Relative reductions in non-point source pollution loads by urban trees

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Background

Trees modify the fate and transport of water, nutrients, and sediment in natural and developed landscapes due to their unique physical structure compared to other plant species, basic physiological processes, and long lifespan. Since 2003, it has been the policy of the Chesapeake Bay Program (CBP) partners to increase tree canopy cover for water quality and other benefits. While tree planting best management practices (BMPs) provide opportunities to account for the water quality benefits of new trees, the benefits of existing urban trees that do not meet the definition of forest are not directly accounted for in the Phase 5.3.2 CBP model land uses. Advances in remote mapping technology now allow tree canopy to be mapped and total cover quantified at small spatial scales (O'Neil-Dunne et al. 2014), providing the basic information needed to ascribe water quality benefits to all urban trees of a minimum canopy size.

As the spatial resolution of tree canopy mapping increases, the land use characteristics and management decisions become more evident. In particular, many urban trees likely lack an understory of herbaceous and woody plants, lack a distinct organic soil horizon, are surrounded by soils affected by urban development and compaction, and have an increased probability of fertilization. For these reasons, it is not appropriate to apply the loading rate of forests – the lowest non-point source pollution loading rate among CBP land uses – to urban trees. Here we describe how trees attenuate and store non-point source pollution and describe a method for estimating unique relative pollution loading rates for two new CBP land uses: tree canopy over turfgrass and tree canopy over impervious surfaces.

Attenuation and removal of non-point source pollution by trees

It is well known that nitrogen and phosphorus are essential plant nutrients, and there is strong evidence that organic matter containing nitrogen accumulates in soils beneath trees over time. On a per-hectare basis forests store more carbon annually than urban open space due to higher tree densities. Yet, on a per tree basis urban trees may fare better, the same, or slightly worse than trees in a forest due to the lack of competition for resources and/or different environmental stresses (McHale et al. 2009). Later we show that average annual uptake of N and P per tree ranges from ~ 0.31 to 1.20 lbs. and 0.17 to 0.60 lbs., respectively. Trees, and in particular the root system, increase soil organic matter contents by physically incorporating organic matter, adding plant litter to carbon stores, exuding carbon from the roots, and root die-off (Day, Wiseman et al. 2010). Soil under urban trees has been shown to have a higher carbon content than bare soil or soil under grass (Takahashi et al. 2008; Huyler et al. 2014), therefore allowing greater potential for nutrient uptake and cycling (Jo and McPherson 1995). Carbon cycling, in turn, drives N retention via uptake and microbial utilization (Lovett, Weathers et al. 2002).

In addition to storing nitrogen in biomass and soils, trees promote biogeochemical processes that convert biologically active nitrogen to inactive forms. Nitrogen inputs include organic nitrogen, nitrogen oxide gases, and ammonium nitrate particles that can be deposited as both wet and dry deposition. These inputs of nitrogen can be transformed through biological processes in soil into nitrate-N, a highly soluble form that leaches from through soils and easily transported by groundwater flowpaths (Wakida and Lerner 2005). Conversely, nitrate-N can undergo denitrification in urban systems (Groffman et al. 2004), a microbial process that transforms nitrate-N into inert dinitrogen gas and returns nitrogen to the atmosphere.

Removal of nitrate-N via denitrification is strongly influenced by soil moisture (Groffman et al. 2004; Kaushal et al. 2008). Trees promote greater soil moisture by creating preferential hydrologic flow paths and absorbing water via root systems (Day, Wiseman et al. 2010). In urban areas, turfgrass roots are likely not reaching groundwater, while deeper-rooted trees may uptake and re-distribute soil moisture from farther belowground upwards toward the surface (Day, Wiseman et al. 2010). This assists the plant community by promoting growth and ultimately increasing nutrient utilization. Greater soil moisture near the land surface, where

carbon and nitrogen are also concentrated, may also promote greater rates of denitrification (Gift et al. 2010; Groffman et al. 2004; Raciti et al. 2011; Zhu, Dillard, and Grimm 2005).

In contrast to nitrogen-N, the primary form of phosphorus (orthophosphate) is less soluble and primarily transported from landscapes to surface water in overland flow. Phosphorus losses from landscapes have been shown to be strongly dependent on runoff, which can transport phosphorus in particulate and dissolved forms (Staver and Brinsfield 2001). Phosphorus is generally not a major component in groundwater because it is in forms that will be bound to soil particles (Correll 1998) and most P has been shown to remain in the top three feet of soil (Daniels et al. 2010).

The primary retention mechanism for phosphorus is from irreversible binding of phosphorus to soil clay minerals. Over time, orthophosphate forms insoluble compounds through associations with metals such as iron, aluminum, and calcium in the soil (Busman, Lamb et al. 2002). These fixed forms of phosphorus are generally unavailable to plants. Therefore, retention of P is best achieved by increasing infiltration of water, bringing the nutrients in that water into contact with soil, and the formation of insoluble compounds in the soil. Tree roots reduce soil compaction and create soil macropores that increase water infiltration. Increased infiltration leads to greater pollutant/soil interaction. Additionally, trees remove soil water through evapotranspiration, thereby increasing storage capacity of soil water for future precipitation (Day, Wiseman et al. 2010).

Lastly, sediment sources in urban areas include the particles from regional and local atmospheric deposition. Trees have been shown to increase trapping of particles when compared to grass, a difference attributed to reduced overland flow, allowing particles to settle out via sedimentation (Leguedois, Ellis et al. 2008). As more water is retained beneath urban trees, the majority of sediments that would otherwise be transported by that water are likely to be retained and added to soil stores via adsorption onto organic matter and soil surfaces (Leguedois, Ellis et al. 2008).

Absolute versus relative loading rate calculations

Despite strong evidence that trees promote the attenuation and removal of non-point source pollution, we know of no studies that have quantified absolute loading rates for urban tree canopy land uses. There is very limited pollution concentration data available for runoff and

subsurface flow beneath urban tree canopies that can be used to calculate representative, statistical, edge of field (EOF) loading rates for nitrogen, phosphorus, and/or sediment. This is in contrast to forested watersheds where surface water quantity and quality can be more easily evaluated (for example see: Campbell et al. 2004). Furthermore, pollution fluxes determined from streams in uniform watersheds integrates many biotic and abiotic processes from upland to riparian areas (Vannote et al. 1980). Because urban tree canopy land uses are small by definition, it is unlikely that non-point source pollution in surface water can be traced back to them in complex urban watersheds especially where larger patches of forest may also exist.

Spatial and temporal variation of inputs also makes quantifying absolute loading rates challenging among all CBP land uses. Atmospheric deposition and fertilizer are the primary inputs of nitrogen, phosphorus, and sediment to developed areas. Total atmospheric deposition (i.e., wet and dry deposition) is well documented and varies regionally over the Chesapeake Bay watershed (Linker, Dennis et al. 2013), and is often elevated in densely developed areas, relative to agricultural, forested, and suburban areas (Lovett, Traynor et al. 2000). Atmospherically sourced phosphorus is generally deposited as dust or aerosol (Correll 1998), while fertilizer includes orthophosphate and polyphosphate (which readily converts to orthophosphate when in contact with water). Variation in turfgrass fertilization rates have been documented (Aveni, Berger et al. 2013), but are extremely difficult to predict spatially. Fertilization is one of the primary reasons that nutrient loads from turfgrass are elevated in the Chesapeake Bay model relative to open space (~ 5x and 2x for N and P, respectively) and forests (~7x and 12x for N and P, respectively).

No matter whether the source of nutrients is from atmospheric deposition or fertilizer, hydrologic processes ultimately govern the fate and transport of non-point source pollution to surface waters. Therefore, given (1) the lack of data needed to estimate absolute pollution loads of tree canopy land uses and (2) high spatial variability in pollution inputs, we choose to estimate reductions in non-point source pollutant loads by trees by modeling changes in water yield relative to turfgrass and impervious surfaces – the land cover types beneath tree canopy. While we have already described how trees store and aid in pollution removal, this approach nevertheless relies on our best professional judgment that changes in water quality are proportional to changes in water yield. This judgment is reasonable because variation in pollutant concentrations in streamwater is often small compared to variation in stream discharge.

Methods

We used fundamental principles in watershed hydrology to estimate the relative reduction in water yield by tree canopy compared to two underlying land uses – turfgrass and impervious surfaces – over which tree canopy extends and can be mapped using remote sensing technology. A general water balance equation (Eq. 1) is shown below where I is inputs, O is outputs, and ΔS is the change in water stored in soils. For comparison, water balance equations (Eq. 2 to 5) for two existing CBP land uses and those land uses with tree canopy are also shown. In these equations, inputs include precipitation (P), and/or laterally flowing subsurface water (T_i, throughflow), and outputs include runoff (R), evapotranspiration (ET), gravitational soil water that drains beneath the plant rooting zone (i.e., leaching, L), evaporation (E), and throughflow (T_o). The subscripts g and t refer to parameters specific to turfgrass and tree canopy, respectively.

General Mass Balance:	$I = O + \Delta S$	**(Eq. 1)**
Turfgrass:	$P = R + ET_g + L + \Delta S$	**(Eq. 2)**
Canopy over Turfgrass:	$P = R + ET_g + ET_t + L + \Delta S$	**(Eq. 3)**
Impervious	$P + T_i = R + E + T_o + \Delta S$	**(Eq. 4)**
Canopy over Impervious:	$P + T_i = R + ET_t + T_o + \Delta S$	**(Eq. 5)**

For water quality purposes, we are ultimately interested in the proportion of precipitation that becomes stream/surface flow, also known as *water yield*. Equation 6 describes the relative reduction in water yield from turfgrass with tree canopy relative to turfgrass without canopy, and Eq. 7 describes the relative reduction in water yield from impervious surfaces with tree canopy relative to impervious surfaces without canopy. The subscripts in equations 6 and 7 are used simply to identify the underlying land use (*g* is turfgrass and *i* is impervious) and whether or not that land use is covered by tree canopy (*c*). The role of tree canopy in modifying water yield varies with the severity of precipitation and the quality of vegetation (Keim, Skaugset, and Weiler 2006). To account for spatial and temporal variation in precipitation, we used eleven years (2005 to 2015) of daily weather data (National Climatic Data Center 2016) from each of

eight regional locations spanning the Chesapeake Bay Watershed (Figure 1). The ∑ symbol in equations 6 and 7 indicates that the volume of runoff, soil leachate, and change in throughflow will be estimated from daily weather data (unless otherwise noted), and the final results based on the mean annual cumulative total across all sites and years.

$$f_r = \left[1 - \frac{\sum R_{gc} + \sum L_{gc}}{\sum R_g + \sum L_g}\right] \times 100 \qquad \textbf{(Eq. 6)}$$

$$f_r = \left[1 - \frac{\sum R_{ic} + \sum T_{ic}}{\sum R_i + \sum T_i}\right] \times 100 \qquad \textbf{(Eq. 7)}$$
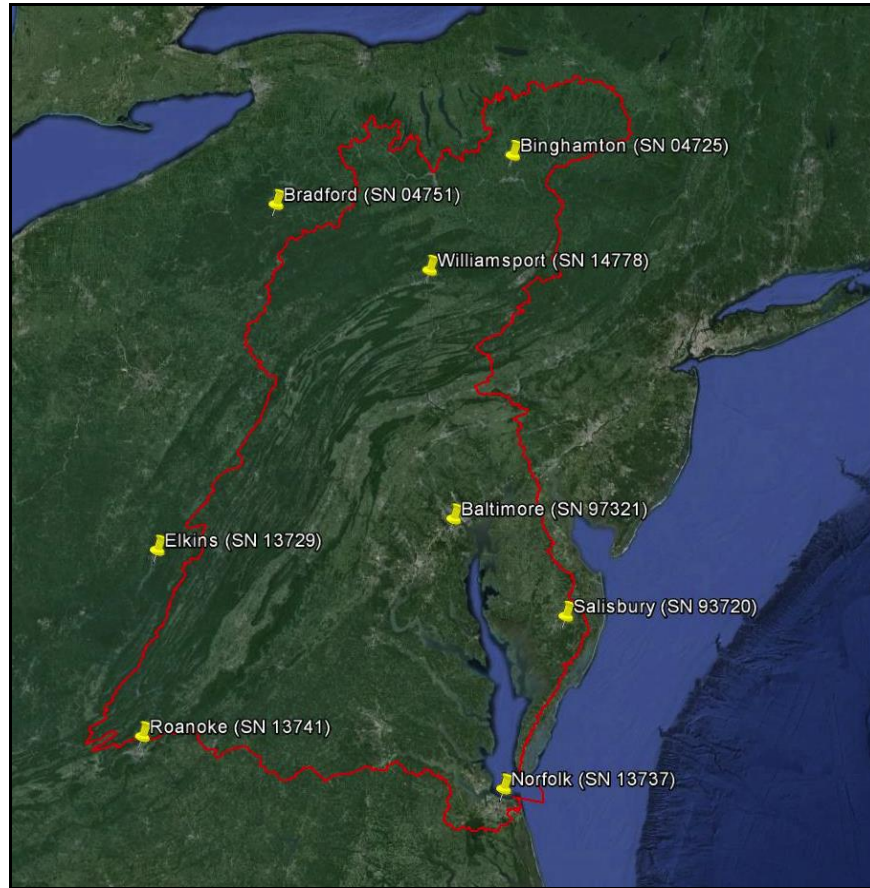

Figure 1: Weather station locations used in this analysis (figure created in Google Earth)

Precipitation is assumed to be the only input of water to areas mapped as tree canopy over turfgrass. In CBP reporting, riparian forest buffers are a stand alone BMP. This restricts areas mapped as tree canopy over turfgrass to upland sites where the water table is likely below the plant-rooting zone (~2 ft. deep). This assumption likely underestimates the hydrologic benefit of trees in developed areas as trees on residential property have been shown to access water below this depth, uplift, and redistribute it in shallow soil horizons at night (Day, Wiseman et al. 2010). For tree canopy over impervious surfaces, we include a source of shallow, subsurface water (T, throughflow) that trees can access and use to meet basic physiological needs. Throughflow originates from other pervious urban land uses and can be taken up and transpired by trees. The throughflow element is necessary because water and nutrients required for plant growth and function cannot infiltrate through impervious surfaces.

Calculating Runoff

For each of the four land use types, we estimated runoff using the Soil Conservation Service Curve Number Method (Eq. 8), where R is runoff, P is precipitation, I_a is the initial abstraction, and S is the potential maximum retention after runoff begins (all units in inches, USDA 1989).

$$R = \frac{(P - I_a)^2}{(P - I_a) + S} \qquad \textbf{(Eq. 8)}$$

In order to isolate the effects of tree canopy interception beyond the water retaining properties of the underlying land use (i.e., turfgrass and impervious surfaces), we introduced a tree canopy interception term, C_i (units also in inches), into the basic curve number equation (Eq. 9). This term accounts for the amount of precipitation adsorbed to leaves and branches after throughfall stops and, effectively, reduces the amount of precipitation that reaches the ground before initial abstractions occur.

$$R = \frac{(P - C_i - I_a)^2}{(P - C_i - I_a) + S} \qquad \textbf{(Eq. 9)}$$

The amount of precipitation retained in the canopy varies with tree age, species, canopy health, and season. Tree canopy land uses are identified and mapped using satellite imagery with a resolution of one square meter and minimum height of two meters (O'Neil-Dunne et al. 2014), and therefore likely include trees that are ten years old at a minimum. For young to mature deciduous trees, interception capacity ranges from 0.02 to 0.11 inches per storm, whereas interception capacity for coniferous trees of similar age ranges from 0.02 to 0.18 inches per storm (Breuer, Eckhardt, and Frede 2003). For deciduous trees, most but not all interception capacity is lost during the winter as the branches and trunk still provide some interception capacity, whereas conifers retain full interception capacity year round. Because the current mapping methodology only indicates the presence of a tree and provides no other information on tree species or quality of the canopy, C_i in our model was set at 0.05 inches per storm during the growing season (April through October) – below the mean range of interception capacity – and zero during the dormant season. This amount of credit is similar to that given by a state agency for canopy interception in structural BMPs (0.043 in per storm; Minnesota Pollution Control Agency 2016), which likely includes a younger population of trees from new installations rather than a well established tree canopy.

The curve number method was originally designed to estimate stormflow following large precipitation events with flood planning as the most obvious application (Garen and Moore 2005). During the development of this method, observations of precipitation and runoff volume at the watershed scale revealed that the ratio of initial abstractions to potential maximum water retention (I_a/S) was approximately equal to 0.2 (USDA 1989). However, more recent research has demonstrated that this assumption significantly underestimates runoff at smaller scales, and that $I_a/S = 0.05$ is a more appropriate assumption for small urban areas (Woodward et al. 2003). Substituting 0.05 S for I_a in Equation 9 yields the following:

$$R = \frac{\left(P - C_i - 0.05 \times S\right)^2}{P - C_i + 0.95 \times S} \qquad \textbf{(Eq. 10)}$$

In the curve number method, the total maximum water retaining capacity (S) is further simplified to a dimensionless 'curve number' factor, CN, ranging from 0 to 100 (Eq. 11). The curve number accounts for the physical attributes of the land surface as well as the hydrologic properties of the underlying soil that affect infiltration. Following recommendations in the

USDA Technical Release 55, *Urban Hydrology for Small Watersheds*, we set $CN = 98$ for all impervious surfaces (with and without tree canopy), $CN = 79$ for turfgrass, and $CN = 74$ for tree canopy over turfgrass. The difference between a CN value of 79 and 74 is modest, and is equivalent to turfgrass in fair versus good condition with hydrologic soil group C (HSG). We used a slightly lower curve number (i.e., less runoff) for canopy over turfgrass to account for the *temporal* effects of canopy interception and improved physical structure of compacted soils by tree roots (Day et al. 2010). Equation 12 is the final equation that we used to calculate runoff.

$$S = \frac{1000}{CN} - 10 \qquad \textbf{(Eq. 11)}$$

$$R = \frac{\left(P - C_i - 0.05 \times \left(\frac{1000}{CN} - 10 \right) \right)^2}{P - C_i + 0.95 \times \left(\frac{1000}{CN} - 10 \right)} \qquad \textbf{(Eq. 12)}$$

Runoff is also influenced by the amount of precipitation and Figure 2 shows how runoff depth varies with precipitation depth based on Equation 12; forested land ($CN = 55$; HSG B) is also shown for reference. As previously mentioned, we used eleven years (2005 to 2015) of daily weather data from each of eight regional locations spanning the Chesapeake Bay Watershed to account for spatial and temporal variation in precipitation.
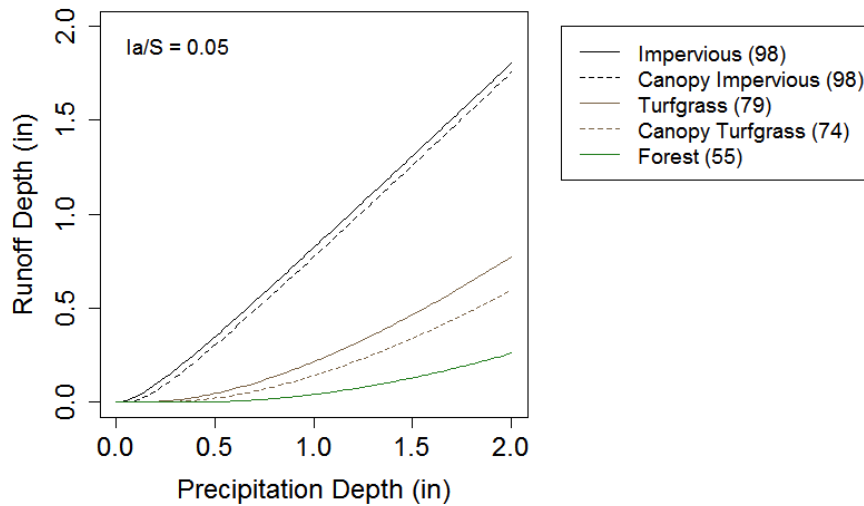
Figure 2: Precipitation vs. runoff depth estimated using the SCS Curve Number Method

For water quality purposes, it is important to note that 'runoff' estimated using the CN method from pervious areas is not the same as 'runoff' from impervious surfaces. In pervious upland areas, runoff includes both infiltration excess overland flow and macro-pore shallow subsurface flow (Garen and Moore 2005). In contrast, runoff from impervious surfaces is exclusively overland flow that is highly connected to surface waters by storm drains and pipes. This implies that on-site retention drives the water quality benefits of tree canopy over turfgrass, where as minimizing downstream erosion drives the water quality benefits of tree canopy over impervious surfaces. While we have no way of quantifying how tree canopy over turfgrass alters the balance between the two components of runoff (i.e., infiltration excess overland flow vs. shallow subsurface flow), it is highly likely that trees reduce infiltration excess overland flow (Asadian and Weiler 2009; Leguédois et al. 2008).

Runoff from impervious and other highly compacted surfaces is particularly problematic in developed areas because water is delivered over shorter periods of time to surface waters that erode stream banks (Walsh, Roy et al. 2005). Water quality can be impaired both by infrequent, large storm events as well as by more frequent, smaller events that deliver quick pulses of nutrients and sediments to receiving waters (Walsh, Fletcher et al. 2005). Trees reduce rainfall intensity and volume, and decrease runoff rates by intercepting precipitation on leaves and branches even when limited by surrounding impervious surfaces (Asadian and Weiler 2009; Nowak, Wang, and Endreny 2007; Wang, Endreny, and Nowak 2008; Xiao et al. 1998).

The results of our runoff calculation are shown in Figure 3. Across all sites and years, annual relative runoff reduction by tree canopy over turfgrass ranged from 18.0 to 39.2 % with a mean value of 29.0 %. Annual runoff reduction by tree canopy over impervious surfaces ranged from 3.5 to 10.6 % with a mean value of 7.0 %. Because sediment does not have a dissolved form, we made a conservative assumption that sediment retention beneath tree canopy over turfgrass had an efficiency factor of 0.20, resulting in a recommended relative reduction for sediment of 5.8% (29.0% relative reduction in runoff x 0.2).
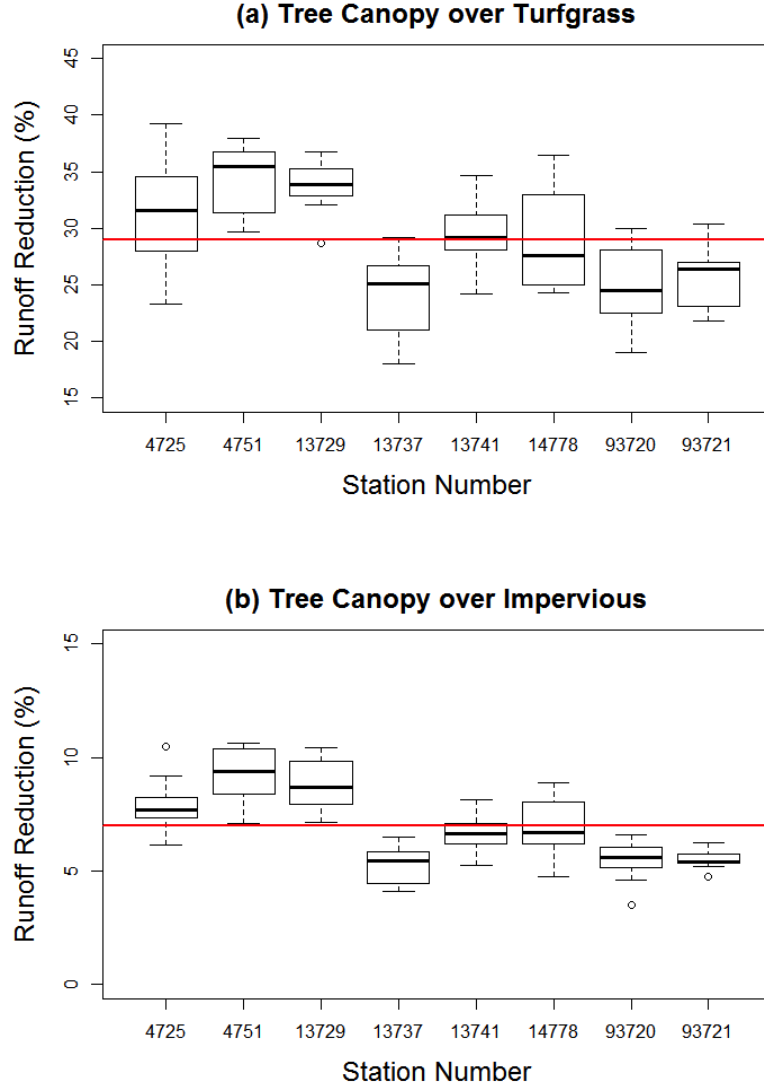
Figure 3: Annual reduction in runoff by tree canopy relative to (a) turfgrass and (b) impervious surfaces. Red line indicates the mean relative reduction in runoff across all sites and years.

Calculating Leaching

For pervious urban areas including turfgrass and tree canopy over turfgrass, the precipitation remaining after interception and runoff infiltrates (I) into soil (Equation 13). All or a portion of this water is temporarily stored in the soil, and in well-drained areas the maximum amount of soil water storage that is available for evapotranspiration (S_{max}) is equal to the soil's water holding capacity. Water holding capacity varies with soil texture (lowest in both very

sandy and very clayey soils) and ranges from ~1 to 2 inches per foot of soil (Brady and Weil 1996). For this analysis, we used a soil water holding capacity of 2 inches per foot, and a total soil volume based on the typical rooting depth of trees (2 ft) and one square meter of land – the minimum mapping unit of tree canopy.

The actual volume of soil water (S_t) will vary over time as a function of the initial soil water volume after rainfall (S_{t-1}) minus the amount of water evaporated and transpired (*ET*) in between precipitation events. Tracking changes in soil water over time also has the advantage of placing an upper limit on ET. During initial model testing, the soil water volume at the end of the year was almost always equal to the maximum water holding capacity. For this reason, the water holding capacity at the beginning of each year was set to zero ($S_t = S_{max}$). Any rainfall that is infiltrated in excess of the available water holding capacity was assumed to leach (L) below the rooting zone and lost as groundwater (Equation 14).

$$I = P - C_i - R \qquad \textbf{(Eq. 13)}$$

$$L = I - S_{\max} + S_t \qquad \textbf{(Eq. 14)}$$

In between precipitation events, evapotranspiration (ET) by turfgrass and trees reduces the volume of water in soil allowing more infiltrated water to be stored the next time it rains (Equation 15). In the same way that interception varies with tree age, species, canopy health, and season, ET also varies with these factors. Total annual ET rates are similar between turfgrass, trees in natural forest settings, and urban trees ranging from ~15 to 24 inches per year, or 0.04 to 0.064 inches per day (Ford et al. 2011; Penman 1948; Wullschleger et al. 2001; Wullschleger et al. 2000; Wilson et al. 2001; Peters et al. 2010). Again, because the current mapping methodology only indicates the presence of a tree and provides no other information on tree species or quality of the canopy, ET in our model was set at 0.05 inches per day for trees and turfgrass without trees during the growing season (April through October). We assumed that ET of shaded turfgrass was approximately half as effective as non-shaded turfgrass. Therefore, daily rates of ET for turfgrass and canopy over turfgrass were set to 0.05 and 0.08 inches per day during the growing season, respectively. During the dormant season (November through March), ET was only attributed to turfgrass at a rate of 0.025 inches per day.

$$S_t = S_{t-1} - ET \qquad\qquad \textbf{(Eq. 15)}$$

The results of our leaching calculation are shown in Figure 4. Across all sites and years, annual relative leaching reduction by tree canopy over turfgrass ranged from 10.0 to 42.5 % with a mean value of 22.5 %.
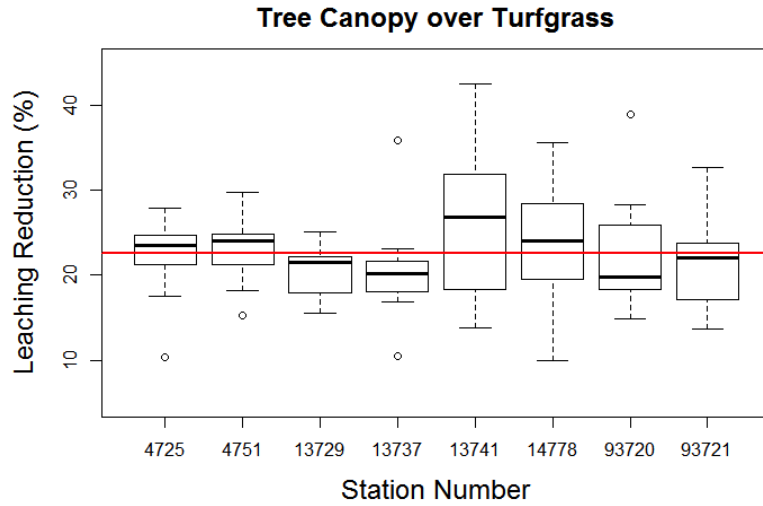

Figure 4: Annual reduction in leaching by trees relative to turfgrass.

Calculating Throughflow

We know of no straightforward way to estimate the mean daily flux of subsurface throughflow, and subsequent nutrient flux, beneath impervious surfaces. Tree roots are highly advantageous, often growing into broken stormwater pipes and culverts, and there is likely a high degree of spatial variation. In addition, a large portion of dissolved nitrogen and phosphorus taken up through roots with water and incorporated in tree tissues is later deposited as leaf litter on impervious surfaces that are highly connected to surface waters. While it is true that decomposing leaf litter contributes nitrogen and phosphorus to road runoff in autumn (Hobbie et al. 2014; Kaushal and Belt 2012), it is entirely possible that the net flux of N and P in litterfall

over the course of a year is zero simply by transforming, concentrating, and redistributing base flow (Janke et al. 2014).

However, a small proportion of N and P are incorporated into woody plant tissues (i.e., branches, bark, heartwood, and sapwood) that represent a long-term store of non-point source pollution. Rather than rely on poorly constrained estimates of throughflow (Eqs. 4 and 5), we choose to estimate relative on-site pollution reduction based on the result of nutrient uptake – biomass growth – and the proportion of N and P stored in wood versus total annual uptake (wood + leaf production) and atmospheric deposition (Eq. 16).

$$R = \left(\frac{W}{W + L + A} \right) \times 100 \qquad \textbf{(Eq. 16)}$$

We estimated annual storage of N and P in tree wood by combining estimates of average annual wood production of urban trees (4.5 to 9.7 kg of C per tree per year, Nowak and Crane 2002) with C, N, and P concentration data in wood from the literature (molar C/N and C/P in wood ~ 300 and 500, respectively; Rastetter et al. 1991; Pettersen 1984; Martin et al. 1998). Based on our calculations (see Appendix 1 for full calculations), 0.038 to 0.083 lbs of N and 0.051 to 0.11 lbs of P are stored in new wood tissues per tree per year. Similarly, we estimated the annual flux of N and P in tree litterfall by combining estimates of annual leaf production (~5 to 20 kg leaf mass per tree per year; Olson 1963; Chapin et al. 2011; Abelho 2001; Martin et al. 1998) with N and P concentration data in tree leaves (~ 25 ppm N and molar N/P ~ 5; Martin et al. 1998; Schaller 1968; McGroddy et al. 2004). These calculations indicate that ~ 0.27 to 1.10 lbs of N and 0.12 to 0.49 lbs of P are taken up each year by trees and used to build leaves. Finally, we used established atmospheric deposition rates (14 kg N ha^{-1} yr^{-1}; National Atmospheric Deposition Program) or precipitation concentration data combined with annual rainfall data (63 ppb inorganic + organic P ; Smullen et al. 1982) to estimate the amount of atmospheric N and P deposited on the canopy of a mature tree (~ 10 m^2). Table 1 shows the fluxes of N and P used to estimate storage in wood relative to total uptake and atmospheric deposition.

Table 1. Average annual nutrient uptake and atmospheric deposition of N and P

Elemental Fluxes	Woody Biomass (lbs. tree^{-1} yr^{-1})	Litterfall (lbs. tree^{-1} yr^{-1})	Atmos. Dep. (lbs. tree^{-1} yr^{-1})	N and P in wood relative to total uptake and atm. Dep. (%)
Nitrogen	0.038	0.69	0.031	5.0 %
Phosphorus	0.051	0.31	0.0013	14 %

To make these results comparable to water yield, we must still make some assumption about the efficiency of nutrient uptake over the course of a year. For this conversion we used a simple assumption based on the proportion of time that trees are transpiring over the course of a year (7/12 months x ½ day = 0.29). Therefore, we estimate that the relative reduction in N and P by trees from throughflow to be 1.5 and 4.0 % respectively.

Summary of results and recommendations

The results of our water yield calculations are summarized in Table 2. Relative reduction in total yield for tree canopy over turfgrass is closer to the relative reduction in leaching due to the greater volume of water exported in soil leachates compared to runoff. Table 3 displays the final recommended relative reductions for N, P, and sediment for tree canopy land uses after adding in the small proportion of N (1.5 %) and P (4 %) stored in woody biomass.

Table 2. Estimated annual reductions in water yield by tree canopy relative to impervious and pervious land covers

Land Use	Precip. (in)	Runoff Red. (%)	Leaching Red. (%)	Total Yield (%)
Canopy over Turfgrass	39.9	29.0	22.5	23.8
Canopy over Impervious	39.9	7.0	NA	7.0

Table 3. Recommended relative reductions in N, P, and sediment for tree canopy land uses

Land Use	Total Nitrogen Red. (%)	Total Phos. Red. (%)	Total Sed. Red. (%)
Canopy over Turfgrass	23.8	23.8	5.8
Canopy over Impervious	8.5	11.0	7.0

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Appendix 1: Biomass Calculations

Woody Biomass

4.5 to 9.7 kg of C per tree per year   (Nowak and Crane 2002)
x 1000 g/kg   conversion factor
x 1 mol C / 12.01 g of C   conversion factor
x 1 mol N / 300 mol C   references listed below
x 14.01 g N / mol N
x 1 lb / 454 g
= 0.038 to 0.083 lbs N per tree per year

mass ratio C/N approximately 300:1 (Rastetter et al. 1991), C is 50% of wood (so 500 mg/g) (Pettersen 1984), 0.2 to 4.0 mg N / g wood for heartwood, sapwood, and branches (Martin et al. 1998)

4.5 to 9.7 kg of C per tree per year   (Nowak and Crane 2002)
x 1000 g/kg   conversion factor
x 1 mol C / 12.01 g of C
x 1 mol P / 500 mol C   (Pettersen 1984)
x 30.97 g P / mol P
x 1 lb / 454 g
= 0.051 to 0.11 lbs P per tree per year

Litterfall

5 to 20 kg per tree per yr   (Olson 1963; Chapin III, Matson, and Vitousek 2011; Abelho 2001)
         (Martin et al. 1998)
x 1000 g / kg   unit conversion factor
x 25 mg N / 1 g of litter   (Martin et al. 1998)
x 1 g / 1000 mg   unit conversion factor
x 1 lb / 454 g   unit conversion factor
= 0.27 to 1.10 lbs N per tree per year

5 to 20 kg per tree per yr   (Olson 1963; Chapin III, Matson, and Vitousek 2011; Abelho 2001)
         (Martin et al. 1998)
x 1000 g / kg   unit conversion factor
x 25 mg N / 1 g of litter   (Martin et al. 1998; Schaller 1968)
x 1 g / 1000 mg   unit conversion factor
x 1 mol N / 14.01 g N   unit conversion factor
x 1 mol P / 5 mol N   (McGroddy, Daufresne, and Hedin 2004)
x 30.97 g P / mol P   unit conversion factor
x 1 lb / 454 g   unit conversion factor
= 0.12 to 0.49 lbs P per tree per year

Atmospheric Deposition

14 kg N ha^{-1} yr^{-1} (NADP via Marion)
x 1000 g / 1 kg   unit conversion factor
x 1 lb. / 454 g   unit conversion factor
x 1 ha / 10000 m^2   unit conversion factor
x 10 m^2   canopy area of single tree
= 0.031 lb. N per tree per year

Appendix 1, continued

<u>Atmospheric Deposition</u>

TP = 63 ug/L in atmospheric dep.   (Smullen, Taft, and Macknis 1982)
x 1 g / 10^6 ug
x 1 lb. / 454 g
x 1000 L / m^3
x 39.9 in of rainfall   (National Climatic Data Center)
x 1 m / 39.37 in
x 10 m^2
= 0.0013 lbs P per tree per year