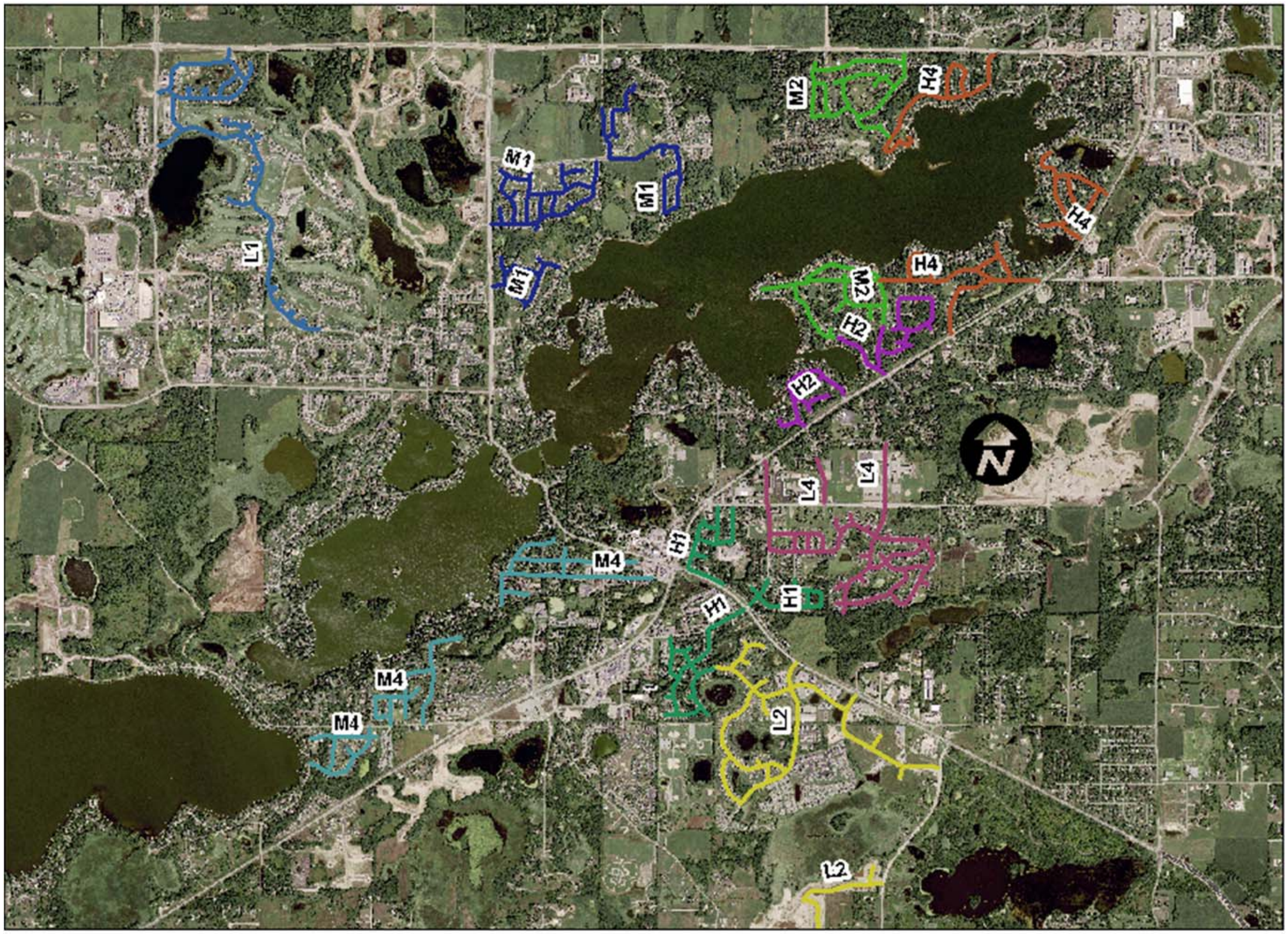

Figure 26. Location of street sweeping routes, Prior Lake, MN.

Table 27. Street sweeping route details. (Route naming convention = canopy class + sweeping frequency. For example, 'H1' = high canopy , swept once per month).

Study Route	Total Curb-Miles	Over-street Tree Canopy Cover (%)	Tree Canopy Cover within a 20 ft buffer* (%)	Sub-Section	Sub-Section Curb-miles	Sub-Section Over-street Tree Canopy Cover (%)	Sub-Section Canopy Cover within a 20 ft buffer* (%)
H1	6.8	6.9%	22.9%	a	1.7	7.2%	21.5%
				b	2.0	6.2%	19.8%
				c	3.1	7.5%	25.6%
H2	4.6	15.1%	34.5%	a	1.9	14.8%	34.2%
				b	2.7	15.6%	34.6%
H4	8.3	19.0%	36.8%	a	2.4	25.7%	45.1%
				b	2.5	18.5%	34.5%
				c	3.4	13.3%	32.4%
M1	9.3	0.6%	9.4%	a	1.8	0.9%	9.7%
				b	4.4	0.8%	12.7%
				c	3.1	0.1%	5.0%
M2	8.1	6.2%	21.5%	a	4.2	4.2%	20.2%
				b	3.9	8.6%	22.9%
M4	8.3	10.5%	25.5%	a	1.9	2.3%	19.1%
				b	3.7	11.7%	26.0%
				c	2.7	15.0%	29.5%
L1	7.4	0.4%	3.4%	a	7.4	0.4%	3.4%
L2	8.8	0.1%	2.9%	a	7.3	0.1%	3.6%
				b	1.5	0.0%	0.2%
L4	9.5	0.5%	6.7%	a	0.4	1.4%	10.5%
				b	9.0	0.5%	6.5%

*Twenty foot buffer measured from curb lines.

Appendix D. Miles Swept Audit

Table 28. Swept miles audit results.

Reported Miles Swept ≤ 80% Median Miles Swept (per route) Audit of GPS data vs. GIS route mile analysis				
Route	Date	Difference, Reported vs. Median (%)	Audit Findings	Correction (mi)
L1	5/18/11	-50	No irregularities	-
L1	8/17/11	-38	No irregularities	-
L1	6/13/12	-25	No irregularities	-
L2	9/1/10	-64	No irregularities	-
L2	10/7/10	-36	No irregularities	-
L2	5/4/11	-36	No irregularities	-
L4	10/18/10	-55	GPS data not retrievable	-
L4	9/14/10	-45	No irregularities	-
L4	11/2/10	-36	No irregularities	-
L4	8/9/11	-27	No irregularities	-
L4	12/20/11	-27	No irregularities	-
M1	11/10/10	-31	Portions of middle section not swept.	-1.5
M2	7/19/11	-33	Portions of south section not swept	-1.2
M2	8/2/11	-33	Portion of north section note swept	-3.0
M2	6/20/12	-33	South section not swept	-3.8
M2	7/3/12	-22	No irregularities	-
M2	7/31/12	-22	Portion of north section note swept.	-1.2
M4	11/28/11	-44	Middle and south sections not swept; portions of north section not swept	-4.8
M4	3/19/12	-44	Middle section not swept, portions of north and south section not swept	-4.5
M4	10/10/11	-33	South segment not swept	-1.8
M4	10/19/10	-22	No irregularities	-
M4	2/16/11	-22	No irregularities	-
M4	3/26/12	-22	South segment not swept; portions of middle section not swept.	3.6
H1	8/26/10	-25	Portions of northwest section not swept	-1.7
H1	3/7/12	-25	Portions of northwest section not swept	-1.0

Reported Miles Swept ≤ 80% Median Miles Swept (per route) **Audit of GPS data vs. GIS route mile analysis**				
Route	Date	Difference, Reported vs. Median (%)	Audit Findings	Correction (mi)
H2	11/17/11	-29	No irregularities	-
H2	6/12/12	-29	No irregularities	-
H4	8/8/11	-67	Portions of middle and south sections not swept	-0.8
H4	10/19/10	-44	South section not swept	-3.3
H4	10/10/11	-44	South section not swept, portions of middle section not swept	-3.5
H4	12/12/11	-44	No irregularities	-
H4	10/4/10	-33	Portions of middle section not swept	-2.8
H4	10/11/10	-33	Portions of middle section not swept	-2.0
H4	11/1/10	-33	Portions of middle section not swept	-2.1
H4	11/22/10	-22	No irregularities	-
H4	5/16/11	-22	No irregularities	-
H4	8/22/11	-22	No irregularities	-
H4	10/3/11	-22	No irregularities	-
H4	4/2/12	-22	No irregularities	-
H4	4/30/12	-22	No irregularities	-

Reported Miles Swept ≥ 80% Median Miles Swept (per route)
Audit of GPS data vs. GIS route mile analysis

Route	Date	Difference, Reported vs. Median (%)	Audit Findings	Correction (mi)
L1	3/21/12	+25	3rd, 4th pass apparent in some portions of route.	-
L1	10/20/10	+33	No irregularities	-
L2	6/13/12	+55	No irregularities	-
M2	3/13/12	+22	Portions of north and south sections not swept	-1.2
M2	12/13/11	+100	No irregularities	-
M4	10/4/10	+22	No irregularities	-
M4	10/11/10	+22	No irregularities	-
M4	6/6/11	+22	No irregularities	-
M4	8/8/11	+22	No irregularities	-
M4	1/9/12	+44	No irregularities	-
M4	7/16/12	+344	No irregularities	-
H1	10/7/10	+25	No irregularities	
H1	9/1/10	+38	Northwest section not swept	-2.0
H1	5/4/11	+50	No irregularities	-
H1	9/21/11	+50	No irregularities	-
H1	8/25/11	+63	No irregularities	-
H2	3/20/12	+29	No irregularities	-
H2	9/14/10	+43	No irregularities	-
H2	10/18/10	+43	GPS data not retrievable	-
H2	11/2/10	+43	No irregularities	-
H2	2/17/11	+114	No irregularities	-
H2	12/20/11	+143	No irregularities	-
H4	10/25/10	+22	North section not swept	-2.5
H4	9/12/11	+22	No irregularities	-
H4	9/13/10	+33	No irregularities	-
H4	3/12/12	+33	No irregularities	-
H4	3/5/12	+89	No irregularities	-
H4	7/16/12	+100	No irregularities	-

Reported Miles Swept within +/- 20% of Route Median Miles Swept (per route)
Random audit of GPS data vs. GIS route mile analysis

Route	Dates		Audit Findings	Corrections
L1	11/18/10	9/9/11	(none)	(none)
	3/11/11	10/5/11		
	6/15/11	4/18/12		
L2	8/25/10	8/17/11	a) Southeast section not swept b) Fishpoint Road not swept on main segment	a) -4.3 mi b) -1.5 mi
	9/16/10	9/9/11		
	10/20/10	9/21/11		
	11/18/10	10/19/11[b]		
	4/20/11	5/2/12		
	5/18/11[a]	5/16/12		
	7/13/11	5/31/12		
L4	8/17/10	7/19/11	(none)	(none)
	8/24/10	9/20/11		
	9/21/10	10/25/11		
	10/12/10	11/17/11		
	10/26/10	11/29/11		
	4/19/11	3/6/12		
	4/26/11	4/10/12		
	6/1/11	5/15/12		
	6/14/11	6/5/12		
	6/21/11	6/20/12		
M1	8/26/10	9/28/11	c) Portions of north segment not swept d) Portions of north segment not swept	c) -0.7 mi d) -0.3 mi
	9/9/10	10/26/11		
	3/11/11[c]	11/23/11		
	5/11/11	3/14/12[d]		
	8/10/11	6/6/12		
	8/31/11			
M2	8/17/10[e]	5/24/11	e) South segment not swept	e) -3.8 mi
	9/8/10	6/21/11		
	9/21/10	10/25/11		
	3/14/11	11/8/11		
	4/12/11	5/22/12		
	5/10/11	6/5/12		
M4	8/9/10	7/18/11	f) Middle and south segments not swept	f) -4.6 mi
	8/30/10	8/1/11		
	9/7/10	8/15/11		
	9/13/10	9/19/11		
	10/25/10[f]	10/24/11		
	11/1/10	11/7/11		
	11/22/10	4/2/12		
	4/18/11	4/9/12		

Reported Miles Swept within +/- 20% of Route Median Miles Swept (per route) **Random audit of GPS data vs. GIS route mile analysis**			
Route	**Dates**	**Audit Findings**	**Corrections**
	5/12/11 5/21/12 5/23/11 6/18/12 5/31/11 7/9/12 6/13/11 7/23/12		
H1	2/18/11 4/4/12 4/6/11 6/27/12 11/18/11 7/25/12	(none)	(none)
H2	4/5/11 10/4/11 5/3/11 11/29/11[g] 6/29/11 6/26/12 7/12/11 7/24/12 9/7/11	g) Portions of north section not swept	g) -2.0 mi
H4	8/9/10 7/25/11 8/31/10 10/17/11 11/8/10 10/31/11 3/29/11 1/9/12 4/4/11 4/23/12 5/2/11 5/7/12 5/9/11 6/4/12 7/5/11 6/25/12 7/11/11	(none)	(none)

Appendix E. Inventory of Sweeping Events

Table 29. Inventory of sweepings conducted in each route by month and year.

Month	**Year 1 Sweepings**	**Year 2 Sweepings**
January	(none) **Total=0**	M4(1), H4(1) **Total=2**
February	L2(1), L4(1), M4(1), H1(1), H2(1), H4(1) **Total=6**	(none) **Total=0**
March	L1(1), L4(1), M1(1), M2(2), M4(4), H4(1) **Total=8**	L1(1), L2(2), L4(4), M1(1), M2(2), M4(4), H1(1), H2(1), H4(5) **Total=21**
April	L1(1), L2(2), L4(4), M1(1), M2(2), M4(4), H1(1), H2(2), H4(4) **Total=21**	L1(1), L2(2), L4(4), M1(1), M2(2), M4(5), H1(1), H2(1), H4(4) **Total=21**
May	L1(1), L2(2), L4(4), M1(1), M2(2), M4(5), H1(1), H2(2), H4(5) **Total=23**	L1(1), L2(3), L4(5), M1(1), M2(2), M4(4), H1(2), H2(3), H4(4) **Total=25**
June	L1(1), L2(2), L4(5), M1(1), M2(2), M4(3), H1(1), H2(2), H4(4) **Total=21**	L1(1), L2(2), L4(4), M1(1), M2(2), M4(4), H1(1), H2(2), H4(4) **Total=21**
July	L1(1), L2(2), L4(4), M1(1), M2(2), M4(4), H1(1), H2(2), H4(4) **Total=21**	L1(1), L2(2), L4(5), M2(3), M4(5), H1(1), H2(2), H4(4) **Total=24**
August	L2(1), L4(4), M1(1), M2(2), M4(4), H1(1), H4(4) **Total=17**	L1(1), L2(2), L4(5), M1(3), M2(3), M4(5), H1(1), H2(2), H4(5) **Total=27**
September	L1(1), L2(2), L4(3), M1(1), M2(2), M4(3), H1(1), H2(2), H4(3) **Total=17**	L1(1), L2(2), L4(4), M1(1), M2(2), M4(4), H1(1), H2(2), H4(4) **Total=21**
October	L1(2), L2(3), L4(4), M1(1), M2(1), M4(3), H1(1), H2(2), H4(4) **Total=21**	L1(2), L2(3), L4(4), M1(1), M2(1), M4(5), H1(1), H2(2), H4(5) **Total=23**
November	L1(1), L2(2), L4(3), M1(1), M2(1), M4(5), H1(1), H2(2), H4(5) **Total=21**	L1(2), L2(3), L4(4), M1(1), M2(1), M4(3), H1(1), H2(2), H4(4) **Total=21**
December	(none) **Total=0**	L4(2), M1(1), M2(1), M4(2), H2(1), H4(2) **Total=9**
TOTAL	**176 sweepings**	**215 sweepings**

Appendix F. Comparison of Correlation Coefficients for Sweeper Waste Characteristics and Tree Canopy Cover at Variable Buffer Distances

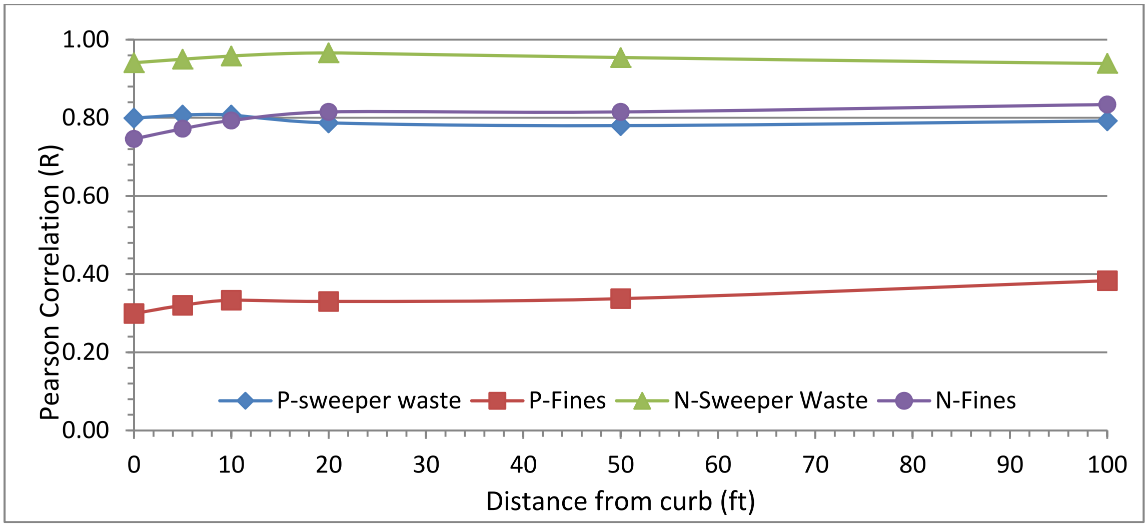

Figure 27. Pearson correlations for tree canopy cover within variable distances from the curb vs. nutrient concentrations in sweeper waste and sweeper waste fractions.

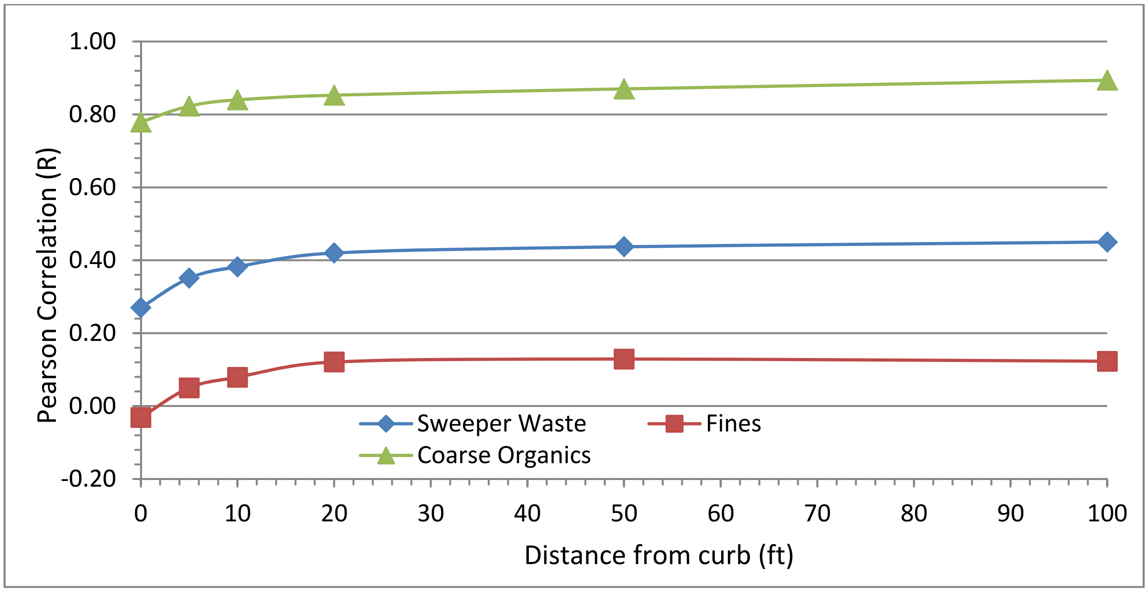

Figure 28. Pearson correlations for tree canopy cover within variable distances from the curb vs. recovered solids (sweeper waste and sweeper waste fractions).

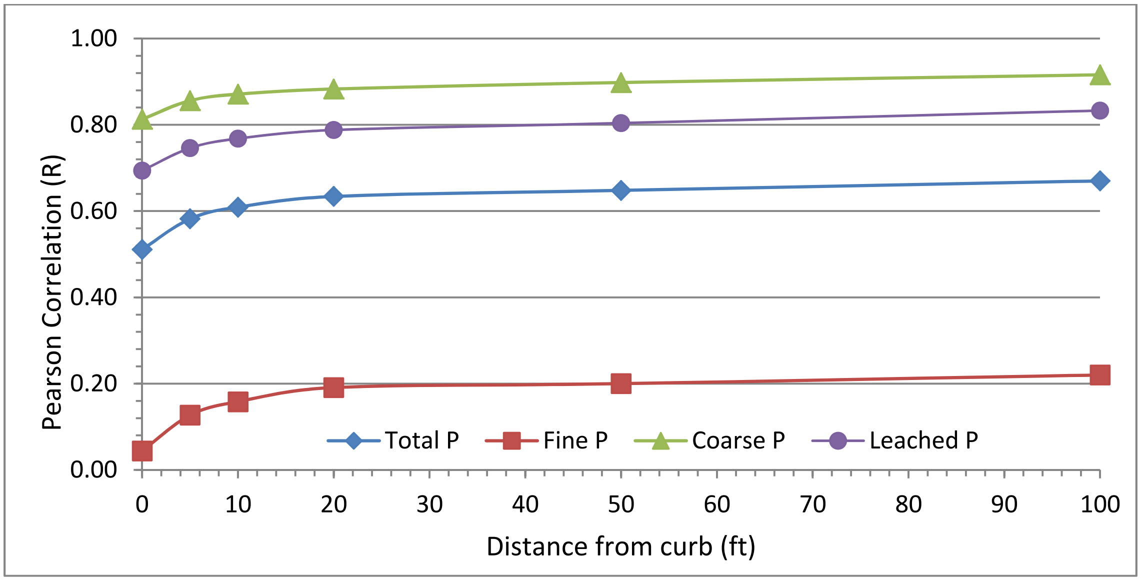

Figure 29. Pearson correlations for tree canopy cover within variable distances from the curb vs. phosphorus recovered in sweeper waste and sweeper waste fractions.

Appendix G. Comparison of Assigned and Observed Sweeping Intervals

Street Sweeping Study, Study Route Sweeping Schedule

	Monday		Tuesday		Wednesday		Thursday	Friday
	am	pm	am	pm	am	pm		
Week 1	H4	M4	L4	H2	L2	H1		
Week 2	H4	M4	L4	M2	M1			
Week 3	H4	M4	L4	H2	L2	L1		
Week 4	H4	M4	L4	M2				

Table 30. Assigned sweeping frequencies and average sweeping intervals for the nine sweeping routes.

Route ID	Assigned Frequency, (day)	Average sweeping interval April –Nov (days)	Average sweeping all months included (days)
L1	28	33.1	41.9
L2	14	17.8	19.9
L4	7	8.5	9.8
M1	28	29.8	37.8
M2	14	16.3	21.4
M4	7	8.5	9.5
H1	28	33.6	37.9
H2	14	18.8	21.1
H4	7	8.5	9.5

Appendix H. ‘Florida-based Yardstick’ (Beretta et al., 2011).

Florida-based metrics for nutrient recovery through maintenance and good housekeeping practices.

Table 31. TP and TN metrics for particulate matter recovered through street sweeping, catch basin cleanout and other BMPs in Florida (Beretta et al., 2011).

TP	**Street Sweeping (SS)**			**Catch Basin (CB)**			**BMP**		
(mg/kg)	Mean	Median	St. Dev.	Mean	Median	St. Dev.	Mean	Median	St. Dev.
C*	482.6	381.2	476.9	530.9	300.8	524.9	474.6	295.7	412.6
R	425.8	374.9	284.7	559.2	426.4	543.0	702.8	382.7	670.5
H	622.0	349.7	778.5	566.6	536.9	363.3	759.4	513.7	972.1
TN	**Street Sweeping (SS)**			**Catch Basin (CB)**			**BMP**		
(mg/kg)	Mean	Median	St. Dev.	Mean	Median	St. Dev.	Mean	Median	St. Dev.
C	789.1	429.6	944.2	1459.7	467.2	2237.8	1999.0	602.1	3104.1
R	1439.0	832.4	2169.9	1803.9	773.8	2955.8	3587.7	1169.0	4991.9
H	826.6	546.4	654.8	1926.3	785.4	2587.8	2342.4	969.2	3496.6

*Land use codes: C=commercial, R=residential, H=highway.

Appendix I. Additional Validation Exercises, Nutrient Crediting Metrics

Table 32. Summary statistics for TP and TN concentrations in sweeper waste, various subsets of recovered loads (March-Nov sweepings).

	TP (mg/kg)				**TN (mg/kg)**			
	Mean	**Median**	**St. Dev.**	**CV**	**Mean**	**Median**	**St. Dev.**	**CV**
All Sweepings	776.0	672.8	367.6	**0.47**	3390.0	2914.0	2280.1	**0.67**
By Sweeping Frequency								
1X	745.8	675.4	297.9	0.40	2708.4	2410.8	1773.6	0.65
2X	829.4	715.8	389.5	0.47	3394.4	2598.6	2256.1	0.66
4X	780.4	687.0	375.0	0.48	3682.2	3346.1	2370.9	0.64
Tree Canopy Classification								
Low	656.1	606.3	266.4	0.41	2157.8	1878.6	1462.3	0.68
Medium	848.2	740.0	361.8	0.43	3820.0	3494.8	2140.7	0.56
High	861.0	737.0	427.9	0.50	4407.4	3821.9	2504.5	0.57
By Month								
March	550.9	504.5	249.4	0.45	985.6	603.0	956.9	0.97
April	576.4	545.1	151.1	0.26	2131.2	1828.2	1578.3	0.74
May	751.6	658.8	258.9	0.34	2733.8	2733.8	2114.3	0.77
June	775.8	702.9	384.0	0.49	3292.4	3292.4	2506.9	0.76
July	617.3	572.9	246.8	0.40	2443.2	2443.2	1550.2	0.63
August	676.3	609.6	278.6	0.41	3051.0	3051.0	1559.2	0.51
September	817.3	735.6	278.4	0.34	4209.2	4209.2	1780.3	0.42
October	1275.5	1274.7	416.5	0.33	5570.4	5570.4	2325.6	0.42
November	985.4	948.7	349.4	0.35	4197.6	4197.9	2155.1	0.51

Table 33. Percent difference between estimated and observed recovered nutrient loads within monthly windows. Estimates are based on observed median concentration in each month of the year for H, M, and L tree canopy cover classes (see section 2.6). Trial #1 and Trial #2 are instances for which metrics were based on a random sample (1/2) of the data set.

Month	**Sweeper Waste***		**Fines**		**Coarse Organics**	
	TP (mg/kg)	**TN (mg/kg)**	**TP (mg/kg)**	**TN (mg/kg)**	**TP (mg/kg)**	**TN (mg/kg)**
Trial #1 – Monthly Median Concentrations by Tree Canopy Type						
Mar	9%	-18%	-5%	-9%	22%	9%
April	8%	-12%	6%	**31%**	2%	15%
May	-11%	**-29%**	-6%	-9%	-21%	0%
June	1%	17%	6%	-12%	-6%	-4%
July	-7%	-15%	-9%	-7%	-25%	-5%
August	6%	-4%	-3%	16%	-6%	6%
September	-9%	-4%	-17%	-2%	8%	-3%
October	1%	4%	-6%	-5%	3%	-2%
November	-3%	5%	-1%	8%	-10%	0%
Grand Total	**0.05%**	**-3.3%**	**-2.8%**	**-0.4%**	**-5.2%**	**0.5%**
Trial #2 - Monthly Median Concentrations by Tree Canopy Type						
Mar	9%	**-56%**	6%	-2%	-5%	-2%
April	-5%	**-32%**	-8%	16%	-4%	13%
May	-8%	-11%	-10%	-9%	-19%	7%
June	-21%	16%	-13%	-5%	**-34%**	0%
July	-7%	-23%	-5%	-5%	-21%	-4%
August	-3%	7%	-5%	16%	11%	2%
September	2%	0%	-2%	4%	-6%	-4%
October	-1%	-11%	8%	-3%	-10%	3%
November	-6%	6%	-7%	0%	-12%	5%
Grand Total	**-4%**	**-8%**	**-4%**	**-1%**	**-13%**	**3%**

*Based on mass of contributing fraction only (no rocks or trash).

Key: Brown=under-predicted by >10%, Orange=over-predicted by >10%, **Bold Red** = prediction >(+/- 25%).

Table 34. Percent difference between estimated and observed recovered nutrient loads within monthly windows. Estimates based on observed median concentration in each month of the year (see section 2.6). Trial #1 and Trial #2 are instances for which metrics were based on a random sample (1/2) of the data set.

Tree Canopy Cover	**Sweeper Waste***		**Fines**		**Coarse Organics**	
	TP (mg/kg)	**TN (mg/kg)**	**TP (mg/kg)**	**TN (mg/kg)**	**TP (mg/kg)**	**TN (mg/kg)**
Trial #1 – Monthly Median Concentrations by Tree Canopy Type						
0.1%	4%	13%	3%	-6%	14%	-2%
0.4%	-23%	**39%**	**-30%**	2%	**39%**	15%
0.5%	8%	6%	8%	0%	13%	-5%
0.6%	-15%	**-34%**	-15%	9%	**-34%**	-4%
6.2%	-7%	-4%	-18%	-6%	-20%	1%
6.9%	15%	11%	16%	-2%	4%	3%
10.5%	-2%	-11%	-9%	2%	-17%	3%
15.1%	-12%	-7%	**-26%**	9%	-20%	7%
19.0%	13%	-2%	31%	-6%	15%	-5%
Grand Total	**0.05%**	**-3.3%**	**-2.8%**	**-0.4%**	**-5.2%**	**0.5%**
Trial #2 - Monthly Median Concentrations by Tree Canopy Type						
0.1%	4%	10%	6%	-9%	19%	1%
0.4%	-21%	**35%**	**-26%**	0%	**45%**	17%
0.5%	12%	4%	15%	-2%	19%	-4%
0.6%	-12%	**-35%**	-9%	7%	**-33%**	-3%
6.2%	-10%	-19%	-11%	0%	-24%	4%
6.9%	10%	-4%	15%	0%	-2%	8%
10.5%	-7%	-25%	-7%	7%	-23%	6%
15.1%	-16%	-2%	**-31%**	5%	**-30%**	10%
19.0%	3%	1%	10%	-8%	-10%	-4%
Grand Total	**-4%**	**-8%**	**-4%**	**-1%**	**-13%**	**3%**

*Based on mass of contributing fraction only (no rocks or trash).

Key: Brown=under-predicted by >10%, Orange=over-predicted by >10%, **Bold Red** = prediction >(+/- 25%).