STORMWATER MANAGEMENT BENEFITS OF TREES

DRAFT REPORT

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1. INTRODUCTION

Trees provide us with a host of wildlife and habitat benefits, energy savings, social and health benefits, and economic benefits. Trees also act as natural reservoirs by intercepting and storing rainfall, which can reduce runoff volume and mitigate its effects (Midwest Urban Tree Canopy Project 2011).The benefits of trees as stormwater management practices, especially in urban and suburban settings, have recently been more widely recognized. Here, we summarize recent work describing and quantifying the stormwater management benefits of trees, especially at the individual tree and property/site scales.

2. TREE PROCESSES THAT AFFECT STORMWATER RUNOFF

Three primary processes—interception, transpiration, and infiltration—can reduce the amount of rain falling on trees that becomes stormwater runoff.

- **Interception** occurs first, when precipitation collects on leaves, branches, and trunks and evaporates or is absorbed. This process reduces the amount of water reaching the ground, delaying the onset and reducing the volume of peak flows (U.S. EPA 2013).
- **Transpiration** is the transfer of water from the soil through the tree and its eventual release in a gaseous form through microscopic pores in the leaves and stems (Herrera Environmental Consultants 2008).
- **Infiltration** is the movement of surface water through the soil. Tree roots, combined with the organic material that typically builds on the soil at the base of trees, promote the infiltration of runoff through shallow subsurface zones, reducing both the rate and volume of stormwater runoff (U.S. EPA 2013).

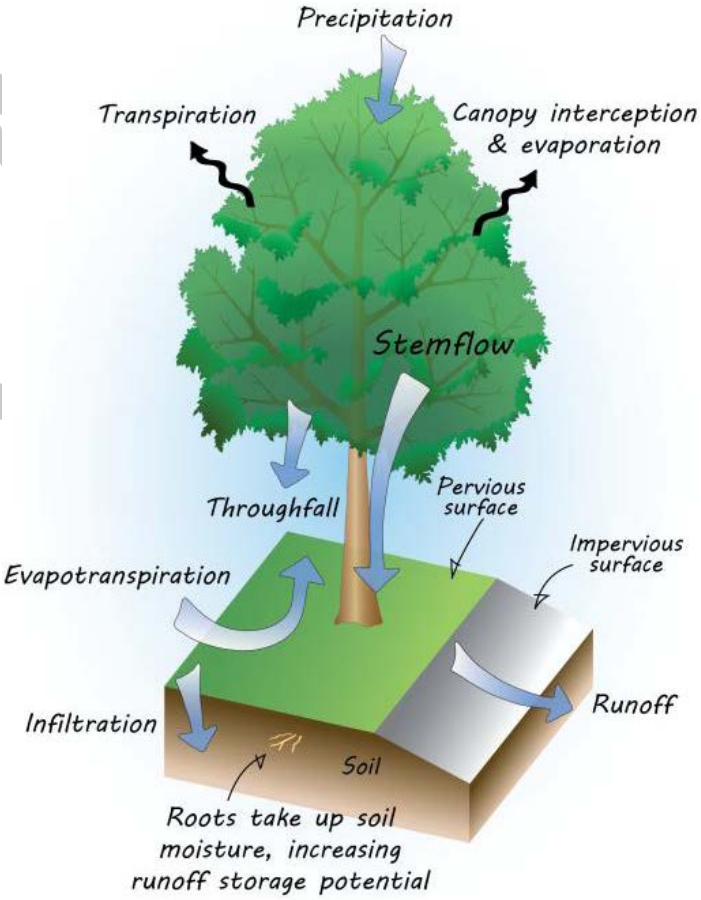

Figure 1. Diagram of water movement through trees. Source: US EPA 2013

Pollutant removal is another important function performed both by trees and by the soils they grow in. Along with water, trees take up nutrients and trace amounts of chemicals, including metals, organic compounds, fuels, and

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solvents from the soil (US EPA 2013). Inside the tree, pollutants may be transformed into less harmful substances, used as nutrients, or stored in roots, stems, and leaves.

2.1. Interception

There is a reasonably robust body of literature regarding the interception of precipitation by trees. Research indicates that conifers generally intercept more water annually than deciduous trees, which can be explained by the greater foliage surface area of conifers and the presence of foliage on conifers during winter months (Herrera Environmental Consultants 2008).

Measured rainfall interception for individual trees ranges from 8% to 68% of a rainfall event (Capiella et al. 2006, Herrera Environmental Consultants 2008), and is dependent on the tree species and rainfall characteristics. Canopy interception measured for conifer stands ranges from 15% to 51% of annual precipitation, and interception in hardwood stands ranges from 8% to 20% (Xiao et al. 2000, Herrera Environmental Consultants 2008).

2.2. Transpiration

Evapotranspiration (ET) is the sum of water evaporated from soil and plant surfaces and the water lost as a result of transpiration, a process in which trees absorb water through their roots and transfer it up to the leaves, where it evaporates into the environment through leaf pore transpiration (Shanstrom 2011a). Transpiration from plants and trees continues to reduce water volumes stored in the soil long after a rainfall event ends.

Only a few recent studies have attempted to quantify the rate of transpiration associated with different types of trees (Herrera Environmental Consultants 2008). These studies found that conifers transpired 10-12% of precipitation, while deciduous trees during leaf-on transpired up to 25% of precipitation. Evergreens have lower transpiration rates because they are more efficient than deciduous trees at retaining moisture, due to the structure of their leaves (Metro, 2002). Those percentages can sometimes amount to a substantial portion of smaller storms falling on individual trees. A mature tree can, on average, transpire 100 gallons of water per day (Akbari et al. 1992; Metro 2002), while an acre of mature forest can take up at least 1,800 gallons of water every day (Envirocast, 2003). Transpiration rates (along with rooting depth and trunk growth) can, however, be restricted under slow soil drainage rates (Bartens et al. 2009).

2.3. Infiltration

The growth of tree roots, as well as the decomposition of roots and leaf litter, increase soil infiltration rates and overall infiltration capacity. Numerous studies have quantified the impact of trees on infiltration rates (Hererra Environmental Consultants 2008). A study of infiltration before and after forest fires found that infiltration rates decreased by 20-30 percent (Wondzell 2003). A study completed in the North Carolina piedmont found that when the forest understory and leaf litter were removed from a mixed pine-hardwood forest, the resultant lawn had infiltration rates that were 65% lower compared to the forested condition (Kays 1980).

Conversely, field-scale studies of changes in stormwater runoff following the clear-cutting of forested basins in New Hampshire and Oregon showed increases in runoff of 23-32% for deciduous forest (Hornbeck et al. 1997, Martin and Hornbeck 2000) and 32% for coniferous forest (Jones 2000) in the clear-cut basins when compared to adjacent forested controls. On average, forests produce 30% to 50% less runoff than do grass lawn areas (Pitt et al. 1986), which in turn produce significantly less runoff than impervious surfaces.

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Though trees have been shown to measurably increase the infiltration capacity of underlying soils in natural areas, this may not always be true in urbanized ones. Removal of leaves and organic buildup by homeowners, businesses, and municipal grounds crews is common and may degenerate the organic layer, and human and animal traffic may compact soils (Herrera Environmental Consultants 2008).

There is, however, a robust and rapidly evolving body of research regarding the ability of trees to provide infiltration benefits despite these limitations – and on ways to best engineer tree-planting areas in urban environments to both grow healthy trees and maximize the stormwater management benefits they provide. In one such study, black oak (Quercus velutina Lam.) and red maple (Acer rubrum L.) trees were installed in cylindrical planting sleeves surrounded by clay loam soil at two compaction levels (bulk density = 1.3 or 1.6 g cm^{-3}) in irrigated containers. Roots of both species penetrated the more compacted soil, increasing infiltration rates by an average of 153% compared to an unplanted control (Bartens et al. 2008).

In addition to infiltrating runoff, soil stores rain water during and after a storm, making it available for plant growth. For example, one properly planted tree surrounded by suspended pavement, with 1000 cubic feet of uncompacted soil with 20% soil water storage capacity, can hold the 1 inch, 24 hour storm event from 2,400 square feet of impervious surface—an area much larger than just the area under the tree canopy (Shanstrom 2011). This example calculation, like most of those that are used to design bioretention systems with trees, accounts only for soil storage, not for interception or evapotranspiration.

2.4. Pollutant removal

Most recent research involving the pollutant removal efficiency of tree-related stormwater practices has focused primarily on tree-scale bioretention practices. Several recent literature reviews of lab and field studies of bioretention pollutant removal have concluded that bioretention systems, whether vegetated with trees or plants, are one of the most effective BMPs for pollutant removal (Shanstrom 2011a, Davis et al. 2012). Pollutant removal mechanisms include filtration, adsorption, and uptake and sequestration in plant material (Capiella et al. 2005, Davis et al. 2009). Over time, trees also increase the amount of organic matter in the soil, which binds many pollutants (Capiella et al. 2005).

High concentration and load reductions are consistently found for suspended solids, metals, polycyclic aromatic hydrocarbons (PAH), and other organic compounds (Denman 2006, Davis et al. 2009). The presence of vegetation also substantially improves retention of total nitrogen and total phosphorus; vegetated media is much more effective at removing dissolved phosphorus from solution and at reducing nitrate leaching from bioretention soil mixes or media (e.g., Henderson et al. 2007, Henderson 2009, Lucas and Greenway 2011, and the International BMP Database). Limited research suggests that bioretention can also effectively manage other pollutants, such as pathogenic bacteria and thermal pollution (Davis et al. 2009). Innovations in bioretention design to maximize nutrient removal, such as the “upturned elbow” to create an anerobic zone that facilitates denitrification (Brown et al. 2009, Davis et al. 2009), and the addition of media such as iron filings to bioretention mixes to improve phosphorus sorption (Erickson et al. 2012, Traver et al. 2013), also show great promise.

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3. MAXIMIZING STORMWATER –RELATED BENEFITS AT THE TREE OR SITE SCALE

Consideration of soil and the overall site are critical to success, even (and perhaps especially) when the project seems as simple as planting a tree. Healthy trees require space, proper soil, drainage, and adequate water —and as the sites considered for tree planting become smaller and more urban, it becomes even more critical to keep these factors in mind (Capiella et al. 2006).

A soil's porosity (amount of available pore space), permeability (how interconnected pore spaces are), and infiltration rate (how quickly the water moves through the soil) are critical to the success of a tree (Sanders et al. 2013) and its ability to absorb stormwater (U.S. EPA 2013). These soil properties affect the amount of air, moisture, and nutrients that are available in the root zone and how much runoff is absorbed into the ground instead of flowing over the ground.

Big trees with large, dense canopies manage the most stormwater – and designing tree plantings to accommodate the largest size tree possible will increase their stormwater utility function (Figure 2).

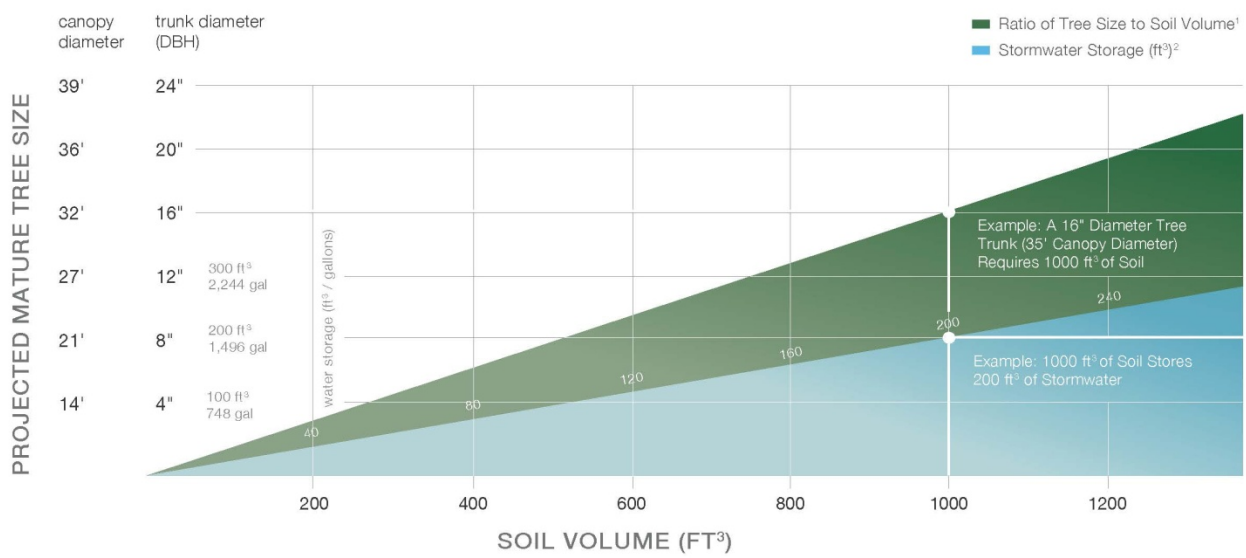

Figure 2. Comparison of uncompacted soil volume to projected mature tree size (trunk and canopy diameter), with estimates of stormwater storage per tree (Deep Root Partners 2011).

The effects of site-scale development, including the addition of impervious surfaces, along with the compaction of soils by heavy construction equipment, create challenges for both stormwater management and successful tree growth by reducing or preventing the infiltration of runoff into the ground (US EPA 2013). One way to address these problems, providing a solution for both, is to preserve existing trees and to generally minimize the disturbance of a site during development (Capiella et al. 2006). In urban areas and in many re-development situations, where historic land uses and compaction preclude the effective use of these strategies, tree planting areas can still be designed to increase infiltration and limit compaction, and can even be

engineered to receive and process stormwater from streets, parking lots, and rooftops (Capiella et al. 2006, Casey Trees 2008, Day et al. 2012).

3.1. Soil Restoration and Tree Planting

Trees are a part of almost every urban and suburban development, yet mature urban trees are rare. There can be many reasons why these trees fail to grow to useful sizes, but the most critical is that they generally don't have access to sufficient amounts of soil, resulting in a short death and replacement cycle (Marritz 2012). Planting trees in conditions that will support long-term growth is one of the most important ways to ensure that trees can reliably function as green infrastructure. Simply planting "a million trees", as envisioned in green infrastructure initiatives in cities like Los Angeles, New York, Salt Lake City and Philadelphia, isn't likely to result in long-term success for trees at development sites or in urban areas unless those trees are planted in ways that ensure their long-term success.

Healthy soils support vigorous tree and plant growth that intercepts rainfall, returning much of it to the sky through evaporation and transpiration. Healthy soil also provides additional important stormwater management functions including efficient water infiltration and storage, adsorption of excess nutrients, filtration of sediments, biological decomposition of pollutants, and moderation of peak stream flows and temperatures (Washington DOE 2012). In recognition of these benefits, several states have implemented soil restoration (including topsoil preservation, minimum compaction, compost or other soil amendment, deep tillage, and other strategies) as a required or optional stormwater management practice on development or redevelopment sites (see sidebar).

The nexus between soil restoration on development sites and the success of trees planted following typical development practices is an area of active and ongoing research. For example, since 2007, the Soil Rehabilitation Experiment Site (SRES) at Virginia Tech is being used to evaluate the effects of several soil improvement practices on soil physical properties and tree establishment (Day et al. 2012). Researchers are monitoring soil carbon sequestration, greenhouse gas emissions, soil infiltration and permeability, rooting depth, and a host of other factors to fully characterize the potential of these practices for restoring soils damaged by land development. Preliminary results demonstrate that "Soil Profile Rebuilding"--which includes a subsoiling procedure, addition of organic matter in the form of compost, replacement or addition of topsoil followed by tilling, and subsequent planting with woody plants--substantially improves tree establishment and growth during the first five years after planting when compared to typical land development practices (Day et al. 2012).

Soil Restoration Resources

Washington State's *Building Soil* guidebook for implementing soil quality and depth standards during development and redevelopment projects: http://www.soilsforsalmon.org/pdf/Soil_BMP_Manual.pdf

Virginia Tech's Soil Profile Rebuilding specification: http://urbanforestry.frec.vt.edu/SRES/specification.html

Stone Environmental technical memo on soil restoration standards, and options for use as a stormwater BMP in Vermont: http://www.vtwaterquality.org/stormwater/docs/manualrevision/sw_Tech_Memo_Soil_Restoration.pdf

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3.2. Engineered Systems for Trees in Urban Settings

Techniques like minimal site disturbance, tree preservation, and soil preservation can all be reasonably planned for on larger lots, or in new development projects—but often these practices are simply not feasible in urban areas and smaller historic village centers. Impervious surfaces and compacted soils create major challenges, preventing the infiltration of runoff into the ground. In these situations, un-compacted soil volumes sufficient for growing healthy trees to maturity can be provided by designing tree planting areas to increase infiltration and limit compaction. In addition, tree planting area can also often be engineered to receive and process street and rooftop runoff. Several types of engineered systems that can support healthy trees in urban settings are briefly highlighted below.

3.2.1. Suspended pavement and structural cells

In a suspended pavement or structural cell system, pavement or the intended ground surface is supported by a network of pillars, piles, or structural cells (U.S. EPA 2013). The suspension system supports the weight and forces of the pavement above and allows the soil below to remain uncompacted over time, accommodating tree roots and both filtering and managing stormwater runoff (Figure 3).

Figure 3. A structural cell system under construction on Cherry Street in Burlington, VT.

3.2.2. Structural soil

Structural soils are engineered soil mixes with a high porosity that allow tree roots to penetrate freely, and stormwater to infiltrate rapidly and then be stored until it percolates into the soil beneath (Day and Dickinson 2008). Tree root systems and the structural soil that supports them combine to form a shallow but extensive reservoir for capturing and storing stormwater.

Systems that include structural soils are designed to be used under asphalt or concrete pavements, or in tandem with pervious pavements, as the load-bearing and leveling layer. In addition to providing a compactable base for pavements, structural soil provides a soil component to the aggregate mix that facilitates root growth—common road bases do not have this tree-friendly component (U.S. EPA 2013). Two examples of structural soils that have been developed and tested in the United States are Cornell University's CUSoil and Carolina Stalite (Day and Dickinson 2008).

3.2.3. Stormwater tree pits

A stormwater tree pit is similar to a traditional street tree pit design, but is modified so the pit accepts and treats storm water runoff and provides an improved planting environment for the tree (Capiella et al. 2006). When tree pits provide enough uncompacted soil volume to grow large-sized trees, they become an integral part of stormwater management (U.S. EPA 2013). While tree pits can be individual, connecting multiple tree pits by using soil paths or drains can increase soil volume for both trees and stormwater management opportunities (Casey Trees 2008, U.S. EPA 2013).

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3.2.4. Forested bioretention and bioinfiltration

Bioretention and bioinfiltration facilities are shallow, landscaped depressions that contain a layer of prepared soil, a mulch layer, and vegetation. These facilities provide filtering of storm water runoff by temporarily ponding water during storms. Bioretention facilities have underdrain systems, while bioinfiltration facilities allow runoff to infiltrate into existing site soils (infiltration rates greater than 0.5 inches per hour) (Capiella et al. 2006).The concept design for a forested bioretention system is intended not only to incorporate trees and shrubs, but to improve growing conditions for trees and decrease potential engineering conflicts (Capiella et al. 2006). The small footprint of these facilities (generally 5% of the impervious area they receive drainage from) means that they may be used in many applications.

More on Engineered Systems for Trees

Urban Watershed Forestry Manual, Part 2: Conserving and Planting Trees at Development Sites: http://www.treesearch.fs.fed.us/pubs/19936

Tree Space Design: Growing the Tree out of the Box: http://caseytrees.org/wp-content/uploads/2012/02/tree-space-design-report-2008-tsd.pdf

Stormwater to Street Trees: Engineering Urban Forests for Stormwater Management: http://water.epa.gov/polwaste/green/upload/stormwater2streettrees.pdf

Managing Stormwater for Urban Sustainability Using Trees and Structural Soils: http://www.vtfpr.org/urban/documents/TreesAndStructuralSoilsManual.pdf

3.3. Tree Selection, Siting, and Planting

The urban landscape represents an especially harsh environment for trees, complete with a variety of pollutants, temperature extremes, hydrologic modifications, compacted soils, invasive plants, and many other factors that make it difficult to sustain healthy trees. Part 3 of the Urban Watershed Forestry Manual (2006) presents several well-tested design principles for successful urban tree planting, adapted from Urban (1999) and GFC (2001):

1. Provide adequate soil volume to support trees at maturity. A general guideline is to provide at least two cubic feet of usable soil for every one square foot of mature canopy (the area within the projected mature dripline of the tree). Soil volumes of planting areas should be designed to be interconnected so trees can share rooting space.

2. Preserve and improve soil quality. Limit clearing and grading to protect native soils at the site. Soil volume should be accessible to air, water, and nutrients. This is best done by separating paving from tree's rooting area, which also allows for periodic inspection of the planting area. Soils should be amended where needed to improve drainage and fertility.

3. Provide adequate space for tree to grow. Design surrounding infrastructure to accommodate long-term growth of tree, and space trees appropriately to allow for long-term growth and management.

4. Select trees for diversity and site suitability. Plant a variety of species that are tolerant of the climate and soil conditions as well as any urban impacts at the site.

5. Protect trees from other impacts. Develop designs that protect the tree over its entire life from pedestrian traffic, toxic runoff, browsing, high temperatures, and other urban impacts.

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A robust variety of resources are widely available to support proper site selection, decision making about which tree species to plant, site preparation and tree planting, and tree establishment and ongoing maintenance (see sidebar below).

Tree Selection, Siting, and Planting Resources

Vermont Urban and Community Forestry Program's Community Forestry Library Tree Planting References: http://www.vtfpr.org/urban/for_urbcomm_library.cfm#Planting

Vermont Urban and Community Forestry Program's Tree Selection Tool: http://www.vtfpr.org/urban/treeselectiontool.cfm

Center for Watershed Protection and US Forestry Service's *Urban Watershed Forestry Manual, Part 3: Urban Tree Planting Guide*: http://www.na.fs.fed.us/pubs/uf/watershed3/urban_watershed_forestry_manual_part3.pdf

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