Review of the Available Literature and Data on the Runoff and Pollutant Removal Capabilities of Urban Trees

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Introduction

The Center for Watershed Protection reviewed a total of 159 publications to evaluate the research questions defined in the scope of this project:

1. What is the effectiveness of urban tree planting on reducing runoff, nutrient and sediment?
2. How does effectiveness vary by species, over time, with differences in planting sites (e.g., distance from impervious cover or other trees, soil conditions, geographic location) and with different maintenance strategies?

For the purposes of this project, the term "urban tree planting" is defined as all tree planting in the urban environment that does not result in a forest-like condition. This includes trees that are planted with no special engineering to accept or treat runoff (e.g., street and yard trees), trees that are designed to accept and treat runoff (e.g., using structural soils and structural cells), and trees that are planted within BMPs such as bioretention or ponds to provide enhanced performance.

A limited number of studies directly address the water quality benefits of urban trees, and an even smaller subset provide results that can be used to develop effectiveness values for urban tree planting. Of greater applicability were the 49 studies on the hydrologic benefits of urban trees. These studies attempt to quantify one or more components of the tree's hydrologic cycle, which, combined, can inform estimates of runoff reduction provided by urban trees. Nutrient and sediment reduction can then be inferred from runoff reduction through modeling. We also reviewed a number of studies on the water quality and runoff reduction benefits of non-urban forests, which may be considered an upper limit to any credit assigned to urban tree planting, based on the assumption that trees and forests in urban environments do not function as well as natural forests due to factors such as compacted soils, lack of understory, open-grown trees and numerous impacts on tree health.

Because trees planted in the riparian zone (i.e., within 100 feet of a waterbody) are often treated and credited as a best management practice (BMP) in state and local stormwater management manuals, this review focused primarily on the benefits of trees in upland areas. Urban trees provide a host of other benefits, including air quality improvement, habitat for wildlife, temperature reduction and energy savings. While some of these ancillary benefits were also addressed in the literature reviewed, this synthesis focuses solely on nutrient, sediment and runoff reduction.

Of the studies reviewed, 48 focused on factors affecting the mortality, growth, condition and survival rates of urban trees. These studies can inform recommendations on the urban tree credit by supporting qualifying conditions for water quality credit assigned to trees planted in the urban landscape, and supporting projections of ultimate tree size and mortality rates for use in determining the appropriate water quality credit for tree planting.

In addition to the published literature, the Center also reviewed the available models, calculators and existing credit systems for urban trees. A summary of this review and each tool's potential utility in developing a national credit for urban trees is provided as part of this synthesis.

Overview of Tree Benefits

Protecting existing trees and planting new ones in urban areas has great potential for helping to meet water quality requirements such as total maximum daily loads (TMDLs) and stormwater management regulations. However, trees are unlike most other urban BMPs, which have a defined drainage area and are engineered to capture and remove pollutants from stormwater runoff. While trees affect processing of nutrients from the soil, atmosphere and groundwater (Figure 1), their primary impact on water quality is attributed to the prevention of water pollution by reducing the amount of runoff generated from areas where tree canopy is present. In the absence of tree canopy, rain falling on urban surfaces such as parking lots, streets and lawns picks up various pollutants as it runs off the landscape. Therefore, the cumulative effect of tree canopy is to temporarily detain rainfall and gradually release it, regulating the flow (volume and peak) of stormwater runoff downstream and thereby preventing pollutants in rainfall and on urban surfaces from being transported to local waterways.

The specific processes by which urban trees impact runoff are shown in Figure 1 in blue. Additional mechanisms by which trees positively influence water quality are shown in green in Figure 1, while potential contributors to runoff pollution are shown in red.

When it rains, trees capture rainfall in their canopies (**rainfall interception**). Intercepted rainwater is temporarily stored in the canopy before being released by **evaporation** directly into the atmosphere or transmitted to the ground via stems, branches, and the tree trunk (**stemflow**) for root absorption. The water delivered to the base of trees penetrates the soil rapidly (**infiltration**) by following interconnected pathways in the soil formed by large roots and macropores. Rainfall that is not intercepted by the canopy later reaches the underlying ground as **throughfall.** This water can be lost to evaporation, transpiration by the underlying vegetation, or infiltration or it can become **runoff.** If the underlying ground cover is pervious, leaf litter and other organic matter, soil macropores, and small depressions all work to slow runoff, hold water and further promote infiltration. The infiltrated water can feed into local waterways through **interflow** or replenish groundwater supplies (**recharge**). In between storms, trees can also absorb water from the soil by root uptake and releases the unused portion back into the atmosphere in the form of water vapor through **transpiration**. This increases soil water storage potential, effectively lengthening the amount of time before rainfall becomes runoff.

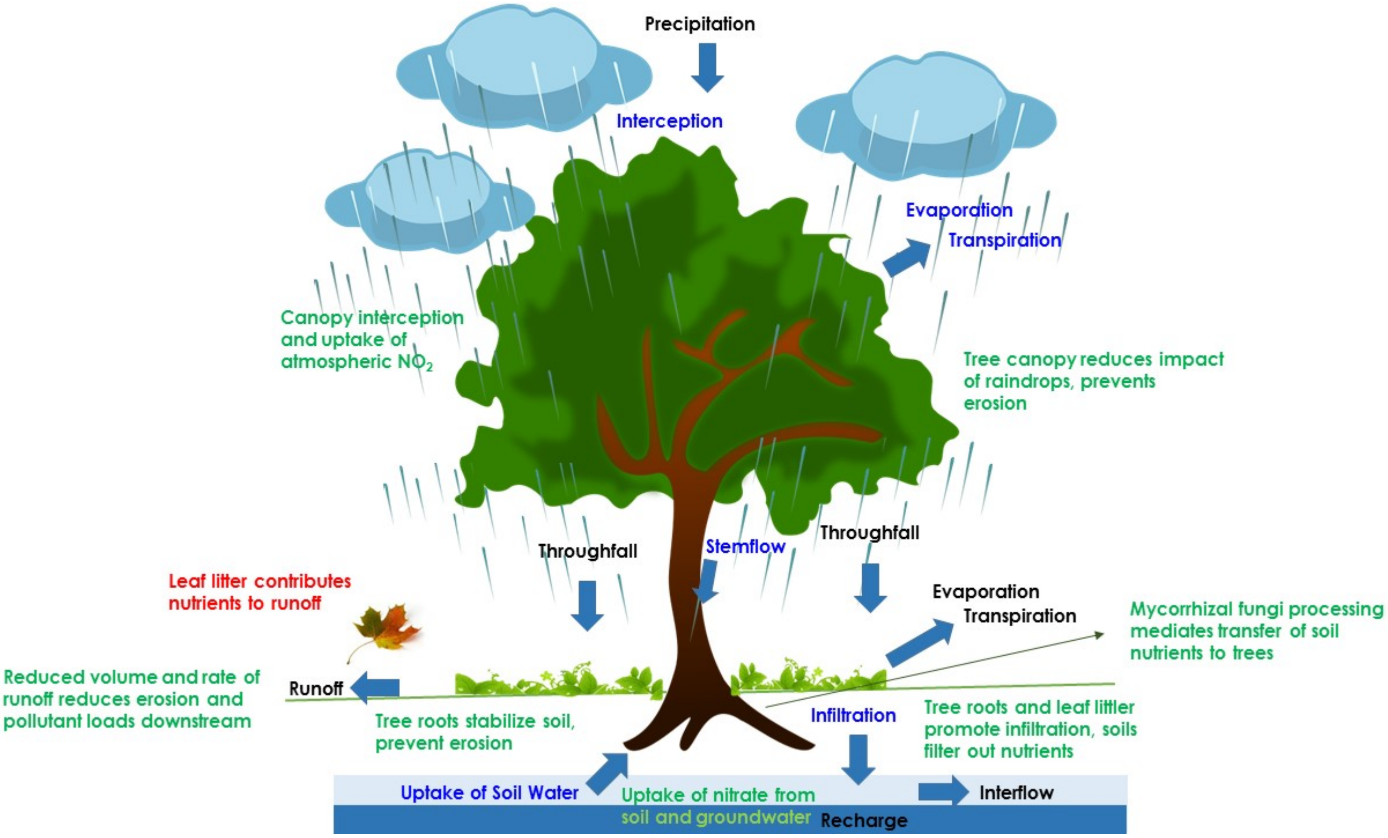

Figure 1. Urban Tree Impacts on Hydrology and Water Quality

The ability of an urban tree to reduce runoff is determined by how much rainfall is intercepted and evaporated in the canopy or infiltrated into the soil. The removal of soil water by trees through transpiration also affects runoff by increasing soil water storage potential, effectively lengthening the amount of time before rainfall becomes runoff. By preventing rain from becoming runoff, trees decrease the volume of runoff that is available to pick up sediment and nutrients from the urban landscape. This correlation between runoff and water quality is widely accepted and many stormwater runoff models calculate pollutant loads as a product of runoff volume and pollutant concentration. Trees provide additional water quality benefits through uptake of pollutants from the atmosphere, soil and groundwater, and may contribute nutrients to surface waters through leaf litter, but these components are more challenging to quantify given the available data and its variability.

While these processes and mechanisms for reducing runoff and pollutants are well known, the amount by which trees reduce runoff is highly variable, and by extension water quality as well. For example, interception alone is influenced by numerous factors, including the intensity, duration and frequency of rainfall; canopy architecture, leaf area, leaf angle distribution, leaf surface characteristics; and meteorological factors such as wind speed and vapor pressure deficits. Evapotranspiration is similarly influenced by a number of environmental and structural factors. Studies that quantify these processes offer results that are often site-specific or event-specific. All of these factors present a challenge with translating these results into water quality credits that reflect the "average" condition. A summary of the available research is provided below.

Hydrologic Benefits

Trees affect water quality primarily by reducing the amount of stormwater runoff that reaches surface waters. Trees reduce runoff through rainfall interception by the tree canopy, by releasing water into the atmosphere through evapotranspiration (ET), and by promoting infiltration of water through the soil and storage of water in the soil and forest litter. Major findings from the literature review for each of these processes are summarized below.

Interception

Canopy interception of rainfall is an important and significant component of the tree water balance. Table 1 summarizes the values found in the literature on annual rainfall interception by urban trees and forests, which range from 6.5 to 66.5% for all trees, 6.5 to 27% for deciduous trees and 27-66% for evergreen species, as a percent of annual rainfall. Some of the studies only reported interception as a volume per tree per year. Note that most of the studies in Table 1 are from semi-arid climates, so further analysis will be needed to adapt them to humid regions.

More studies are available on rainfall interception by natural forests, and these results are summarized in Table 2 for comparison to the urban tree results. Even in the natural environment, rainfall interception by forests is extremely variable and difficult to measure, as noted by Crockford and Richardson (2000) in a review of interception studies. The range of annual interception by deciduous forests shown in Table 2 is 10-22% and 15-46% for evergreen forests. Both sets of data generally agree that evergreen intercept more rainwater than deciduous trees (more than double in some cases) since they have leaves year-round.

Table 1. Rainfall Interception Studies of Urban Trees

Study	Location	Interception (% of annual rainfall)[1]	Species/Condition[2]	Type of Study[3]
Kirnbauer et al. 2013	Hamilton, Ontario, CA	6.5-11 17-27	G. biloba (D), P. acerifolia (D), A. saccharinum (D) L. styraciflua (D)	Modeling
Livesley et al. 2014	Melbourne, Victoria, Aus.	29 44	E. saligna (E) E. nicholii (E)	Measured
Xiao and McPherson 2002	Santa Monica, CA	27.3 15.3 66.5	All park and street trees Small jacaranda mimosifolia (D) Mature tristania conferta (E)	Modeling
Xiao et al. 1998	Sacramento County, CA	11.1	Tree canopy in the County	Modeling
Xiao et al. 2000	Davis, CA	15 27	Pear (D) Oak (E)	Measured
Xiao and McPherson 2011a	Oakland, CA	14.3 25.2 27.0	Sweetgum (D) Gingko (D) Lemon (E)	Measured
Wang et al. 2008	Baltimore, MD	18.4	Tree canopy in Dead Run subwatershed (D)	Modeling
Band et al. 2010	Fairfax, VA	14.5	Tree canopy in Accotink watershed (D)	Modeling
Band et al. 2010	Baltimore, MD	15.7	Tree canopy in Gwynns Falls watershed (D)	Modeling
Band et al. 2010	Montgomery County, MD	19.6	Tree canopy in Rock Creek watershed (D)	Modeling
Asadian and Weiler (2009)	Vancouver, BC	49 61	Douglas fir (E) Western red cedar (E)	Measured
Study	Location	Interception (m^3 per tree/yr)	Species/Condition	Type of Study
Berland and Hopton 2014	Cincinnati, OH	6.7	Average value	Modeling
McPherson and Simpson 2002	Modesto, CA	3.2	Average value	Modeling
McPherson and Simpson 2002	Santa Monica, CA	7.0	Average value	Modeling
McPherson et al. 2011	Los Angeles, CA	0.4 (low) 5.6 (high)	Crapemyrtle Jacaranda (D)	Modeling
Soares et al. 2011	Lisbon, Portugal	4.5	Average value	Modeling
CWP, 2014	Montgomery County, MD	7.57	15-20 year old 9-15” DBH tree	Modeling

[1] represents the % of rain falling on the tree canopy that is captured through interception

[2] D = deciduous, E = evergreen

[3] Measured = studies that infer interception by subtracting measured throughflow and stemflow from measured rainfall; modeled = studies that model interception using models such as i-tree

Table 2. Rainfall Interception by Natural Forests

Study	Interception (% of annual rainfall)	Type of Forest/Location	Type of Study
Zinke (1967), cited in Xiao et al. (2000)	15-40	Conifer stands	Compilation of 39 Studies
	10-20	Hardwood stands	
Baldwin (1938), cited in Xiao et al. (2000)	59	Old growth forests	Unknown
Dunne and Leopold (1978) cited in Herrera Environmental Consultants (2008)	13[1]	Deciduous trees	Compilation of measured studies
	28[1]	Conifers	
Molchanov (1960) cited in Reynolds et al. (1988)	34-46	Spruce forest/USSR	Measured
	24-27	Pine forest/USSR	
	24	Birch forest/USSR	
	22	Oak forest/USSR	
Heal et al. (2004)	44	Conifers/UK	Measured
Link et al. (2004)	22.8-25	Old-growth Douglas fir forest/Western Cascades, WA	Measured
Deguchi et al. (2006)	16.8	Deciduous forest/Japan	Measured

[1] these studies were unavailable so it is unknown whether these values represent percent of annual rainfall versus storm event or study period rainfall

Although interception losses depend on factors such as leaf area index (LAI) and tree structure, they are largely dependent on storm characteristics (Xiao et al. 2000). The most critical time for trees to play a role in reducing runoff is during and right after a storm (KDGT 2013). KDGT (2013) suggests that, because of this, continuous simulation modeling may be the best approach for estimating rainfall interception.

Evapotranspiration

Evaporation and transpiration occur simultaneously and there is no easy way of distinguishing between the two processes. When vegetation is small, water is predominately lost by soil evaporation, but once the vegetation is well developed, transpiration becomes the main process. As described in KDGT (2013), rainfall interception, advection, turbulent transport, total leaf surface area and available water capacity are all factors that combine to control ET rates, and the relative importance of each variable can fluctuate due to climate, soils and vegetative conditions.
Given the complexity of quantifying ET, no studies were found that quantify annual ET rates for trees in urban areas. Most studies instead evaluate how one or more factors influence ET, develop and test models for estimating ET, or measure ET values for a particular species during the growing season. KDGT (2013) describe the different methods of estimating ET, as well as the advantages and limitations of each.

Sinclair et al. (2005) documented the influence of soil moisture on ET and found that ET is highest when soil moisture is highest, and decreases as soil moisture decreases. Wang et al. (2011) found that transpiration rates were highest during a summer day and lowest during a winter night because of the great influence of the evaporative demand index, consisting of air temperature, soil temperature, total radiation, vapor pressure deficit, and atmospheric ozone. Guidi et al (2008) concluded that ET was strongly correlated to plant development and mainly dependent on its nutritional status rather than on the differences between species. A modeling study by Band et al. (2010) in suburban watershed in Baltimore County, MD, identified the importance of ET on runoff reduction and noted that the major effect of tree canopy on runoff production was the ability to remove soil water by transpiration, allowing more pore space for infiltration. However, Litvak et al (2014) found that in summer, total plot ET of urban lawns with trees was lower than lawns without trees by 0.9–3.9 mm d^{-1} in the Los Angeles metropolitan area. Another study from Los Angeles by Pataki et. al (2011) raised concerns that certain tree species may place too much of a demand on the local water supply because of high ET rates.

Tables 3 and 4 present a summary of transpiration studies on urban trees while Table 5 summarizes similar data from natural forests. Most studies do not emphasize rates of transpiration during cloudy or overcast days, but instead focus on the interpretation of data collected during periods when maximum rates of sap flow occur. There is quite a wide range of results for the average daily volume of water an urban tree can transpire, from 0.2 gallons to 46.7 gallons per tree per day. Studies that report rates of transpiration show a more narrow range of results, from 0.1 to 2.39 mm/day for urban trees. These rates are comparable to that of natural forests, which range from 0.5 to 3.0 mm/day.

Table 3. Transpiration Rates by Urban Trees During the Growing Season

Study	Location	Average Daily Transpiration Rate (mm/day)	Species / Condition[1]	Type of Study
Wang (2012)	Beijing, China	1.47	Horse Chestnut - *Aesculus chinensis* (D), 10.5-19.2 DBH	Measured
Chen et al. (2011)	Liaoning Province, China	1.31-1.51	*Cedrus deodara, Zelkova schneideriana, Metasequoia glyptostroboides, Euonymus bungeanus*	Measured
Peters et al. (2010)	Minneapolis St. Paul, Minnesota	1.1[2]	*Fraxinus Pennsylvanica, Quercus rubra, Juglans nigra, Tilia Americana, Ulmus pumila, Ulmus thomasii* (D)	Measured
		1.9[2]	*Picea glauca, Picea pungens, Pinus strobes, Picea abies, Pinus nigra, Pinus sylvestris* (E)	Measured
Cermak et al. (2000)	City of Brno, Czech Republic	2.17	Red Maple - *Acer campestre L* (D), roots covered by asphalt, 18” DBH, shaded	Measured
		2.39	Red Maple - *Acer campestre L* (D), roots covered by asphalt, 50” DBH, exposed to sunlight	
Pataki et a. (2011)	Los Angeles, CA	0.1-2.2	Urban forest plots with mixed species	Measured

[1] D = deciduous, E = evergreen

[2] Converted from $kg/m^2/day$ assuming $1kg = 0.0010m^3$

Table 4. Gallons of Water Transpired by Urban Trees During the Growing Season				
Study	**Location**	**Average Daily Transpiration Volume (gal/tree/day)**	**Species / Condition**[2]	**Type of Study**
Pataki et al. (2011)	Los Angeles, CA	0.2[1]	Laurel Sumac - *Malosma laurina*, unirrigated	Measured
		0.8[1]	*Pinus canariensis*, unirrigated	
		2.3[1]	Blue Jacaranda - *Jacaranda mimosifolia*, irrigated	
		3.4[1]	Kurrajong - *Brachychiton populneus*	
		3.4[1]	Redwood - *Sequoia sempervirens*	
		5.0[1]	Lacebark –*Brachychiton discolor*	
		11.3[1]	Grand Eucalyptus - *Eucalyptus grandis*	
		12.0[1]	Crape Myrtle - *Lagerstroemia indica*	
		12.5[1]	California Sycamore - *Platanus racemosa*, campus	
		13.0[1]	Canary Island Pine - *Pinus canariensis*, LAPD	
		13.4[1]	Goldenrain tree - *Koelreuteria paniculata*	
		17.9[1]	Chinese elm - *Ulmus parvifolia*	
		19.4[1]	*Pinus canariensis*, campus	
		23.7[1]	Laurel Fig - *Ficus microcarpa*	
		23.7[1]	Honey Locust - *Gleditsia triacanthos*	
		26.2[1]	Jacaranda - *Jacaranda chelonia*	
		27.1[1]	*Platanus racemosa*, street	
		46.7[1]	London Planetree - *Platanus hybrida*, street	
Green (1993)	Palmerston North, New Zealand	10.5[3]	10 year old isolated walnut (D)	Measured
Cermak et al. (2000)	City of Brno, Czech Republic	17[3]	Red Maple - *Acer campestre L* (D), roots covered by asphalt, 18” DBH, shaded	Measured
		37[3]	Red Maple - *Acer campestre L* (D), roots covered by asphalt, 50” DBH, exposed to sunlight	

[1] Converted from kg/tree/day assuming 1 gallon = 3.79 kg of water

[2] D = deciduous, E = evergreen

[3] Converted from liters/tree/day

Table 5. Transpiration Rates by Natural Forests During the Growing Season

Study	Location	Average Daily Transpiration Rate (mm/day)	Type of Forest/Location	Type of Study
Wullschleger et al. (2000)	Eastern TN	1.1-3.0[1]	Large red maples in a upland oak forest	Measured
Wullschleger et al. (2001)	Eastern TN	1.1 (average) 2.2 (maximum)	Upland oak forest (white and red oak, black gum, red maple, yellow poplar)	Measured / Modeled[2]
Cienciala et al. (1997)	Central Sweden	0.5[3]	100 year old stand sub-boreal forest (pine and spruce)	Measured
		0.9[3]	50 year old stand sub-boreal forest (pine and spruce)	
Ford et al. (2011)	Coweeta Basin, Western NC	1.1	Mixed deciduous hardwood forest	Measured
		2.4	White pine forest	

[1] Measurements are for individual trees
[2] Sap flow measurements for individual trees were used to model stand transpiration
[3] Measurements taken during a dry period in July

Because of the difficulty in measuring ET by trees over annual timeframes, some studies use a water balance approach to estimate ET for a watershed by subtracting discharge from precipitation or by measuring changes in discharge before and after forest clearing. For example, Boggs and Sun (2011) estimate mean annual ET rates for a forested watershed (77% of annual rainfall) compared to an urbanized watershed with 44% impervious cover (58% of annual rainfall) in the central NC piedmont. Hibbert (1969) found that water yield from a 22-acre catchment in the southern Appalachians increased over 5 inches annually when the catchment was converted from hardwood forest to grass. During years when grass production was high, water yield from the catchment was about the same as or less than the expected yield from the original forest. As grass productivity declined, water yield gradually increased. Hibbert (1969) attributes the changes in water yield to changes in ET.

Infiltration

Studies on the effects of urban trees on soil infiltration are limited. The studies reviewed demonstrate that trees can increase soil infiltration rates, even in highly compacted soils such as those typically found in the urban environment. Only two studies quantified this increase, with Bartens et al. (2008) showing that tree roots increased soil infiltration rates by an average of 63% over unplanted controls and 153% for severely compacted soils. Kays (1980) showed a 35% decrease in suburban forest infiltration rates with removal of the understory and leaf litter. Chen et al (2014) identified soil rehabilitation with compost to be an important practice for mitigating urban soil compaction and also found the presence of trees contributes to an increase in soil hydraulic conductivity.

Studies also demonstrated that trees can increase infiltration rates in structural soils. Bartens et al (2009) grew green ash and swamp white oak in CU Soil and Carolina Statlite-based mix subjected to three simulated below-system infiltration rates for two growing seasons. Green ash grown in CU Soil had an increased infiltration rate by 27 times compared with unplanted CU Soil control sites (Bartens et al 2008). Infiltration rate affected both transpiration and rooting depth. In a factorial experiment with ash, rooting depth always increased with infiltration rate for Stalite, but this relation was less consistent for CU Soil. Transpiration rates under slow infiltration were 55% (oak) and 70% (ash) of the most rapidly transpiring treatment (moderate for oak and rapid for ash).

Le Coustumer et al. (2012) found that hydraulic conductivity declined over time for both vegetated and unvegetated biofilters, except those planted with the tree *Melaleuca ericifolia*. Hydraulic conductivity for the biofilter planted with *M. ericifolia* initially decreased from 155 to 100 mm/h over the first 40 weeks, but then increased to 295 mm/h after 60 weeks, finishing at around 240 mm/h at the end of testing (72 weeks). The authors hypothesize this is due to the importance of thick roots that help to maintain permeability of the soil over time through the creation of macropores.

Three other studies were reviewed that quantify the impact of trees on infiltration rates in non-urban environments. Mlambo et al. (2005) found that soil infiltration rates under tree canopy (0.12 +/- 0.02 mm/s) were 50% higher than outside the canopy (0.06 +/- 0.03 mm/s), and that infiltration rates were significantly higher under large trees than medium or small trees. Lal (1996) found that after the deforestation of a Nigerian forest, infiltration rates decreased by 20 to 30 percent. Wondzell and King (2003) summarized the literature on infiltration rates in burned and unburned forests of the Pacific Northwest and Rocky Mountain regions and showed that infiltration rates were around 35% lower in burned forests than unburned ones (value estimated from chart).

Runoff Reduction

The combined effect of trees' ability to intercept and evapotranspire rainfall and promote infiltration of water into the soil is that the overall proportion of rainfall that becomes runoff is reduced. Most studies on runoff reduction provided by urban forests use hydrologic models to estimate the impact of trees on reducing stormwater runoff. The most commonly used models are American Forest's CITYgreen software, which is based on TR-55 (USDA SCS, 1986) and uses runoff curve numbers that predict runoff based on land use type, and the US Forest Service's i-tree (formerly known as UFORE), which is based on hydrodynamic canopy models. These modeling studies show that, as forest cover in a municipality or watershed increases, runoff decreases (and the inverse is also true). However, these results are more challenging to translate into an annual percent reduction in runoff at the scale of an individual tree or urban forest plot. Table 6 summarizes the results from the studies reviewed on runoff reduction by urban trees and forests. As indicated in the description in Table 6, each study has a unique approach to quantifying runoff reduction.

For both the CITYgreen and i-Tree models, analyses identical to those described in Table 6 have been conducted for dozens of municipalities across the US. Only one CITYgreen study was reviewed for this synthesis because the method upon which it is based (the runoff curve number method) was developed for agricultural watersheds and has been shown to be relatively inaccurate in estimating runoff from forest.[i] For both CITYgreen and i-Tree, the results do not allow for assignation of a runoff reduction value to an acre of trees or a single tree. Therefore, rather than summarizing the result of additional i-Tree studies, it may be more instructive to explore the use of i-Tree to model reductions associated with tree canopy. Wang et al. (2008), Armson et al. (2013) and Herrera Environmental Consultants (2008) all found that runoff reduction was more pronounced when trees were planted over/near impervious cover.

Table 6. Studies of Runoff Reduction by Urban Trees

Study	**Results**	**Description**
American Forests (1999)	19% increase in runoff	Modeled increase in runoff associated with loss of 14% forest cover
Armson et al. (2013)	58% reduction in runoff in summer and 62% in winter	Measured reduction from plot containing a tree pit and surrounded by asphalt
Wang et al. (2008)	2.6% runoff reduction	Modeled reduction associated with increasing tree cover over turf from 12 to 40%
	3.4% runoff reduction	Modeled reduction associated with increasing tree cover over impervious surface from 5 to 40%
Xiao and McPherson (2011b)	88.8% runoff reduction	Measured runoff reduction for bioswale integrating structural soils and trees[1]
Page et al. (2014)	80% runoff reduction	Measured runoff volume captured and treated by Silva Cell with tree[1]
Sanders (1986)	7% increase in runoff	Modeled increase in runoff associated with loss of 22% forest cover
	5% reduction in runoff	Modeled reduction associated with increasing tree cover over non-surfaced areas from 37% to 50%

[1] study did not include unplanted controls

In addition to reducing total runoff volume, tree canopy can delay peak runoff because of its ability to intercept and slowly release rainfall (Asadian and Weiler 2009). Research on the ability of tree canopy to delay throughfall reports a delay in throughfall of 0.17 hours to 3.7 hours after rainfall (Asadian 2010, Xiao 2000).

Studies of runoff reduction by natural forests (measured by comparing precipitation to streamflow within forested basins) show that deciduous forested basins retain 24-54% of rainfall, and evergreen forests retain 43-50% of rainfall (Post and Jones, 2001). Other studies infer runoff reduction by measuring changes in runoff from streams draining forested basins before and after clearcutting. For example, experiments conducted on three forested watersheds at the Hubbard Brook Experimental Forest in New Hampshire found that clear-felling and three successive years of herbicide application caused annual water yields to increase by an average of 32%. Increases in annual water yield diminished rapidly as forests regenerated and were undetectable within 7-9 years after treatment (Hornbeck et al. 1997). Moore and Wondzell (2005) report mean changes in annual water yields after forest harvesting of 8-43% in the Oregon Cascades, 14-26% in the Oregon Coast and South Coastal British Columbia and 15-80% in snow-dominated small catchments. Douglas and Swank (1972) summarized 23 experiments from mixed deciduous hardwood forests in the Appalachian Highlands, including Coweeta and Hubbard Brook mentioned above. They found a linear relationship between streamflow increase during the first year after forest removal and the percentage reduction of the forest stand, where first year increase = -1.43 + 0.13(% basal area reduction). Bosch and Hewlett (1982) conducted a review of 94 catchment experiments across the world as an update to a review by Hibbert (1967). Pine and eucalypt forest types were found to cause on average 40 mm change in water yield per 10% change in forest cover and deciduous hardwood and scrub ~25 and 10 mm, respectively.

Water Quality

The primary way that urban trees affect water quality is by reducing the amount of stormwater runoff that reaches surface waters. Trees also improve soil and water quality through uptake of soil nutrients by plants and soil microbes. Tree roots stabilize the soil and tree canopies reduce the impact of raindrops, both of which reduce soil erosion. Urban trees, especially street trees, may contribute phosphorus to the environment because there is no forest floor or intact riparian ecosystem to process and recycle the nutrients resulting from degradation of leaves. Most of the studies reviewed focused on the effects of urban trees on the quality of stormwater runoff.

Effects of Trees on the Quality of Stormwater Runoff

Twelve studies directly address the effects of urban trees on the quality of stormwater runoff. Of these, nine were field studies of the pollutant removal performance of stormwater treatment systems that include trees (e.g., Silva cells). However, only four of these studies (Denman 2006, Denman et al. 2011, Denman et. al 2015, Read et al. 2008) included unplanted controls to separate out the benefits provided by the tree vs. the filter media, and only one of those (Denman 2006) reported results that represent the water quality performance associated with the trees. Read et al. (2008) did not report results for trees versus other types of vegetation. In addition, the studies, which are summarized in Table 7, evaluate different species of nutrients and/or use varying methods to calculate percent pollutant removal.

The values shown in Table 7 represent the percent removal of each pollutant provided by stormwater treatment systems with trees. Note that even where studies incorporated unplanted controls, the results reflect the pollutant removal of the entire system. Only the Denman (2006) study provides sufficient data to separate out the pollutant removal associated with just the trees. For the aforementioned study, the results show 82%, 85% and 95% removal of TN by the three bioretention systems with trees, compared to of -7%, 0%, and 36% removal by their respective unplanted controls. The difference between pollutant removal effectiveness of these planted and unplanted systems can be assumed to represent the enhanced TN reductions provided by the trees, with values of 59%, 85% and 89%.

Table 7. Pollutant Removal by Stormwater Treatment Systems with Trees

Study	Treatment System Type	Parameter and % Reduction						
		TN	NOx	DIN	TKN	TP	FRP	TSS
Denman 2006	Street Tree Bioretention	82-95						
Denman et. al 2011; Denman et al. 2015	Biofiltration		2-78				70-96	
Geronimo et al. 2014	Tree Box Filter							80-98
Page et al 2014	Silva Cell				71, 84	72		86
Roseen et al. 2009	Street Tree			62		-54		88
UNHSC, 2012	Tree Box Filter (Non-proprietary)	10		8				88
UNHSC, 2012	Filterra	15				52		85
Xiao and McPherson 2011a	Bioswale	95.3[1]						95.5[2]

[1] average of all nutrient species results

[2] average of results from TSS and TDS

Of the other studies on water quality benefits of urban trees, a modeling study by Band et al. (2010) estimated that current tree cover in Baltimore County, MD's Baisman Run watershed reduced TSS by 445kg over the simulation period, TP by 2kg, TKN by 12kg and NO2+NO3 by 4 kg. These results were based on modeling using UFORE-Hydro that simulated changes in flow due to changes in watershed land cover, and applied national median EMC values to estimate associated changes in pollutant loads. Matteo et al. (2006) ran a watershed-scale model of the water quality impacts of roadside and riparian buffers, but did not provide enough information about the area of the forested buffers to scale the results down to an individual tree planting site or forest plot. This is similar to the results presented by Goetz et al. (2003) and by the CITYgreen and i-Tree studies reviewed in the previous section in that the results are only applicable if the urban tree canopy credit is based on a percent tree canopy for a given watershed or municipality.

Groffman et al. (2009) measured nitrate leaching from urban forest and grasslands and found that annual nitrate leaching was higher in grass than in forest plots, except for one highly disturbed site that had hydrologic N losses well in excess of atmospheric inputs. Nitrate losses from forest plots in this study were 0.05 to 0.79 g N/m/yr; however, nitrogen inputs to the system were not measured. Another study by Groffman et al. (2004) found nitrate yields of 0.11 to 0.14 kg N/ha/yr and TN yields of 0.48 to 0.58 kg N/ha/yr from a forested basin, and estimated N retention of 95% by this basin, compared to 75% for a suburban basin and 77% for an agricultural basin.

Two studies were reviewed that address urban trees and water quality but do not specifically deal with stormwater runoff. Zhang et al. (2011) measured organochlorine pesticides in rainfall, canopy throughfall and runoff and found that the canopy was able to intercept 40% of the wet and dry deposited pollutants compared to a site with no trees, but further research in needed to determine the ultimate fate of the pollutants. Conversely, Xiao and McPherson (2011a) found that nutrients were added as rainfall passed through the tree canopy due to canopy leaching of pollutants that were previously deposited from atmospheric sources.

Numerous studies have evaluated the water quality benefits of natural forests. Table 8 summarizes measured nutrient and sediment exports from undisturbed forests. It also presents ratios of pollutant loading from forests that have undergone disturbance (e.g., ice damage, insect defoliation, fire) and forests that were harvested (using a range of methods such as cattle grazing, clearcutting, strip cutting, and whole tree removal) compared to the pre-disturbance or control sites for those particular studies. Given the limited amount of data on the water quality benefits of urban trees and forests, the data from undisturbed forests could be applied to establish upper bounds of pollutant removal. The ratios for disturbed and harvested forest could potentially be useful if culled to look only at studies that represent conditions commonly found in urban forest patches or planting sites (e.g., sparse cover, die-off from lack of watering, compacted soils).

Table 8. Nutrient and Sediment Loads from Non-Urban Forests[1]

Type of Forest	**Pollutant Export (lbs/acre/year)**[1] **(n)**		
	TN	TP	TSS
Undisturbed	2.14[3] (123)	0.16[2] (14)	41.9[2] (17)
	Ratio of Pollutant Export from Harvested/Disturbed Forest:Reference[4]		
Disturbed	3.09	2.04	2.04
Harvested	7.03	3.12	3.05

[1] based on studies of eastern forests compiled by Justin Hynicka from Maryland DNR for urban tree canopy land use recommendations

[2] median value

[3] calculated as the sum of median values for NO3 and TKN

[4] mean ratio of harvested or disturbed pollutant export to pollutant export from reference sites

Since the literature on hydrologic benefits of urban trees is much more plentiful than water quality benefits, another possible avenue to explore for a credit is to model the connection between runoff reduction and pollutant reduction. As an example, Cappiella et al. (2005) use the Simple Method (Schueler 1987) to estimate annual nutrient loads from forest land based on measured nutrient concentrations in runoff and measured runoff coefficients from forest land. For urban tree planting scenarios, where soils may be highly disturbed and compacted, these runoff coefficients can be adjusted downward to reflect urban conditions. For example, curve numbers provided with TR-55 for forests are higher (i.e., produce more runoff) when litter and understory are removed. The section on models and calculators provides a review of possible options for modeling the water quality benefits of urban trees.

Pollutant Uptake

Most studies on pollutant uptake by trees focus on nutrient uptake by trees in the riparian zone. These studies were not included in the literature review because the focus of this work is on the benefits of upland urban trees. A few studies were available from the field of phytoremediation—the process of using plants to remove contamination from soil and water— which show trees' potential to remove pollutants through plant uptake, adsorption and microbial activity. Phytoremediation has mainly been applied to remove metals, pesticides, and organic compounds from soil and groundwater but could potentially be applied to nutrients in stormwater runoff. Tree species typically used for phytoremediation include willow, poplar (cottonwood hybrids), and mulberry, because they have deep root systems, fast growth, a high tolerance to moisture, and are able to control migration of pollutants by consuming large amounts of water (Metro, 2002; IRTC, 2001; Shaw and Schmidt, 2007). Once pollutants are taken up by plants, one or more activities may occur. Pollutants can be moved into the above-ground portions of the plants, accumulate in the root zone, be broken down through natural processes of plant growth, or be transformed into inert material and discharged through plant leaves or shoots. Biological uptake is seen as only a temporary removal process because the pollutants may be returned to the system when the plant dies, unless it is harvested.

Studies on the use of constructed wetlands to treat wastewater demonstrate the ability of trees to remove pollutants. Bolton and Greenway (1999) found that a constructed maleleuca wetland receiving secondary treated sewage effluent was able to store 46% of the N, 21% of the P and 11% of the K which flowed through the wetland. Total N storage in the tree terraces was 91-106 g N/m^2, total P storage was 31-34 g P/m^2, and total K storage was 41-52 g K/m^2.

Leaf Litter

An emerging topic in urban stormwater management is the effect of nutrients and carbon from leaf litter on urban streams. Leaf litter represents a major energy source (DOC) and source of nutrients to streams where water soluble compounds readily leach from the leaves within hours to days following immersion, with macro-invertebrates and bacteria decompose the leaf material in-stream. In urban-suburban areas, leaf litter collects in curbs and gutters that is flushed through the storm drain system, contributing nutrients to urban streams that are generally already impaired for excessive nutrients, or impaired biota.

While many urban areas have less than 40% tree canopy, leaf litter input to streams from riparian and upland areas does occur. This results in a large and steady supply of leaves to streams (aka the "gutter subsidy"). In a recent Scientific and Technical Advisory Committee workshop report (Sample et al 2015) and Nowak (2014) provided data for Baltimore, MD estimating an urban tree canopy biomass nutrient load of 28.8 lbs/ac/yr and 2.95 lbs/ac/yr of N and P, respectively. If a fraction of this load washes off into the stream, leaf drop alone would be a considerable component of modeled nutrient loadings rates. In an outfall netting study in Easton, MD, Stack et al (2013) found an average of 4.7 TN lb/ac/yr and 0.36 TP lb/ac/yr in catchments with 24% canopy cover. The difference between these loading rates is attributed in part to the aged leaf litter at the outfall and leaf litter reaching the streams compared to the total canopy used to estimate the biomass by Nowak (2014). Street sweeping studies have also quantified the potential impact of leaf litter on urban nutrient loadings. Baker et al (2014) and Berretta et al. (2011) found that organic matter comprised 10% of the load collected by street sweepers. Waschbusch (2003) also found a similar estimate from a street sweeping study and this contributed to 30% of the total phosphorus load. This 'gutter subsidy' was estimated by Baker et al (2014) to be 2 lbs - 6 lbs P/curb-mile in residential catchments with up to 20% tree canopy. Templer et al (2015) found that up to 52 ± 17% of residential litterfall carbon (C) and nitrogen is exported through yard waste removed from the City of Boston, which is equivalent to more than half of annual N outputs as gas loss (i.e. denitrification) or leaching. While, recent studies illustrate the available supply of leaf litter in urban areas, further research is needed to better quantify the fate, transport, and processing of leaf litter in urban watersheds and how to best account for this source as part of an urban nutrient mass balance.

Urban Tree Growth and Survival

The urban landscape can be a harsh environment and as a result urban trees tend to have a shorter lifespan than their rural counterparts. The growth and mortality of urban trees has been studied to evaluate which factors affect mortality and to isolate design, planting or a management practices that result in faster growth and better overall survival rates. A summary of this literature is provided below and is organized by the major factors influencing urban tree growth and mortality. The first section summarizes what is known about the life expectancy of an urban tree.

Mortality Rates of Urban Trees

Roman's 2013 dissertation on urban tree mortality found an overall annual mortality rate of street trees in Oakland CA of 3.7%, with the highest mortality rates found for small/young trees. The same study evaluated survival of trees planted through a residential planting program in Sacramento, CA and found a survival rate of 70.9% at five years post-planting. Factors related to mortality includes size class, foliage condition, planting location and tree care practices (Roman 2013).

Roman and Scatena (2011) conducted a survey of street trees in Philadelphia and analyzed data from previous survivorship studies and determined that street tree annual survival rates were 94.9-96.5%, which equates to a mean life expectancy of 19-28 years. A study of street trees in New York City found that the highest mortality rates occurred in the first few years after planting (Lu et al. 2010).

Planting Stock

Vogt (2015) found that use of balled & burlapped (B&B) or container stock as well as good overall tree condition rating were positively related to tree survivability and/or growth in an Indianapolis study (Vogt 2015). On the other hand, Jack-Scott (2012) found that bare root and B&B trees have equivalent rates of survivability.

Planting Techniques

Proper planting techniques can affect tree growth and mortality, in particular the depth at which the tree is planted. Planting the root collar or main structural roots below grade has adverse impacts on survival and growth (Arnold et al. 2007). Gilman and Grabosky (2004) studied live oak transplants and found that soil over the root ball resulting from deep planting intercepted water, resulting in more tree stress and greater likelihood of tree death in the first 4 weeks after planting. A visible root flare was positively related to tree survivability and/or growth, as was correct mulching techniques (Vogt 2105).

Planting Area Size and Soil Volume

Available soil volume is perhaps one of the most commonly cited factors affecting tree growth and survival. Some studies that evaluate this factor measure actual soil volume available to the tree, while others infer it from indirect measures such as the dimensions of the planting space. A 2013 study in Milwaukee found that trees were more likely to die as planting space width in the tree lawn decreased (Koeser 2013), while Vogt (2015) also found that the planting area width was positively related to tree survivability and growth. The Milwaukee study found that, as tree lawn width increased from 60 to 120 cm, the odds of survival increased only marginally and more substantial increases in width resulted in more noteworthy odds ratios (Koeser 2013). For example, trees planted in lawns with a width of 300cm were twice as likely to survive compared to trees planted in 60cm width spaces (Koeser 2013).

Sanders and Grabosky (2014) found that reduced soil access of trees in parking lots was consistently associated with reduced tree size and a 2013 study by the same authors found that, of a survey of trees in New Jersey, trees with more available soil grew larger than trees with a small amount of soil. The 2014 Sanders study showed that trees have reduced growth when there is less than $20m^2$ ($215ft^2$) of soil surface, and an extreme reduction in canopy size with a tree pit of 2m by 3m. A dramatic increase in canopy size is achieved when trees are planted in linear strips of at least $40m^2$ ($430ft^2$), as opposed to $6m^2$ ($65ft^2$) planting pits. Day and Amateis (2011) found that the ultimate tree size was strongly related to the unpaved soil surface area (but not soil depth) and that trees growing in parking lot cutouts smaller than $5.3m^2$ (approximately 57 ft^2) attained only limited size, regardless of soil conditions.

At sites where planting space is limited, such as streetscapes, structural soils can be used to provide additional soil volume for trees. These soils support the adjacent pavement and allow tree roots to grow underneath. Rahman et al (2011) found that *Pyrus calleryana* ‘Chanticleer’ a commonly planted urban tree in Manchester, UK, grew almost twice as fast in Amsterdam soil than when planted into 1.5 m^2 cut out pits in pavement. The enhanced growth and physiological performance of the trees grown in Amsterdam soil meant they provided peak evapotranspirational cooling 5 times higher than those grown in pavements.

Several studies identify a minimum soil volume that is associated with greater tree growth or survivability (Table 9, compiled from Lindsey and Bassuk, 1991 and other sources). Many of these estimates are quite high (up to 7,000 ft^3 using the recommendations from Helliwell, 1986) and would be next to impossible to achieve in most street tree plantings. Some of these recommendations are either simple rules of thumb, or are based on plant factors other than empirically determined water use rates (Lindsey and Bassuk, 1991). The question then becomes what is the minimum soil volume we can get away with and still have healthy trees?

Table 9. Soil Volume Recommendations for Urban Trees (Modified from Lindsey and Bassuk 1991)

Study	**Minimum Soil Volume Recommendations**	**Basis for Recommendation**
Kent et al (2006)	1,500 ft^3	Study evaluated 1,127 parking lot trees at Walt Disney World and found 100% trees planted in 1,500ft^3 of soil were in good condition
Lindsey and Bassuk (1991)	220 ft^3 for a medium sized tree, or 2ft^3 of soil per ft^2 of crown projection	Based on estimates of whole tree water loss using pan evaporation data
Urban (1999)	400ft^3 bare minimum, but 1,000ft^3 for optimal growth	
Cervelli (1986)	570ft^3	
Arnold (1980)	224ft^3 for a 21-40 foot high tree	
Bakker (1983)	2.5ft^3 of soil for every ft^2 of crown projection	
Vrecenak and Herrington (1984)	5,543ft^3 for a 64ft diameter tree	
Perry (1985)	600ft^3 for a 10" caliper tree	
Kopinga (1985)	2,500 ft^3 for a large tree	
Helliwell (1986)	Rooting volume of 1/10th of the canopy volume	
Moll and Urban (1989)	1,200ft^3 for a tree with expected caliper of > 25"	

Many jurisdictions in the U.S. and Canada have incorporated requirements for minimum soil volume into their tree planting specifications. These are typically variable based on the size of the tree and sometimes vary with the planting design (e.g., a planting trench versus a single planter). A summary of each state or province's recommendations is provided at: http://www.deeproot.com/blog/blog-entries/soil-volume-minimums-organized-by-stateprovince.

Fertilization Practices

Harris et al (2008) found that fertilization at the time of planting does not increase trees growth (even at stressful urban sites), while Gilman (2004) showed that there is no benefit to adding amendments or liquid additives in terms of tree survival/growth rates.

Irrigation

Mortality studies by Vogt (2015) in Indianapolis and Koeser (2013) in Florida showed that irrigation of planted trees increases survivability, while Gilman (2004) found that more irrigation resulted in faster growth. Neilson et al. (2007) found that the variation in growth rates of street trees in Denmark was attributed to the variation among street planting pits in their ability to retain water. The faster the water loss rate, the slower the tree growth. Denman et. al (2015) found that street trees planted in biofiltration systems that were irrigated with stormwater generally grew larger compared to those irrigated with tap water.

Land Use

Lu (2010)'s study of street trees in New York City found that land use has a significant effect on mortality, while Koeser (2013) showed that trees adjacent to construction sites in Milwaukee were nearly twice as likely to die as those not exposed to development activities.

Other Factors

At the municipal scale, considerations that affect mortality include the size of trees at planting. If large planting initiatives use large numbers of trees of a uniform size, they will all reach maturity around the same time (if planted in similar sites), potentially causing a large portion of the urban forest to die or need to be removed at the same time (Sanders 2013). Roman (2013) found that population growth of street trees in Oakland, CA was constrained by high mortality of young/small trees.

Models, Calculators and Existing Credit Systems for Estimating Urban Tree Benefits

Given the paucity of research studies that quantify the hydrologic and water quality benefits of urban trees, scientists and regulators have developed models that can be used to assign a value to the benefits provided by urban trees. Urban tree benefit calculators, as well as credit systems for state or local stormwater management regulations are often based on these models. This section summarizes the relevant models and calculators as well as existing credit systems for estimating urban tree benefits.

i-Tree Tools

i-Tree is a software suite in the public domain from the US Forest Service that was initially released in August 2006 and previously known as the Urban Forests Effects model (UFORE). The i-Tree suite of tools that are applicable for determining the runoff and pollutant removal benefits of urban trees are described below. Of this suite of tools, i-Tree Eco appears to be the best option for isolating the annual runoff reduction benefit provided by individual trees.

i-Tree Eco is a software application designed to use field data from complete inventories or randomly located plots throughout a community along with local hourly air pollution and meteorological data to quantify urban forest structure, environmental effects, and value to communities. Model outputs are given for the entire population and, for smaller scale projects, results are also provided for individual trees. Reporting includes annual rainfall interception by trees by species and land use. The precipitation interception model implemented in Eco was developed based on i-Tree Hydro (Wang et al. 2008), which uses a similar physics-based approach as Xiao et al. (1998). However, the effect of trees on annual avoided runoff was improved by taking into account the interception by trees and ground cover depressions, infiltration into pervious cover, as well as runoff on impervious cover. The actual scenario is compared to a hypothetical scenario in which the same area of interest is not covered by vegetation. The effect of vegetation in reducing surface runoff is calculated as the difference in runoff between the two scenarios and can be summarized for individual trees, species in the analysis domain, and species in land use types (Hirabayashi 2013a). Limitations of this tool are that the outputs are given in cubic feet as opposed to a percent annual runoff reduction and they are based on the individual tree characteristics so would require numerous scenario runs to determine an average value for a typical urban tree.

i-Tree Streets (an adaptation of the Street Tree Resource Analysis Tool for Urban Forest Managers [STRATUM]) focuses on the ecosystem services and structure of a municipality's street tree population. It makes use of a sample or complete inventory to quantify and put a dollar value on the trees' annual environmental and aesthetic benefits, including stormwater control. Streets uses regional tree growth models and regional default costs and benefits, which can be customized for local conditions. Data on the benefits and costs of maintaining street trees come from field research and laboratory modeling for 16 national climate regions. The stormwater report feature of Streets presents the reductions in annual stormwater runoff due to rainfall interception by trees (measured in gallons or cubic meters). A one-dimensional mass and energy balance model based on methodology in Xiao et al. (2000) and Xiao et al. (1998) is used to simulate rainfall interception that describes precipitation, leaf drip, stem flow, and evaporation. This model has not been calibrated or validated with measured data from individual trees or an urban watershed. Thus, findings are approximations. The model may overestimate if the rainfall interception is used to represent avoided runoff. Not all of the rainwater intercepted by trees would become runoff if there were no trees at all since the rainwater that reaches the ground may be intercepted by depressions and/or infiltrate into the ground (Hirabayashi 2013b).

i-Tree Hydro is a vegetation-specific urban hydrology model that simulates hydrological processes of precipitation, interception, evaporation, infiltration, and runoff at the watershed scale using data inputs of weather, elevation, and land cover along with nine channel, soil, and vegetation parameters (Wang et al. 2008). Hydro is a combination of two modules: a base module designed to simulate hourly changes in stream flow due to changes in urban tree and impervious cover characteristics and a water quality module that uses outputs from the base program to simulate changes in water quality. The result is hourly and total changes in stream flow and water quality for the input watershed, based on the percent canopy and impervious cover in the watershed. Default Event Mean Concentrations (EMCs) are used from Smullen et al. (1999) based on data from NURP, USGS, and NPDES data sources. These EMCs are applied to the runoff regenerated from pervious and impervious surface flow, not the baseflow values, to estimate effects on pollutant load across the entire modeling time frame. A major assumption in the water quality module is that pollutant loads are reduced proportional to runoff volume.

i-Tree Design provides a simple estimation of the benefits provided by individual trees. With inputs of location, species, tree size, and condition, the outputs are tree benefits related to greenhouse gas mitigation, air quality improvements, and stormwater interception. This tool relies on average species growth equations and other geographic parameters that are generalized from city, county, state, and climate region data. Consequently, i-Tree Design is intended to be a starting point for understanding trees' value in the community rather than a scientific accounting of precise values. The stormwater values are based on methods and models derived from the i-Tree Streets application.

The Runoff Reduction Method

The Runoff Reduction Method (Hirschman et al. 2008) is used by the State of Virginia to document compliance with the State's stormwater management regulations and is also the basis of a stormwater retrofit crediting protocol adopted by the Chesapeake Bay Program (Schueler and Lane 2015). In this method, site pollutant loads are calculated as the product of the flow-weighted mean concentrations in urban runoff and the volume of runoff generated by the 90th percentile rainfall event (which represents the majority of runoff volume on an annual basis). Larger events would be difficult and costly to control for the same level of water quality protection. Environmental site design practices, including forest conservation and site reforestation are first used on a site to reduce the amount of runoff. A runoff reduction and mass load removal credit for TN and TP is then given for use of BMPs that intercept, evapotranspire, infiltrate or otherwise reduce runoff. The total removal (TR) is calculated the nutrient mass reduction, which is a product of Runoff Reduction (RR) and Pollutant Removal (PR): $TR = RR + [(100-RR) * PR]$, where:

- RR = total annual runoff volume reduced through canopy interception, soil infiltration, evaporation, transpiration, rainfall harvesting, engineered infiltration, or extended filtration.
- PR = the change in EMC as runoff flows into and out of a BMP. Pollutant removal is accomplished via processes such as settling, filtering, adsorption, and biological uptake.

The Runoff Reduction values provided with the method were derived from 58 studies and the Pollutant Removal values were derived from 48 studies for 15 stormwater BMPs. The BMP that most closely approximates tree planting in the Runoff Reduction Method is Sheetflow to Conservation Areas and Filter Strips. Since the studies on Pollutant Removal are lacking for this BMP (as with tree planting), the Pollutant Removal is (conservatively) set at zero, resulting in a Total Removal % that is equal to the Runoff Reduction %. This is not the case for other stormwater BMPs where more data is available on Pollutant Removal based on water quality monitoring studies of inflow/outflow.

State and Municipal Stormwater Credit Programs

Many state and municipal governments have established stormwater credit programs that grant runoff or impervious reduction credit for conservation of existing trees or planting of new trees. Programs offering credits for forest conservation or reforestation on development or redevelopment sites typically allow the designer to subtract out the conservation or planting area from the total site area or impervious area when computing water quality volume (WQv) or recharge volume (Rev). Table 10 presents several examples of this type of credit.

Table 10. Examples of State Level Stormwater Credits for Non-Structural Practices that Include Trees (Source: Stone Environmental, 2014)

State	Natural Conservation Area	Stream Buffers	Protect Existing Trees	Site Reforestation	Environmentally Sensitive Rural Development	Credits Offered*
Vermont	X	X			X	REv, WQv (partial)
Maine	X					REv, WQv
Massachusetts					X	REv, WQv
Minnesota	X	X		X		WQv, CPv, Qp10 (partial) Option for local jurisdictions to implement
Pennsylvania		X	X			WQv, REv, CPv, Qp10 (up to 25% of required volume)
Georgia	X	X			X	WQv, CPv (partial), Qp25 (partial)

* Rev = recharge volume, WQv = water quality volume, CPv = channel projection volume, Qp10 = overbank flood control for the 10-year storm, Qp25 = overbank flood control for the 25-year storm

A smaller number of stormwater programs offer impervious surface or runoff volume reduction credits for preserving or planting <u>individual</u> trees. Typically, credits are greater for preserving existing trees than for planting new ones, and the credits also vary by evergreen versus deciduous species and whether the tree is within a certain distance of an impervious surface. The most common credit is a reduction in directly connected impervious area that must be treated on the site. A summary of municipal credits for individual trees is provided in Table 11. Unfortunately, most of these credit programs do not provide details on how the credits were derived.

Minnesota is unique in that it is the first state to give evapotranspiration, infiltration, and interception credit for individual trees, factoring in their size. Tree credits are determined based on evapotranspiration and canopy interception. The evapotranspiration credit is derived from the Lindsey-Bassuk equation for evapotranspiration (Lindsey and Bassuk 1991) that relates the total water use of a tree to 4 measurements: 1) canopy diameter, 2) leaf area index, 3) the evaporation rate per unit time, and 4) the evaporation ratio. However, it should be noted that the equation is a proxy for the evapotranspiration rate and a better estimate would be gained by use of a digital model such as i-Tree or other continuous-modeling simulators or programs (KDGT 2013). The canopy interception credit is based on mean values of interception capacity based on Breuer et al. (2003) for the typical tree type multiplied by the canopy area at maturity. The Minnesota Pollution Control Agency’s Minimal Impact Design Standards (MIDs) BMP calculator incorporates these assumptions in order to estimate BMP volume reductions and annual pollutant load reductions for total phosphorus and total suspended solids for BMPs that include trees, such as tree trenches and tree boxes. Pollutant removal for infiltrated and evapotranspired water is assumed to be 100% and is calculated by multiplying the volume of water reduced by event mean concentrations for TSS and TP from the International Stormwater Database, version 3.

Table 11. Examples of Municipal Stormwater Credit Programs that Include Individual Trees (Source: Stone Environmental, 2014)

Municipality	Year Enacted	Type of Credit	Distance from Impervious Surface	Credit Details*
Pine Lake, GA	2003	Volume reduction	Applies to all existing or newly planted trees	Provides credit for saving existing trees, regardless of tree position relative to impervious surfaces. Credit helps to meet site runoff requirements and is based on the size of the tree: • Trees < 12” DBH = 10 gallons/inch • Trees > 12” DBH = 20 gallons/inch *This credit was developed with input from Dr. Greg McPherson, US Forest Service, based on an estimate of water use by a typical tree*
Portland, OR	2004	Impervious surface reduction	Within 25 feet	A portion of impervious cover underneath tree canopy may be subtracted from the site impervious cover as follows: • New deciduous trees = 100 ft^2 • New evergreen trees = 200 ft^2 • Existing trees = ½ the existing canopy
Sacramento, San Jose and Santa Clara, CA	2007	Impervious surface reduction	Within 25 feet	A portion of impervious cover underneath tree canopy may be subtracted from the site impervious cover as follows: • New deciduous trees = 100 ft^2 • New evergreen trees = 200 ft^2 • Existing trees = ½ the existing canopy
Indianapolis, IN	2009	Impervious surface reduction	Within 10 feet	An impervious cover reduction credit of 100 ft^2 is given for each new tree. Existing trees are eligible but no reduction is specified.
Seattle, WA	2009	Impervious surface reduction	Within 20 feet	Impervious surface reduction credits are as follows: • 50 ft^2 for tree for evergreens • 20 ft^2 for deciduous trees *This credit was modified from a recommendation by Herrera Environmental Associates (2008)*

Table 11. Examples of Municipal Stormwater Credit Programs that Include Individual Trees (Source: Stone Environmental, 2014)

Municipality	Year Enacted	Type of Credit	Distance from Impervious Surface	Credit Details*
Philadelphia, PA	2011	Impervious surface reduction	Within 10 feet (new) or 20 feet (existing)	New trees (min. 2-inch caliper deciduous or 6 ft. tall evergreen): • 100 ft^2 DCIA reduction per new tree. Existing trees (at least 4-inch caliper): • Existing trees = ½ the existing canopy • Can only be applied to adjacent DCIA
Washington, DC	2013	Volume reduction	Applies to all existing or newly planted trees	Volume credits are: • Preserved trees: 20 ft^3 each • Planted trees: 10 ft^3 each *This credit was based on the 100ft^2 impervious area reduction provided by many municipal credit systems, and converted to a volume reduction based on capture of the 1" rainfall.*

* Many of these credits are based on the projected canopy coverage of the tree, while others do not provide any details on how the credits were derived.

Annotated Bibliography (selected references)

American Forests, 1999 (Runoff reduction)
Using CityGreen software, forest loss from 1973-1999 was calculated for a 1.5 million acre portion of the Chesapeake Bay region near the Baltimore-Washington corridor. During the study time period, average tree cover went from 51% to 37% and areas with heavy tree cover declined from 55% to 37%. Tree loss resulted in a 19% increase in runoff (for each 2 year peak storm event), an estimated 540 million ft^3 of water. In the study area, the existing tree canopy reduces the need for retention storage by 540 million cubic feet. The model relies on modified formulas from TR-55 to estimate stormwater runoff.

Armson et al. 2013 (Runoff reduction)
This study assessed the impact of trees upon urban surface water runoff by measuring the runoff from 9m^2 plots covered by 1) grass, 2) asphalt, and 3) asphalt with a tree planted in the center. It was found that, while grass almost totally eliminated surface runoff, the tree plots significantly reduced runoff, with 26% runoff in winter and 20% in summer (as a percentage of rainfall). The trees and their associated tree pits reduced runoff from asphalt by 58% in the summer and 62% in winter. The reduction was attributed primarily to infiltration into the tree pit and canopy interception, although the tree's canopy covered about 35% of the plot. Relative to the amount if rain falling just on its canopy crown, the runoff reduction by the tree was estimated to be 170% in summer and 145% in winter.

Bartens et al. 2008 ((Infiltration)
This study examined whether tree roots can penetrate compacted subsoils and increase infiltration rates in the context of an infiltration BMP that uses structural soils and includes large canopy trees. One goal of the study was to determine if tree roots would grow into the compacted subsoils typically found under/adjacent to such a practice. The study found that tree roots increased soil infiltration rates by an average of 63%, and as much as 153%, over unplanted controls.

Bartens et al. 2009 (ET)
In this study, two trees were grown in structural soil mixes and were subject to three simulated infiltration rates for two growing seasons. Reduced infiltration rates were correlated with lower transpiration rates. Transpiration rates for one growing season were reported to be 0.80 to 1.14 µg/cm^2/s for the green ash (depending on soil treatment) and 0.76 to 1.39 µg/cm^2/s for the swamp white oak. The study also found that larger trees can take up more total water than smaller trees with higher transpiration rates.

Berland and Hopton, 2014
This study estimated canopy interception by street trees along geographic and demographic gradients in Cincinnati. Using i-tree, interception ranged from 59.2 to 214.3 m3 per km of effective street length. The mean interception value used in the model was 6.7m3 per tree, which the researchers note may overestimate runoff reduction.

CWP, 2014
Data from i-tree STREETS was used to plot the volume of rainfall intercepted per year versus trunk diameter and the trunk diameter versus age of the tree. Polynomial regressions were generated from these plots. Regression functions all had R^2 values of at least 0.999. The functions were tied and plotted for 3 tree species found in Montgomery County, MD and for the average “Broadleaf Deciduous Large” value from the i-Tree database for the Piedmont south climate region. I-tree uses a computer model described in Xiao et al. (1998) to generate rainfall interception. The statistical analysis showed an average annual interception volume of 2,000 gallons per tree for a 15-20 year old tree that is 9-15” DBH.

Denman 2006
Study of the performance of a pilot scale street tree bioretention system in reducing nitrogen loads in urban stormwater. Three tree species were planted in three soils of different hydraulic conductivity and irrigated with synthetic stormwater, along with 3 unplanted soil profiles used as controls and irrigated with tap water. The trees grew well in the irrigated soil. Nitrogen content (ammonium, oxidized nitrogen and organic nitrogen) of leach water was measured. Leached nitrogen loads were significantly reduced in systems with a tree. Compared to the total nitrogen input, the load leached in December 2004 from the L. confertus profiles following a 5 hour collection period was 95% less for the low SHC, 85% for the medium SHC and 82% for the high SHC soils. In the unplanted profiles the low SHC soil reduced nitrogen by 36%, whereas the medium (0%) and high SHC soils (-7%) did not remove nitrogen. This study does not appear to be peer reviewed.

Denman et al. 2011
Similar study design as above but this study measured soluble N and P in leachate. Some seasonal variability was found, with higher leaching of N and P in the warmer months. Again, tree growth was good. No significant differences in evergreen versus the one deciduous species planted. P removal did not occur until after the first summer. This study showed greater variability than the previous one. The NOx reduction provided by soils with trees, averaged over time, ranged from 2% to 78%. Reduction of filterable reactive phosphorus ranged from 70% to 96%. No specific values were provided for the unplanted controls for comparison. This study does not appear to be peer reviewed.

Geronimo et al. 2014
This study evaluated pollutant removal and runoff reduction by a tree box filter. The system reduced runoff by 40% for a hydraulic loading rate of 1m/day. It was found out that the hydraulic loading rate was dependent on the total runoff volume received by the system. TSS removal ranged from 80% to 98% at varying hydraulic loading rates. No unplanted control site was tested to evaluate the effects of the tree versus other mechanisms; however the study states that the filtration capacity of the tree box filter was presumed to be the main pollutant removal mechanism.

Groffman et al. 2009
This study measured nitrate (NO3) leaching and soil:atmosphere nitrous oxide (N2O) flux in four urban grassland and eight forested long-term study plots with a range of disturbance, soil type and landscape position in the Baltimore, Maryland metropolitan area from 2002-2005. Annual NO3 leaching ranged from 0.05 to 0.79 g N m yr for the forest plots and was lower than in grass plots, except in a very dry year and when a disturbed forest plot was included in the analysis. Although NO3 leaching was higher in urban grasslands than in forest plots, the difference was not as large or consistent as expected, and the most intensively fertilized plots did not have the highest leaching losses. The N2O results were even more surprising because there were few differences between forest and grass plots, and, again, the more intensively fertilized grasslands did not have greater fluxes. These results suggest that N cycling in urban grasslands is complex and that there is significant potential for N retention in these ecosystems. Grass plots consistently produced less leachate volume than forest plots. It is suspected that the difference was due to higher evapotranspiration on the grass plots due to higher soil temperatures and the longer growing season in urban grassland versus forest ecosystems. A complication in the leaching comparisons was the fact that one of our forest plots was extensively disturbed and had very high N losses. Although leaching from most of the forest plots was very low, consistent with many previous studies of forest ecosystems, data from our highly disturbed forest plot showed that forests can have hydrologic N losses well in excess of atmospheric inputs. Likely causes of the high N losses from the highly disturbed forest plot include soil disturbance and invasion by exotic plant and earthworm species. These results suggest that not all forest components of urban landscapes are functioning as strong N sinks.

Guevara-Escobar et al 2007
This work evaluated rainfall interception and distribution patterns of gross precipitation around the canopy of a single evergreen tree Ficus benjamina (L.) in Queretaro City,

Mexico. Nineteen individual storms occurring from July to October, 2005, were analyzed. Interception loss was 59.5% of gross rainfall and was primarily attributed to evaporation, which was not limited due to the low relative humidity and high temperatures. The study showed a screen effect of the tree crown on gross precipitation and if not accounted for in study designs, will lead to underestimation of interception losses. The screen effect was important and accounted for 18.7% of the interception losses by the tree canopy alone.

Herrera Environmental Consultants 2008
This report reviews the literature on the effects of trees on stormwater runoff and makes recommendations for applying the available research to develop a stormwater credit for urban trees in the City of Seattle. The review found that evergreen trees in the Pacific Northwest can intercept on average 20% of annual rainfall (18-25%, depending on season) and can transpire 10% of precipitation. Modeling two scenarios of an evergreen tree planted over 1) an impervious surface and 2) a lawn, and based on the value identified above, the authors estimate that planting a tree over impervious cover results in a 27% reduction in the amount of rainfall that becomes runoff (95% runoff coefficient assumed for impervious cover) and planting a tree over turf results in a 12% reduction in the amount of rainfall that becomes runoff (20% for turf). The result for tree planted near impervious cover approach 30%, a value also suggested in the literature on runoff reduction. The same exercise was repeated for deciduous trees using values of 10% for interception and 5% for transpiration. The authors recommend a credit of 30% of the canopy footprint for evergreens and 15% for deciduous trees, if the tree is located within 10 feet of an impervious surface. Trees located more than 10 feet from an impervious surface would receive half this credit.

Inkiläinen et al 2013
To quantify the amount of rainfall interception by vegetation in a residential urban forest this study measured throughfall in Raleigh, NC, USA between July and November 2010. Throughfall comprised 78.1–88.9% of gross precipitation, indicating 9.1–21.4% rainfall interception. Cumulative rainfall interception over the study period ranged from 9.1- 10.6 and the storm based values ranged from 19.9-21.4. Canopy cover and coniferous trees were the most influential vegetation variables explaining throughfall whereas variables such as leaf area index were not found significant in our models. The results do not appear to reflect interception by trees but are for the entire residential parcel which includes other land cover types.

Kays 1980
Infiltration tests conducted across a North Carolina watershed on various land use types found that a medium aged pine-mixed hardwood forest had a mean final constant infiltration rate of 31.56 inches per hour. When the forest understory and leaf litter were removed, the resultant lawn had a mean infiltration rate of 11.20 inches per hour.

Kirnbauer et al. 2013
i-Tree Hydro was used to derive a simplified Microsoft Excel-based water balance model to quantify the canopy interception potential and evaporation for four monoculture planting schemes on urban vacant lots, based on 7 years (2002–2008) of historical hourly rainfall and mean temperature data in Hamilton, Ontario, Canada. The

results demonstrate that the tree canopy layer was able to intercept and evaporate approximately 6.5%–11% of the total rainfall that falls onto the crown across the 7 years studied, for the G. biloba, P.×acerifolia and A. saccharinum tree stands and 17%–27% for the L. styraciflua tree stand. This study revealed that the rate at which a species grows, the leaf area index of the species as it matures, and the total number of trees to be planted need to be determined to truly understand the behavior and potential benefits of different planting schemes.

Kjelgren and Montague 1998
The study used a two-layer canopy model to study transpiration of tree species as affected by energy-balance properties of a vegetated (turf) and paved surface. Trees over asphalt had consistently higher leaf temperature, than those over turf, apparently due to interception of the greater upwards long-wave radiation flux from higher asphalt surface temperatures. In one study flowering pear over asphalt in a humid environment had higher leaf temp resulting in one-third more total water loss compared to trees over turf. In other studies, however, water loss of green ash and Norway maple over asphalt in an arid environment was either equal to or less than that over turf. Less water loss was due to higher leaf temp over asphalt causing prolonged stomatal closure. Model manipulation indicated that tree water loss over asphalt will depend on the degree of stomatal closure resulting from how interception of increased energy-fluxes and ambient humidity affect leaf-to-air vapor pressure differences.

Livesley et al. 2014
This study measured canopy throughfall and stemflow under two eucalypt tree species in an urban street setting over a continuous five month period. The species with the greater plant area index intercepted more of the smaller rainfall events, such that 44% of annual rainfall was intercepted as compared to 29% for the less dense E. saligna canopy. Stemflow was less in amount and frequency for the roughbarked E. nicholii as compared to the smooth barked species. However, annual estimates of stemflow to the ground surface for even the smoothbarked E. saligna would only offset approximately 10mm of the 200mm intercepted by its canopy. This study provides an evidence base for tree canopy impacts upon urban catchment hydrology, and suggests that rainfall and runoff reductions of up to 20% are quite possible in impervious streetscapes.

Matteo et al. 2006
This study used the generalized watershed loading function model to evaluate watershed-wide impacts of best management practices (BMPs) scenarios representing riparian and street buffers on water quality, quantity, and open space in rural, suburban, and urbanized environments. The proportion of urban forest cover reduced sediment and nutrient loading, decreased stormwater runoff, and increased groundwater recharge in urbanizing watersheds. The model simulated runoff, groundwater recharge, ET, and TN and TP loads for 4 scenarios in each of the 3 settings: 1) baseline, 2) 10 foot roadside tree buffers, 3) 200 foot riparian buffers, and 4) both the riparian and roadside buffers. Results for the suburban catchment were: TSS reduction of 1.83% from baseline, TN 0.06% reduction, TP 2.75% reduction, runoff 5.24% reduction, ET increase of 0.06% and increase in groundwater recharge of 1.67%. Results for the

urban catchment were: TSS reduction of 4.24% from baseline, TN 6.59% reduction, TP 6.57% reduction, runoff 8.75% reduction, ET increase of 2.74% and increase in groundwater recharge of 33.84%. However, the total area of forest associated with each scenario was not reported, making it difficult to apply the result to the individual tree planting site scale. There is also a question about the CNs used in the model for forest (46 for rural forest, 65 for suburban forest and 30 for urban forest), which were taken from TR-55 but the value used for urban forest is for A soils and woods in good condition, and produces less runoff than the suburban and rural sites.

McPherson and Simpson 2002
This paper presents a comparison of the structure, function, and value of street and park tree populations in two California cities. Modesto is covered by 31% trees, while Santa Monica has 15% tree cover. A numerical interception model accounted for the amount of annual rainfall intercepted by trees, as well as throughfall and stem flow (Xiao et al. 1998). The volume of water stored in tree crowns (m3/tree) was calculated from crown projection areas (area under tree dripline), leaf areas, and water depths on canopy surfaces. Hourly meteorological and rainfall data for 1995 (Modesto) and 1996 (Santa Monica) were used as input. Urban forests in Modesto were estimated to reduce stormwater runoff by 3.2m2 per tree, and by 7.0 m2/tree in Santa Monica. Interception differed between cities because of variables such as annual rainfall pattern and tree foliation periods.

McPherson et al 2011
The purpose of this study was to measure Los Angeles's existing tree canopy cover (TCC), determine if space exists for 1 million additional trees, and estimate future benefits from the planting using i-tree. A numerical interception model accounted for the amount of annual rainfall intercepted by trees, as well as throughfall and stem flow (Xiao et al. 1998). The volume of water stored in tree crowns (m3/tree) was calculated from crown projection areas (area under tree dripline), leaf areas, and water depths on canopy surfaces. Hourly meteorological and rainfall data for 1995 (Modesto) and 1996 (Santa Monica) were used as input. Over the 35-year span of the project, planting of 1 million trees was estimated to reduce runoff by approximately 51 to 80 million m3. The average annual interception rate per tree ranged from a low of 0.4m3 for the crapemyrtle (representative of small trees in the inland zone) to a high of 5.6m3 for the jacaranda (representative of medium trees in the inland zone). The difference is related to tree size and foliation period. The crapemyrtle is small at maturity and is deciduous during the rainy winter season, whereas the jacaranda develops a broad spreading crown and is in-leaf during the rainy season.

Page et al 2104
This study evaluated the hydrologic and water quality performance of two suspended pavement systems using Silva cells in North Carolina. Both were planted with a crepe myrtle but no controls were used to test the influence of the trees on results. Pollutant concentrations were significantly reduced, including TP, TN and TSS. TP reductions were at least 72% and TSS reductions were greater than 86%. TN results were not reported but TKN reductions were 71% and 84%. 80% of runoff at the inlet was captured and treated by the practices. Peak flow was mitigated by 62% for stormwater not generating bypass.

Read et al. 2008

Study authors used a pot trial of 20 Australian species to investigate how species vary in the removal of pollutants from semisynthetic stormwater passing through a soil filter medium. Unplanted controls were used that were irrigated with tap water. Five tree species were included in the mix. While plant species improved pollutant removal compared to unvegetated systems (especially for N and P), the study did not provide specific removal values for tree species versus non tree species.

Roseen et al. 2009

This study monitored pollutant removal performance of 6 LID systems from 2004-2006 to evaluate seasonal variations in performance and the influence of cold climates on performance. These were contrasted with data from conventional and manufactured systems. One of the systems was a street tree/filter. Parameters monitored included TSS, TP, dissolved inorganic N, total Zinc and total petroleum hydrocarbons- diesel range. Seasonal performance evaluations indicate that LID filtration designs differ minimally from summer to winter, while smaller systems dependent largely on particle settling time demonstrated a marked winter performance decline. Frozen filter media did not reduce performance. Reported results for the street tree: efficiency ratios of 88% for TSS, 62% for DIN, and -54% for TP. The efficiency ratio was determined to be a more stable estimate of pollutant removal than removal efficiency because it weighs all storms equally and reflects overall influent and effluent concentrations across the entire dataset.

Sivyer et al. 1997

This study used a pan evaporation model to develop a method for predicting irrigation amount and frequency for street trees and tested it on two newly planted deciduous tree species in Norfolk, VA. The calculated daily transpiration rate for a 3” caliper tree during the growing season was estimated at 2.7 gallons per day.

Soares et al. 2011

This study used i-tree to quantify the value of street trees in Lisbon, Portugal. A numerical interception model accounted for the amount of annual rainfall intercepted by trees, as well as through fall and stem flow. The model estimated that Lisbon’s street trees intercepted approximately 186,773m3 of rainfall annually. On average, each tree intercepted 4.5m3 annually. This estimate was considered to be conservative because the rainfall data used were from a year with lower than normal rainfall.

The Kestrel Design Group 2013

In this paper, literature on ET and rainfall interception are reviewed to provide a basis for quantifying these functions as they relate to stormwater BMPs in the State of Minnesota’s stormwater crediting calculator. The paper reviews the various methods for quantifying ET, including direct versus indirect measure approaches, hydrological, micrometeorological and plant physiology approaches, as well as analytical versus empirical approaches. The authors review the advantages and disadvantages of each approach and recommend use of the Lindsey-Bassuk single whole tree water use equation for estimating ET and crediting trees for associated reductions in runoff. The Lindsey-Bassuk equation requires canopy diameter, leaf area index, evaporation rate per unit of time and evaporation rate as inputs and sources of information for each input are identified.

Wang et al. 2008
This study used the UFORE model, which simulates hydrological processes of precipitation, interception, evaporation, infiltration, and runoff using data inputs of weather, elevation, and land cover along with nine channel, soil, and vegetation parameters. The model was tested in the urban Dead Run catchment of Baltimore, Maryland. Total predicted tree canopy interception was 18.4% of precipitation. Key findings included: trees significantly reduce runoff for low intensity and short duration precipitation events; as LAI increases, interception rate increases as well; trees over impervious cover have a greater runoff reduction effect than trees over turf; as potential evaporation increases, interception increases; greater relative interception was seen with lower intensity storms; increasing tree cover over turf from 12% to 40% resulted in 2.6% runoff reduction; and increasing tree cover over IC from 5% to 40% resulted in 3.4% runoff reduction.

Xiao and McPherson 2003
A mass and energy balance rainfall interception model was used to simulate rainfall interception processes for street and park trees in Santa Monica, CA. Annual rainfall interception by the 29,299 trees was 193,168 m3 (6.6 m3/tree), or 1.6% of total precipitation. Rainfall interception ranged from 15.3% (0.8 m3/tree) for a small *Jacaranda mimosifolia* (3.5 cm diameter at breast height) to 66.5% (20.8 m3/tree) for a mature *Tristania conferta* (38.1 cm). In a 25-year storm, interception by all street and park trees was 12,139.5 m3 (0.4%), or 0.4 m3/tree. Rainfall interception varied seasonally, averaging 14.8% during a 21.7 mm winter storm and 79.5% during a 20.3 mm summer storm for a large, deciduous *Platanus acerifolia* tree.

Xiao and McPherson 2011a
A rainfall interception study was conducted in Oakland, California to determine the partitioning of rainfall and the chemical composition of precipitation, throughfall, and stemflow. Rainfall interception measurements were conducted on a gingko (Ginkgo biloba) (13.5 m tall deciduous tree), sweet gum (Liquidambar styraciflua) (8.8 m tall deciduous), and lemon tree (Citrus limon) (2.9 m tall broadleaf evergreen). The lemon, ginkgo, and sweet gum intercepted 27.0%, 25.2% and 14.3% of gross precipitation, respectively. The lemon tree was most effective because it retained its foliage year-round, storing more winter rainfall than the leafless ginkgo and sweet gum trees. Stemflow was more important for the leafless sweet gum. Because of its excurrent growth habit and smooth bark, 4.1% of annual rainfall flowed to the ground as stemflow, compared to less than 2.1% for the lemon and 1.0% for the ginkgo.

Xiao and McPherson 2011b
A bioswale integrating structural soil and trees was installed in a parking lot to evaluate its ability to reduce storm runoff, pollutant loading, and support tree growth. The adjacent control and treatment sites each received runoff from eight parking spaces and were identical except the control used native soils. A tree was planted at both sites. Storm runoff, pollutant loading, and tree growth were measured. The bioswale reduced runoff by 88.8% and reduced solids (TSS, TDS) by 95.5% and minerals (TP, TKN,

NH4, NO3)) by 95.3%. It appears the reductions were calculated based on comparison to that of a control. No runoff was generated at the treatment site for storm events less than 9 mm (70% of events). The engineered soil provided better aeration and drainage for tree growth than did the control's compacted urban soil.

Xiao et al 1998
A one-dimensional mass and energy balance model was developed to simulate rainfall interception in Sacramento County, California. Annual interception was 6% and 13% of precipitation falling on the urban forest canopy for the City of Sacramento and suburbs, respectively. Summer interception at the urban forest canopy level was 36% for an urban forest stand dominated by large, broadleaf evergreens and conifers (leaf area index = 6.1) and 18% for a stand dominated by medium-sized conifers and broadleaf deciduous trees (leaf area index = 3.7). For 5 precipitation events with return frequencies ranging from 2 to 200 years, interception was greatest for small storms and least for large storms.

Xiao et al 2000
A rainfall interception measuring system was developed and tested for open-grown trees. The system was tested on a 9-year-old broadleaf deciduous tree (pear, Pyrus calleryana `Bradford') and an 8-year-old broadleaf evergreen tree (cork oak, Quercus suber) representing trees having divergent canopy distributions of foliage and stems. Interception losses accounted for about 15% of gross precipitation for the pear tree and 27% for the oak tree. Interception losses were attributed primarily to canopy storage. The results also showed that interception losses relative to rainfall decreased with increasing rainfall depth. The analysis of temporal patterns in interception indicates that it was greatest at the beginning of each rainfall event. Rainfall frequency is more significant than rainfall rate and duration in determining interception losses.

Yang and Zhang 2011
In this study the physical and chemical properties of urban soils were characterized for 30 urban sites representing a mix of land cover types and age of development. Three of the site types contained trees and were also the oldest sites (20-30 years) with the least amount of compaction (normal to light). Lawns with trees had the highest final infiltration rate, followed by trees with shrubs but the infiltration rate for these two categories was not significantly different. The highest final infiltration rate was comparable to that of a forest. Measured infiltration rate values for these two land cover types were not provided in the paper.

Zhang et al. 2011
This study was conducted to estimate the fluxes of organochlorine pesticides in rain and canopy throughfall and their contributions to runoff in Beijing. Runoff, rain and canopy throughfall sampling was conducted over a two year period at 3 sites, two of which were completely paved and one of which had a canopy area of 54m2 from landscaping trees. At the impervious sites, the contribution of hexachlorobenzene (HCB) and hexachlorocyclohexanes (HCH)s from rainfall accounted for approximately 50% of the mass in runoff. At the site with significant coverage of landscaping trees, the HCB, HCHs, and DDTs from the net canopy throughfall accounted for approximately 10% of the mass in the runoff. The pollutant concentrations in canopy throughfall represent a

combination of wet deposition and the portion of dry deposition that is washed from the canopy during a storm. For some sampling dates, concentrations were higher in rainfall than throughfall, indicating that the leaves may have been relatively clean prior to the storm event and the canopy was therefore able to intercept the pollutants, at least temporarily. Further research is needed to evaluate the effects of retention capacity of leaves, antecedent dry days, and storm characteristics on pollutant concentrations in throughfall.

References

American Forests. 1999. *Regional ecosystem analysis Chesapeake Bay Region and the Baltimore-Washington Corridor: Calculating the value of nature*. American Forests. Washington, DC.

Armson, D. P. Stringer, A.R. Ennos. 2013. The effect of street trees and amenity grass on urban surface water runoff in Manchester, UK. *Urban Forestry & Urban Greening*, 12(3): 282-286.

Arnold, M.A., McDonald, G.V., Bryan, D.L., Denny, G.C., Watson, W.T., and L. Lombardini. 2007. Below-grade planting adversely affects survival and growth of tree species from five different families. *Arboriculture & Urban Forestry*, 33(1): 64–69.

Asadian, Y. 2010. *Rainfall interception in an urban environment*. Master of Science Thesis, the University of British Columbia. Vancouver. BC.

Asadian, Y. and M. Wieler. 2009. A new approach in measuring rainfall intercepted by urban trees in coastal British Columbia. *Water Quality Research J. Can*. 44: 16-25.

Baker, L.A. S.E. Hobbie, P. Kalinosky, R. Bintner, and C. Buyarski. 2014. Quantifying nutrient removal by street sweeping. *Final Project Report to the Minnesota Pollution Control Agency,* Sept. 2014.

Band, L., Nowak, D., Yang, Y., Endreny, T., and J. Wang. 2010. Modeling in the Chesapeake Bay Watershed: effects of trees on stream flow in the Chesapeake Bay. Report to Forest Service for Agreement No.07-CO-11242300-145.

Bartens, J, S. D. Day, J. R. Harris, Dove, J.E., and T. M. Wynn. 2008. Can urban tree roots improve infiltration through compacted subsoils for stormwater management? *Journal of Environmental Quality*, 37: 2048-2057.

Bartens, J., Day, S. D., Harris, J. R., Wynn, T. M., and J. E. Dove. 2009. Transpiration and root development of urban trees in structural soil stormwater reservoirs. *Environmental Management*, 44: 646-657.

Berland, A. and M. E. Hopton. 2014. Comparing street tree assemblages and associated stormwater benefits among communities in metropolitan Cincinnati, Ohio, USA. *Urban Forestry and Urban Greening*, 13: 734-741.

Berretta, C., S. Raje, and J. Sansalone. 2011. Quantifying nutrient loads associated with urban particulate matter and biogenic/litter recovery through current MS4 source control and maintenance practices. *Final report to Florida Stormwater Association Educational Foundation*, University of Florida. Gainesville, FL.

Boggs, J. L., and G. Sun. 2011. Urbanization alters watershed hydrology in the piedmont of North Carolina. *Ecohydrology*, 4: 256-264.

Bolton, K., and M. Greenway. 1999. Nutrient sinks in a constructed melaleuca wetland receiving secondary treated effluent. *Water Science and Technology*, 40(3): 341-347.

Bosch, J. M. and J. D. Hewlett. 1982. A review of catchment experiments to determine the effect of vegetation changes on water yield and evapotranspiration. *Journal of Hydrology*, 55: 3-23.

Breuer, L., Eckhardt, K., and H.G. Frede. 2003. Plant parameter values for models in temperate climates. *Ecological Modelling* 169: 237-293.
Cappiella, K., Schueler, T., and T. Wright. 2005. Urban watershed forestry manual. part 1: methods for increasing forest cover in a watershed. NA-TP-04-05. USDA Forest Service, Northeastern Area State and Private Forestry. Newtown Square, PA.

Center for Watershed Protection (CWP). 2014. *Impervious cover credit for individual trees.* Memo prepared for Montgomery County Department of Environmental Protection.

Cermak, J., Hruska, J., Martinkova, M., and A. Prax. 2000. Urban tree root systems and their survival near houses analyzed using ground penetrating radar and sap flow techniques. *Plant and Soil*, 219: 103-116.

Chen, Y., Zhang, Z., Li, Z., Tang, J., Caldwell, P., and W. Zhang. 2011. Biophysical control of whole tree transpiration under an urban environment in northern China. *Journal of Hydrology*, 402: 388-400.

Chen, Y., Day, S., Wick, A., and K. McGuire. 2014. Influence of urban land development and subsequent soil rehabilitation on soil aggregates, carbon, and hydraulic conductivity. *Science of the Total Environment*, 494-495: 329-336.

Cienciala, E. ; Kučera, J. ; Lindroth, A. ; Čermák, J. ; Grelle, A. ; Halldin, S. 1997. Canopy transpiration from a boreal forest in Sweden during a dry year. *Agricultural and Forest Meteorology*, 86(3): 157-167.

Crockford, R.H., and D.P. Richardson. 2000. Partitioning of rainfall into throughfall, stemflow and interception: effect of forest type, ground cover and climate. *Hydrological Processes*, 14: 2903-2920.

Day, S.D., and R.L. Amateis. 2011. Predicting canopy and trunk cross-sectional area of silver linden (Tilia tomentosa) in confined planting cutouts. *Urban Forestry & Urban Greening* 10: 317-322.

Deguchi, A., Hattori, S., and H. Park. 2006. The influence of seasonal changes in canopy structure on interception loss: Application of the revised Gash model. *Journal of Hydrology*, 318: 80-102.

Denman, E.C. 2006. Are street trees and their soils an effective stormwater treatment measure? The 7th National Street Tree Symposium.

Denman, E.C., May, P.B., and G. M. Moore. 2015. The potential role of urban forests in removing nutrients from stormwater. Journal of Environmental Quality. Special section on The Urban Forest and Ecosystem Services.

Denman, E.C., P.B. May, and G.M. Moore. 2011. The use of trees in urban stormwater management. This paper has been presented previously at the Urban Trees Research Conference, “Trees, people and the built environment”, 13 & 14 April 2011, Birmingham, UK and the ISA Annual Conference, 25 – 27 April 2011, Sydney.

Douglas, J. E., and W. T. Swank. 1972. Streamflow modification through management of eastern forests. USDA Forest Service Research Paper SE-94. USDA Forest Service, Southeastern Forest Experimental Station, Ashville NC.

Ford, C., Hubbard, R., and J. Vose. 2011. Quantifying structural and physiological controls on variation in canopy transpiration among planted pine and hardwood species in the southern Appalachians. *Ecohydrology*, 4(2): 183-195.

Geronimo, F. K. F., M.C. Maniquiz-Redillas, J.A.S. Tobio, and L.H. Kim, L H. 2014. Treatment of suspended solids and heavy metals from urban stormwater runoff by a tree box filter. *Water Science and Technology,* 69(12): 2460-7.

Gilman, E.F. 2004. Effects of amendments, soil additives, and irrigation on tree survival and growth. *Journal of Arboriculture,* 30(5): 301-310.

Gilman, E.F., and J. Grabosky. 2004. Mulch and planting depth affect live oak (Quercus Virginiana Mill.) establishment. *Journal of Arboriculture*, 30(5): 311-317.

Goetz, S., Wright, R., Smith, A., Zinecker, E., and E. Schaub. 2003. IKONOS imagery for resource management: Tree cover, impervious surfaces and riparian buffer analyses in the mid-Atlantic region. *Remote Sensing of Environment*, 88: 195-208.

Green, S.R. 1993. Radiation balance, transpiration and photosynthesis of an isolated tree. Agricultural and Forest Meteorology, 64(3): 201-221.

Groffman, P.M., Law, N., Belt, K., Band, L.E., and G. Fisher. Nitrogen fluxes and retention in urban watershed ecosystems. *Ecosystems*, 7: 393-403.

Groffman, P. M., C.O. Williams, R. V. Pouyat, L.E. Band, and I.D. Yesilonis. 2009. Nitrate leaching and nitrous oxide flux in urban forests and grasslands. *Journal of Environmental Quality,* 38(5): 1848-60.

Guevara-Escobar, A.; E. González-Sosa, C. Véliz-Chávez, E. Ventura-Ramos, and M. Ramos-Salinas. 2007. Rainfall interception and distribution patterns of gross precipitation around an isolated Ficus benjamina tree in an urban area. *Journal of Hydrology*, 333: 532-541

Guidi, W., Piccioni, E., and E. Bonari. 2008. Evapotranspiration and crop coefficient of poplar and willow short-rotation coppice used as a vegetation filter. *Bioresource Technology*, 99: 4832-4840.

Harris, J.R., Day, S.D., and B. Kane. 2008. Nitrogen fertilization during planting and establishment of the urban forest: A collection of five studies. *Urban Forestry & Urban Greening*, 7: 195-206.

Heal, K.V., Stidson, R.T., Dickey, C.A., Cape, J.N., and M.R. Heal. 2004. New data for water losses from mature Sitka spruce plantations in temperate upland catchments. Hydrological Sciences Journal, 49(3): 477-493.

Helliwell, D.R. 1986. The extent of tree roots. *Arboriculture Journal*, 10: 341-347.

Herrera Environmental Consultants. 2008. *The Effects of Trees on Stormwater Runoff*. Prepared for Seattle Public Utilities. Herrera Environmental Consultants, Seattle, WA.

Hibbert, A.R. 1969. Water yield changes after converting a forested catchment to grass. *Water Resources Research*, 5 (3): 634-640.

Hirabayashi, S. 2013a. I-Tree Eco precipitation interception model descriptions, version 1.3. The Davey Tree Expert Company. Syracuse, NY.

Hirabayashi, S. 2013b. I-Tree Streets/Design/Eco rainfall interception model comparisons. The Davey Tree Expert Company. Syracuse, NY.

Hirschman, D. Collins, K., and T. Schueler. 2008. The runoff reduction method: technical memorandum. Center for Watershed Protection & Chesapeake Stormwater Network, Ellicott City, MD. Pages 1-25.

Hornbeck, J. W., Martin, C. W., and C. Eager. 1997. Summary of water yield experiments at Hubbard Brook Experimental Forest, New Hampshire. *Canadian Journal of Forest Research*, 27(12): 2043-2052.

Inkilainen, Elina, M. R. McHale, G. B. Blank, A. L. James, and E. Nikinmaa. 2013. The role of the residential urban forest in regulating throughfall: A case study in Raleigh, North Carolina, USA. *Landscape and Urban Planning*, 119: 91-103.

Interstate Technology Regulatory Cooperation (ITRC). 2001. Technical/Regulatory Guidelines: Phytotechnology Technical and Regulatory Guidance Document. ITRC.

Jack-Scott, E.J. 2012. Survival and growth factors affecting community-planted urban street trees. *Cities and the Environment*, 4(1): 14pp.

Jones, J.A. 2000. Hydrologic processes and peak discharge response to forest removal, regrowth, and roads in 10 small experimental basins, western Cascades, Oregon. *Water Resources Research.* 36(9): 2621-2642.

Kays, B.L. 1980. Relationship of forest destruction and soil disturbance to increased flooding in suburban North Carolina piedmont. Proceedings of the Third Conference of the Metropolitan tree Improvement Alliance, 118-125. The Metropolitan Tree Improvement Alliance.

Kestrel Design Group Team (KDGT). 2013. The Roles and Effects of Tree Evapotranspiration and Canopy Interception in Stormwater Management Systems and Strategies. MPCA Stormwater Manual Revisions. Prepared by the Kestrel Design Group Team for the Minnesota Pollution Control Agency.

Kirnbauer, M.C., B.W. Baetz, W.A. Kenney. 2013. Estimating the stormwater attenuation benefits derived from planting four monoculture species of deciduous trees on vacant and underutilized urban land parcels. *Urban Forestry and Urban Greening*, 12(3): 401-407.

Kjelgren, R. and T. Montague. 1998. Urban Tree Transpiration over Turf and Asphalt Surfaces. *Atmospheric Environment*. 32(1): 35-41.

Koeser, A., Hauer, R., Norris, K., and R. Krouse. 2013. Factors influencing longterm street tree survival in Milwaukee,WI, USA. *Urban Forestry & Urban Greening*, 12: 562-568.

Lal, R. 1996. Deforestation and land use effects on soil degradation and rehabilitation in western Nigeria I. soil physical and hydrological properties. *Land Degradation and Development*, 7: 19-45.

Le Coustumer, S., Fletcher, T. D., Deletic, A., Barruad, S., and P. Poelsma. 2012. The influence of design parameters on clogging of stormwater biofilters: a large-scale column study. *Water Research*, 46: 6743-6752.

Lindsey, P. and N. Bassuk. 1991. Specifying soil volumes to meet the water needs of mature urban street trees and trees in containers. *Journal of Arboriculture.* 17(6): 141-149.

Link, T.E., Unsworth, M., and D. Marks. 2004. The dynamics of rainfall interception by a seasonal temperate rainforest. *Agricultural and Forest Meteorology*, 124: 171-191.

Litvak, E., Bijoor, N. S., and D. E. Pataki. 2014. Adding trees to irrigated turfgrass lawns may be a water-saving measure in semi-arid environments. Ecohydrology, 7: 1314-1330.

Livesley, S.J., B. Baudinette and D. Glover. 2014. Rainfall interception and stem flow by eucalypt street trees – The impacts of canopy density and bark type. *Urban Forestry and Urban Greening,* 13(1): 192-197.

Lu, J.W.T., Svendsen, E.S., Campbell, L.K., Greenfeld, J., Braden, J., King, K.L., and N. Falxa-Raymond. 2010. Biological, social, and urban design factors affecting young street tree mortality in New York City. *Cities and the Environment*, 3(1): 15pp.

Matteo, M. T. Randhir and D. Bloniarz. 2006. Watershed-Scale Impacts of Forest Buffers on Water Quality and Runoff in Urbanizing Environment. *Journal of Water Resources Planning and Management,* 132(2): 144-15.

McPherson, G.E. and J. R. Simpson. 2002. A comparison of municipal forest benefits and costs in Modesto and Santa Monica, California, USA. *Urban Forestry & Urban Greening*, 11: 61–74.

McPherson, G., J. R. Simpson, Q. Xiao, and C. Wu. 2011. Million Trees Los Angeles canopy cover and benefit assessment. *Landscape and Urban Planning*, 99: 40-50.

Metro. 2002. Green streets: Innovative solutions for stormwater and stream crossings. Portland, OR. 144 p.

Mlambo, D., Nyathi, P., and I. Mapaure. 2005. Influence of *Colophospermum mopane* on surface soil properties and understorey vegetation in a southern African savanna. *Forest Ecology and Management*, 212: 394-404.

Molchanov, A. A. 1960. Gidrologicheskayo rol lesa (Hydrological role of forest). Izd-vo AN SSSR, Moscow, 488 pp.

Moore, R.D., and S.M. Wondzell. 2005. Physical hydrology and the effects of forest hydrology in the Pacific Northwest: a review. *Journal of the American Water Resources Association*, 41(4): 763-784.

Nielsen, C., Buhler, O., and P. Kristoffersen. 2007. Soil water dynamics and growth of street and park trees. *Arboriculture & Urban Forestry*, 33(4): 231–245.

Nowak, D. 2014. Personal communication. Urban tree canopy analysis for Baltimore City. As cited in Sample et al. 2015.

Page, J.L., R.J. Winston, and W.F. Hunt, III. 2014. Soils beneath pavements: An opportunity for stormwater control and treatment. *Ecological Engineering*. In press
Read, J., T. Wevill, T. Fletcher and A. Deletic. 2008. Variation among plant species in pollutant removal from stormwater in biofiltration systems. *Water Research*, 42(4-5): 893-902.

Pataki, D. E., Carreiro, M. M., Cherrier, J., Grulke, N. E., Jennings, V., Pincetl, S., Pouyat, R. V., Whitlow, T. H., and W. C. Zipperer. 2011. Coupling biogeochemical cycles in urban environments: ecosystem services, green solutions, and misconceptions. *Frontiers in Ecology and the Environment*, 9 (1): 27-36.

Peters, E. B., McFadden, J. P., and R. A. Montgomery. 2010. Biological and environmental controls on tree transpiration in a suburban landscape. *Journal of Geophysical Research*, 115(4).

Post, D.A., and J.A. Jones. 2001. Hydrologic regimes of forested, mountainous, headwater basins in New Hampshire, North Carolina, Oregon, and Puerto Rico. *Advances in Water Resources*, 24: 1195-1210.

Rahman, M. A., Smith, J. G., and A. R. Ennos. 2011. Effect of rooting conditions on the growth and cooling ability of Pyrus callerynana. *Urban Forestry and Urban Greening*, 10: 185-192.

Read, J., Wevill, T., Fletcher, T., and A. Deletic. 2008. Variation among plant species in pollutant removal from stormwater in biofiltration systems. *Water Research*, 42: 893-902.

Reynolds, E.R.C., F.B. Thompson, and United Nations University. 1988. Forests, Climate, and Hydrology: Regional Impacts. United Nations University, Tokyo, Japan. http://www.nzdl.org/fast-cgi-bin/library?e=d-00000-00---off-0unu--00-0--0-10-0---0---0prompt-10---4-------0-1l--11-en-50---20-about---00-0-1-00-0-0-11-1-0utfZz-8-00&cl=CL2.1&d=HASH4845310c3238b42b2d2574&gt=2.

Roman, L.A., and F.N. Scatena. 2011. Street tree survival rates: Meta-analysis of previous studies and application to a field survey in Philadelphia, PA, USA. *Urban Forestry & Urban Greening*, 10: 269-274.

Roman, L.A. 2013. Urban tree mortality. A dissertation submitted in partial satisfaction of the requirements for the degree of Doctor of Philosophy in Environmental Science, Policy and Management in the graduate division of the University of California, Berkeley.

Roseen, R., T.P. Ballestero, J.J. Houle, P. Avellaneda , J. Briggs, G. Fowler, and R. Wildey. 2009. Seasonal performance variations for storm-water management systems in cold climate conditions. *Journal of Environmental Engineering*. 135:128-137.

Sample, D., K. Berger, P. Claggett, J. Tribo, N. Goulet, B. Stack, S. Claggett, and T. Schueler. 2015. The peculiarities of pervious cover: A research synthesis on allocating pollutant loads to urban land uses in the Chesapeake Bay. STAC Publication Number 15-001, Edgewater, MD. 57 pp.

Sanders, R. 1986. Urban vegetation impacts on the hydrology of Dayton, Ohio. *Urban Ecology*, 9: 361-376

Sanders, J.R., and J.C. Grabosky. 2014. 20 years later: does reduced soil area change overall tree growth? *Urban Forestry & Urban Greening*, 13: 295-303.

Sanders, J. Grabosky, J., and P. Cowie. 2013. Establishing maximum size expectations for urban trees with regard to designed space. *Arboriculture & Urban Forestry*, 39(2): 68-73.

Schueler, T.R., 1987. Controlling urban runoff: a practical manual for planning and designing urban BMPs. Publication No. 87703. Metropolitan Washington Council of Governments, Washington, DC.

Shaw, D. and Schmidt, R. 2003. Plants for stormwater design. Species selection for the Upper Midwest. St. Paul, MN: Minnesota Pollution Control Agency. 369 p.

Sinclair, T.R., Holbrook, N.M., and N. Zwieniecki. 2005. Daily transpiration rates of woody species on drying soil. *Tree Physiology*, 25: 1469-1472.

Sivyer, D., J.R. Harris, N. Persaud, and B. Appleton. 1997. Evaluation of a pan evaporation model for estimating post-planting street tree irrigation requirements. *Journal of Arboriculture*, 23(6): 250-256.

Smullen, J. T., Shallcross,A. L., and K.A. Cave. 1999. Updating the U.S. nationwide urban runoff quality database. *Water Science Technology,* 39(12): 9-16.

Soares, A.L., Rego, F.C., McPherson, E.G., Simpson, J.R., Peper, P.J., and Q. Xiao. 2011. Benefits and costs of street trees in Lisbon, Portugal. *Urban Forestry & Urban Greening*, 10: 69-78.

Stack, B., N. Law, S. Drescher and B. Wolinski. 2013. Gross Solids characterization study in the Tred Avon Watershed Talbot County, MD. Prepared for Talbot County Department of Public Works. Center for Watershed Protection. Ellicott City, MD.

Stone Environmental, Inc. 2014. Tree credit systems and incentives at the site scale. Montpelier, VT.

Templer, P. H., Toll, J. W., Hutyra, L. R., and S. M. Raciti. 2015. Nitrogen and carbon export from urban areas through removal and export of litterfall. *Environmental Pollution*, 197: 256-261.

United States Department of Agriculture Soil Conservation Service (USDA SCS). 1986. Urban hydrology for small watersheds. Technical Release 55 (TR-55).

University of New Hampshire Stormwater Center. 2012. University of New Hampshire Stormwater Center 2012 Biennial Report.

Urban, J. 1999. Room to grow. *Treelink* 11:1-4.

Vogt, J.M., Watkins, S.M., Mincey, S.K., Patterson, M.S., and B.C. Fischer. 2015. Explaining planted-tree survival and growth in urban neighborhoods: A social–ecological approach to studying recently-planted trees in Indianapolis. *Landscape and Urban Planning*, 136: 130-143.

Wang, J., T.A. Endreny, and D. J.Nowak. 2008. Mechanistic Simulation of Tree Effects in an Urban Water Balance Model. *Journal of the American Water Resources Association*, 44(1): 75-85.

Wang, H., Ouyang, Z., Chen, W., Wang, X., Zheng, H., and Y. Ren. 2011. Water, heat, and airborne pollutants effects on transpiration of urban trees. *Environmental Pollution*, 159: 2127-2137.

Wang, H. 2012. Transpiration rates of urban trees, *Aesculus chinensis*. *Journal of Environmental Sciences*, 24(7): 1278-1287.

Waschbush, R.J. 2003. Data and Methods of a 1999-2000 Street Sweeping Study on an Urban Freeway in Milwaukee County, Wisconsin. Open File Report 03-93. U.S. Department of the Interior, U.S. Geological Survey.

Wondzell, S., and J. King. 2003. Postfire erosional processes in the Pacific Northwest and Rocky Mountain regions. *Forest Ecology and Management*, 178: 75-87.

Wullschleger, S. D., Wilson, K. B., and P. J. Hanson. 2000. Environmental control of whole-plant transpiration, canopy conductance, and estimates of the decoupling coefficient for large red maple trees. *Agricultural and Forest Meteorology*, 104: 157-168.

Wullschleger, S. D., Hanson, P. J., and D. E. Todd. 200. Transpiration from a multi-species deciduous forest as estimated by xylem sap flow techniques. *Forest Ecology and Management*, 143: 205-213

Xiao, Q., E.G. McPherson, J.R. Simpson, and S.L. Ustin. 1998. Rainfall Interception by Sacramento's Urban Forest. *Journal of Arboriculture,* 24(4): 235-244.

Xiao, Qingfu, E.G. McPherson, S.L. Ustin, M.E. Grismer. 2000. A new approach to modeling tree rainfall interception. *Journal of Geophysical Research*, 105(D23): 29, 173-29,188.

Xiao, Q and E.G. McPherson. 2002. Rainfall Interception by Santa Monica's Municipal Urban Forest. *Urban Ecosystems*, 6: 291-302.

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

Xiao, Q. and E.G. McPherson. 2011b. Rainfall interception of three trees in Oakland, California. *Urban Ecosystems*, 14: 755-769.

Yang, J.L., G.L. Zhang. 2011. Water infiltration in urban soils and its effects on the quantity and quality of runoff. *J Soils Sediments*.11: 751-761.

Zhang, W., Y. Youbin; Y. Tong, L. Ou, D. Hu, and X. Wang. 2011. Contribution and loading estimation of organochlorine pesticides from rain and canopy throughfall to runoff in an urban environment. J*ournal of Hazardous Materials*, 185(2-3): 801-806.

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[i] http://www.nrs.fs.fed.us/pubs/jrnl/2012/nrs_2012_tedela_001.pdf