

Review of the Available Science for Urban Tree Planting and Canopy

A total of 115 publications were reviewed by the Expert Panel to evaluate the research questions defined in the scope of this Expert Panel:

1. What is the effectiveness of urban tree canopy 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?

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. Consequently, the data reviewed were not limited to the Chesapeake Bay watershed. 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. The literature was also extended to include studies on trees planted as a part of an urban stormwater best management practice to quantify the impact of urban tree canopy on water quality. 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 urban riparian zone (i.e., within 100 feet of a waterbody) will be credited under a separate best management practice (Urban Forest Buffers), 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.

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. Interception losses depend on factors such as leaf area index (LAI), tree structure, and notably 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 on an annual basis. Quantifying interception on an annual timescale allows for development of an average value across differing rainfall conditions and also accounts for interception during both leaf-on and leaf-off periods. Therefore, the synthesis of studies in this section focuses primarily on those reporting results over an annual timeframe.

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 and these results range from 106 to 2,000 gallons/tree/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 the Chesapeake Bay region.

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) Ginkgo (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 (gallons/ tree/yr) ⁴	Species/Condition	Type of Study
Berland and Hopton 2014	Cincinnati, OH	1,770 (6.7)	Average value	Modeling
McPherson and Simpson 2002	Modesto, CA	845 (3.2)	Average value	Modeling
McPherson and Simpson 2002	Santa Monica, CA	1,849 (7.0)	Average value	Modeling
McPherson et al. 2011	Los Angeles, CA	106 (0.4) (low) 1,479 (5.6) (high)	Crapemyrtle Jacaranda (D)	Modeling
Soares et al. 2011	Lisbon, Portugal	1,189 (4.5)	Average value	Modeling
CWP, 2014	Montgomery County, MD	2,000 (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

⁴ Units of m³/tree/yr are noted in parentheses

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

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 for urban trees while Table 5 summarizes similar data from natural forests. These studies quantify transpiration during the growing season or some portion of it, rather than on an annual basis. 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.

Study	Location	Average Daily Transpiration Rate (mm/day)	Species / Condition¹	Type of Study
Wang (2012)	Beijing, China	1.47	Horse Chestnut - <i>Aesculus chinensis</i> (D), 10.5-19.2 DBH	Measured
Chen et al. (2011)	Liaoning Province, China	1.51	<i>Cedrus deodara</i> , <i>Zelkova schneideriana</i> , <i>Metasequoia glyptostroboides</i> , <i>Euonymus bungeanus</i>	Measured
Peters et al. (2010)	Minneapolis St. Paul, Minnesota	1.1 ²	<i>Fraxinus pennsylvanica</i> , <i>Quercus rubra</i> , <i>Juglans nigra</i> , <i>Tilia Americana</i> , <i>Ulmus pumila</i> , <i>Ulmus thomasii</i> (D)	Measured
		1.9 ²	<i>Picea glauca</i> , <i>Picea pungens</i> , <i>Pinus strobes</i> , <i>Picea abies</i> , <i>Pinus nigra</i> , <i>Pinus sylvestris</i> (E)	Measured
Cermak et al. (2000)	City of Brno, Czech Republic	2.17	Red Maple - <i>Acer campestre</i> L (D), roots covered by asphalt, 18" DBH, shaded	Measured
		2.39	Red Maple - <i>Acer campestre</i> L (D), roots covered by asphalt, 50" DBH, exposed to sunlight	

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
Pataki et al. (2011)	Los Angeles, CA	0.1-2.2	Urban forest plots with mixed species	Measured

¹D = deciduous, E = evergreen² Converted from kg/m²/day assuming 1kg = 0.0010m³

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 ³	Laurel Sumac - <i>Malosma laurina</i> , unirrigated	Measured
		0.8 ³	<i>Pinus canariensis</i> , unirrigated	
		2.3 ³	Blue Jacaranda - <i>Jacaranda mimosifolia</i> , irrigated	
		3.4 ³	Kurrajong - <i>Brachychiton populneus</i>	
		3.4 ³	Redwood - <i>Sequoia sempervirens</i>	
		5.0 ³	Lacebark - <i>Brachychiton discolor</i>	
		11.3 ³	Grand Eucalyptus - <i>Eucalyptus grandis</i>	
		12.0 ³	Crape Myrtle - <i>Lagerstroemia indica</i>	
		12.5 ³	California Sycamore - <i>Platanus racemosa</i> , campus	
		13.0 ³	Canary Island Pine - <i>Pinus canariensis</i> ,	
		13.4 ³	Goldenrain tree - <i>Koeleruteria paniculata</i>	
		17.9 ³	Chinese elm - <i>Ulmus parvifolia</i>	
		19.4 ³	<i>Pinus canariensis</i> , campus	
		23.7 ³	Laurel Fig - <i>Ficus microcarpa</i>	
		23.7 ³	Honey Locust - <i>Gleditsia triacanthos</i>	
		26.2 ³	Jacaranda - <i>Jacaranda chelonina</i>	
		27.1 ³	<i>Platanus racemosa</i> , street	
		46.7 ³	London Planetree - <i>Platanus hybrida</i> , street	

Table 4. Gallons of Water Transpired by Urban Trees During the Growing Season				
Study	Location	Average Daily Transpiration Volume (gal/tree/day)	Species / Condition²	Type of Study
Green (1993)	Palmerston North, New Zealand	10.5 ¹	10 year old isolated walnut (D)	Measured
Cermak et al. (2000)	City of Brno, Czech Republic	17 ¹	Red Maple - <i>Acer campestre</i> L (D), roots covered by asphalt, 18" DBH, shaded	Measured
		37 ¹	Red Maple - <i>Acer campestre</i> L (D), roots covered by asphalt, 50" DBH, exposed to sunlight	

¹ Converted from liters/tree/day²D = deciduous, E = evergreen³Converted from kg/tree/day assuming 1 gallon = 3.79 kg of water

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

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
		2.4	White pine forest	

¹Measurements are for individual trees

²Sap flow measurements for individual trees were used to model stand transpiration

³Measurements 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. Table 6 summarizes these studies, which estimated annual ET rates for forested watersheds of 24% to 77%. 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.

Table 6. Annual ET by Natural Forests			
Study	Location	Results	Description
Boggs and Sun (2011)	Central North Carolina piedmont	Forested watershed retained 77% of annual rainfall, compared to 58% for an urban watershed with 44% impervious cover	ET was estimated by subtracting measured streamflow from precipitation.
Post and Jones (2001)	Oregon, New Hampshire, North Carolina and Puerto Rico	Deciduous forested basins retain 24-54% of rainfall and evergreen forests retain 43-50% of rainfall	ET was estimated by subtracting measured streamflow from precipitation.

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. This same study demonstrated that trees can also increase infiltration rates in structural soils, with green ash grown in CU Soil having an infiltration rate 27 times greater than the unplanted CU Soil control sites (Bartens et al 2008). 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.

In a study of a stormwater biofilter, 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 rate and 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).

Table 7 summarizes the results from the studies reviewed on runoff reduction by urban trees and forests. As indicated in the description in Table 7, each study has a unique approach to quantifying runoff reduction.

Table 7. 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 during a single storm
	5% reduction in runoff	Modeled reduction associated with increasing tree cover over non-surfaced areas from 37% to 50% during a single storm

¹ study did not include unplanted controls

Watershed-scale studies of runoff reduction often provide results in terms of the percent of annual runoff reduced by a given percent of tree cover in the watershed (in comparison to the runoff generated if trees were not present). These results can be translated into a percent runoff reduction per unit area of canopy if watershed areas are provided in the studies. However, not all studies are conducted on an annual basis and the results (streamflow measured at the watershed outlet) reflect not just the effect of trees in the watershed but the cumulative effect of all other land cover types and watershed features.

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 the Chesapeake Bay region CITYgreen study was reviewed for this synthesis because the methodology is the same in all studies and this paper provides results that are most relevant to the Bay. The runoff curve number method upon which CITYgreen is based was developed for agricultural watersheds and has been shown to be relatively inaccurate in estimating runoff from forest (Tedela et al. 2012). 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. This is likely attributable to the greater amount of stormwater runoff generated on impervious surfaces, compared to turfgrass or other pervious areas.

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 natural forests infer runoff reduction by measuring changes in runoff from streams draining forested basins before and after clearcutting. Table 8 summarizes these studies, which show a reduction in annual water yield of 8% to 80% after forest harvesting. In the Hornbeck et al. (1997) study, increases in annual water yield diminished rapidly as forests regenerated and were undetectable within 7-9 years after treatment. Douglas and Swank (1972) summarized 23 experiments from mixed deciduous hardwood forests in the Appalachian Highlands. 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 = $-1.43 + 0.13(\% \text{ basal area reduction})$. 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.

Study	Location	Results	Description
Hornbeck et al. (1997)	Hubbard Brook, New Hampshire	Annual water yields increased by an average of 32% after forest clearing in forested watersheds.	Measured by comparing streamflow in forested basins before and after deforestation.
Moore and Wondzell 2005	Oregon Cascades, Oregon Coast and South Coastal British Columbia	Mean changes in annual water yields after forest harvesting ranged from 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.	Measured by comparing streamflow in forested basins before and after deforestation.

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. Trees, specifically the leaf litter produced by trees, are also a needed source of nutrients and carbon to support stream ecology and are deposited to stream from adjacent riparian areas, or through delivery of leaf litter from the urban drainage system. As discussed below, the research to quantify the excessive nutrient load delivered

by leaf litter in urban watersheds is incomplete. 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

Only one study directly addresses the effects of urban trees on the quality of stormwater runoff. Nine of the studies reviewed 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 9, evaluate different species of nutrients and/or use varying methods to calculate percent pollutant removal.

Table 9. Pollutant Removal by Stormwater Treatment Systems with Trees (<i>note: the pollutant reductions are for the practice and not the effect of trees in the practice</i>).								
Study	Treatment System Type	Parameter and % Reduction						
		TN	NO _x	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	Filtterra	15				52		85
Xiao and McPherson 2011a	Bioswale	95.3 ¹						95.5 ²

¹average of all nutrient species results

²average of results from TSS and TDS

The values shown in Table 9 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%.

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 981 lbs (445kg) over the simulation period, TP by 4.4 lbs (2kg), TKN by 26.5 lbs (12kg) and NO₂+NO₃ by 8.8 lbs (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; yet, it is difficult to put these values into context because the total pollutant inputs to the watershed are unknown. 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 is 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. The washoff of atmospheric deposition from leaves would not be considered an additional source of nutrients; however, tree canopy may delay the delivery of these nutrients to the stream.

Numerous studies have evaluated the water quality benefits of natural forests. Table 10 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 10. Nutrient and Sediment Loads from Non-Urban Forests¹			
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:Reference⁴		
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

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. That is, processes such as nitrate removal from shallow groundwater and denitrification hotspots along the soil water interface are more prominent processes in riparian areas compared to tree in the upland area (Johnson et al 2013). 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.

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 all the leaves were accounted for in the load. However, it is known trees sequester nitrogen prior to leaf fall in trunks, roots and branches leaving low amount of nitrogen in leaf litter. 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 associated with leaf litter 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); soluble phosphorus readily leach following immersion or wetting. 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 $52 \pm 17\%$ 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. While the nutrients, specifically phosphorus is likely a source to urban streams, it is unknown how much of this soluble load is represented in current monitoring of urban outfalls.

Summary

Urban tree canopy has great potential for helping to meet nutrient and sediment load reductions for the Chesapeake Bay TMDL. 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, 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 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—including i-tree HYDRO, the Simple Method (Schueler 1987) and the Runoff Reduction Method (Hirschman et al. 2008)—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. Since the literature on hydrologic benefits of urban trees is much more plentiful than studies of water quality benefits, a possible avenue to explore for a credit is to model the connection between runoff reduction and pollutant reduction.

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. Best professional judgement is needed to develop recommendations that reflect the best available science while accounting for this variability as well as the average operational condition of the entire watershed.

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Annotated Bibliography

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 ft³ 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 9m² 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 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 $\mu\text{g}/\text{cm}^2/\text{s}$ for the green ash (depending on soil treatment) and 0.76 to 1.39 $\mu\text{g}/\text{cm}^2/\text{s}$ 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 R² 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 NO_x 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 make 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 ginkgo (*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.