ABSTRACT

INKILÄINEN, ELINA NOORA MIRJAMI. Urban Residential Forests in Regulating Throughfall and Potential Stormwater Runoff – Case Study of Raleigh, NC. (Under the direction of Dr. Melissa McHale and Dr. Eero Nikinmaa).

The conversion of vegetated land cover to impervious surfaces has made stormwater runoff into a major hydrological concern due to its capacity to deteriorate water quality and stream health in cities. Urban forests are capable of reducing the amount of potential stormwater runoff by regulating throughfall via canopy rainfall interception. The lack of stand-scale studies of urban throughfall hinders realistic estimates of the benefits of urban trees for stormwater regulation. Urban forests are extremely variable with regard to canopy cover and species composition and are to a large extent managed by private residents with varying landscape preferences. To quantify the amount of rainfall interception by vegetation in an urban forest we measured throughfall in Raleigh, North Carolina, USA between July and November 2010. We further analyzed 16 residential yards with varying levels of canopy cover to evaluate the relative importance of different descriptive measures of vegetation in influencing throughfall in an urban watershed. Throughfall comprised 89.7 % (StdErr=0.005) of gross precipitation in the study area. Canopy cover ($p<0.0001$) and the percentage of coniferous trees ($p=0.0305$) were the most influential vegetation variables explaining throughfall whereas leaf area index (LAI) was not found to be significant. Throughfall varied significantly among yards ($p<0.0001$) ranging from 84.0 % (80.2 % canopy cover) to 98.2 % (60.3 % canopy cover). Differences in vegetation between front and backyards resulted in 3.1 % less throughfall in backyards. Thus, residents' management choices at yard-level affect the amount of throughfall reduced at the landscape scale.

Urban Residential Forests in Regulating Throughfall and Potential Stormwater Runoff – Case Study of Raleigh, NC

by
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BIOGRAPHY

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After graduating Elina Inkiläinen hopes to be able to raise awareness of ecosystem services and create methods for sustainable land-use planning both nationally and internationally.

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Introduction:

Increasing attention is directed towards urban forests in efforts of finding ways to mitigate the severe hydrological changes caused by urban development. One of the processes by which trees are capable of reducing the amount of potential stormwater runoff is rainfall interception, i.e. the amount of precipitation that never reaches the ground as throughfall but evaporates directly back into the atmosphere from the canopy.

The amount of rainfall intercepted depends on the characteristics of storms, climate, and vegetation. The frequency of storms has been established as the main driver of the process, apart from storm magnitude and duration. Frequent small showers allow more interception than continuous large storms that quickly fill the canopy storage capacity. Temperature, humidity, and annual rainfall patterns, further control the evaporation of intercepted rainfall. Depending on annual rainfall patterns, evergreen vegetation may be capable of intercepting more rainfall than deciduous vegetation due to maintaining foliage throughout the year. In addition, coniferous canopies have been found to intercept higher amounts of rainfall compared to broadleaved canopies due to generally higher LAI.

Urban forests have different interception patterns than rural forests owing to anthropogenic influences on vegetation structure and the resulting altered microclimate around the canopy. Urban forests are characterized by generally lower and more heterogeneous canopy cover consisting of more species and a larger number of isolated crowns. As per these characteristics, higher air temperature and wind speed are commonly found in urban systems. The diversity of urban forests is added by the heterogeneous group of residents managing their own private plots of land according to diverse landscape preferences. These factors may cause significant variability in throughfall regulation by vegetation across the urban landscape.

Canopy cover and LAI are two most established measurable variables for describing vegetation characteristics in rainfall interception modeling. LAI has so far been preferred over canopy cover in urban studies of isolated tree crowns whereas stand-scale modeling conducted in rural forests has largely relied on canopy cover in predicting interception. Some researchers have reported difficulties in the accurate measurement of LAI owing to measurement techniques used. Heterogeneous canopy structure, common in urban systems, may present further issues for accurate LAI measurement. Thus, canopy cover or another measure of vegetation structure, e.g. vertical structural complexity, may prove to be more applicable to predicting urban rainfall interception at the stand-scale.

We conducted an experiment in the Beaverdam Creek watershed, a low-intensity residential area in Raleigh, North Carolina to understand the importance of urban vegetation - and the residents managing it - in the amount of throughfall reduced. In addition, we aimed at discovering the most influential vegetation variables explaining the process in the urban study area. We measured gross precipitation, throughfall, and vegetation characteristics in 16 residential yards with varying vegetation structure between late July and mid-November, 2010 and recorded an average total of 89.7 % of gross precipitation (466.9 mm) as throughfall from the 20 storms measured. The mixed, dominantly deciduous canopy coverage of 66.8 % was higher than that of most urban areas but characteristic of low-intensity residential areas that are abundant in rapidly expanding cities such as Raleigh. Assuming 2-0.5 % stemflow, we calculated rainfall interception and potential stormwater reductions due to this urban forest to be 8.3-9.8 % of gross precipitation.

Our results are in line with most previous stand-scale studies of urban forests that have found throughfall to account for 86.4-93.4 % of gross precipitation. However, throughfall reductions in the study area seem somewhat lower than those previously measured in rural forests in the subtropical climate zone with similar vegetation characteristics, i.e. throughfall of 77.1-90.0 %. More research is needed to verify whether the smaller throughfall reduction is characteristic of urban forests or a function of the higher within-stand heterogeneity that may increase the drip-line effect.

The performance of vegetation in reducing throughfall was greatly affected by the magnitude and frequency of storms. Gross precipitation i.e. storm magnitude alone explained 93.7 % of variability in throughfall (p=0.0001, RMSE=7.3033) and a canopy that was wet from a previous storm produced on average 1.1 mm more throughfall than a dry canopy. Regardless of the dominantly deciduous vegetation, seasonal changes in leaf area were not sufficient to significantly affect the amount of throughfall produced between the beginning and end of the study period. Most throughfall was produced during large summer storms characteristic of the climate zone.

We found that canopy cover and the percentage of coniferous trees were the most influential variables for throughfall regulation. A model including these variables in addition to gross precipitation, the shared influence of canopy cover and gross precipitation, and canopy dryness index explained 94.2 % of variability (p=0.0001, RMSE=6.9903). Thus, the addition of vegetation variables slightly improved the model explaining throughfall compared to a model including mere storm magnitude. Leaf area index (LAI), the vertical structural complexity (VSC) index, distance to or quantity of trees, the amount of evergreen trees or shrubs or coniferous shrubs were not found influential in estimating throughfall at the 0.05 significance level.

We discovered significant differences in vegetation structure and throughfall among the 16 yards studied. The range in throughfall between yards was 84.0-98.2 % in yards with 30.9-88.9 % canopy cover. Our results suggest that minimum canopy coverage of 80 % comprised of more than 40 % coniferous canopy coupled with significant evergreen shrub coverage may provide up to 16 % reductions in potential stormwater runoff at the yard-scale. As hypothesized, we also found significant differences between front and backyards with regard to vegetation structure and throughfall. Backyards presented 12.2 % higher canopy coverage, 10.7 % more coniferous canopy, and 3.5 % less throughfall compared to front yards. We suggest that the observed differences among and within yards were largely a function of residents' landscape preferences.

Low-intensity residential areas are the holder of significant forest resources in sprawling urban areas such as Raleigh. Our findings suggest that urban residents may be a significant contributor in the amount of stormwater produced in cities. Stormwater benefits may be obtained by targeted management decisions within residential lots. Tree cover especially at a close proximity to streets and streams may help reduce the negative impacts of stormwater runoff. One needs to bear in mind, however, that the benefits are lowest at large storm magnitudes and during storms occurring in leafless seasons.

Chapter 1: Literature Review on Rainfall Interception and Throughfall with a Focus on Urban Forests

Section 1: Introduction

1.1 Urbanization and Hydrology

The most deteriorating form of urbanization, i.e. the conversion from natural, vegetated surfaces to impervious cover, considerably affects our landscape and the existence of valuable ecosystem services. Impervious surfaces prevent rainfall from infiltrating the soil forcing the excess water to turn into stormwater runoff (Cappiella et al., 2005). Stormwater runoff has the potential to carry pollutants, including nutrients and metals, into streams (e.g. Cunningham et al., 2009) and eventually into larger water bodies used for recreation and drinking water. The increased flow of water into streams as 'stormwater peaks' causes bank erosion and flooding, altering sensitive stream habitat and potentially causing damage to properties (Weijters et al., 2009). Moreover, urban heat islands coupled with increased air pollution have been found to enhance the condensation of water vapor around cities, resulting in an increased number of rainy days (Heino, 1978; Kotola and Nurminen, 2003). The urban land use is expanding rapidly; 70 percent of the world's population is projected to live in cities by year 2050 (United Nations, 2010). Thus, landscape planners and stormwater managers are looking to the remaining urban forest for mitigation of these problems (Asadian and Weiler, 2009).

1.2 Benefits of Trees to Water Quality and Quantity

All vegetation is beneficial for the urban hydrological cycle when compared to impervious surface. However, several well known functions of trees make them fundamental in reducing negative stormwater impacts: the ability to store considerable amounts of rainfall in the tree canopy through rainfall interception, taking up and releasing water into the atmosphere through evapotranspiration, and enhancing the infiltration of water through the soil and storage of water in the soil and forest litter (Cappiella et al., 2005).

Trees improve water quality and reduce stormwater peaks by promoting infiltration, taking up soil water and nutrients. Pitt et al. (1986) found that forests produce 30- 50 % less runoff than grass and that even grass was significantly better than impervious surfaces. Runoff from forests has been found to contain significantly lower levels of nutrients than that from turf, fertilized or unfertilized (Bannerman et al., 1993; Garn, 2002; Gilbert, 2006).

Through these benefits to water quality and quantity, trees maintain valuable ecosystem functions at the scale of watersheds, i.e. land areas where all surface water and ground water drains to a certain water body or outlet (Cappiella et al., 2005). A study at Puget Sound, WA, found that watersheds with at least 65 percent forest cover typically had a healthy aquatic insect community (Booth, 2000). Goetz et al. (2003) found similar results in Montgomery County, MD, using IKONOS imagery to map forest and impervious cover in relation to stream health ratings.

Cities characterized by various types of impervious surfaces such as roofs, streets, and parking lots, often face increased stormwater treatment costs. The reductions in runoff volume by trees have been estimated to have a significant monetary value, as simulated by models based on stormwater treatment costs. The importance of the existing canopy coverage of Montgomery, AL, (34%) and Charlotte, NC, (49%) in reducing runoff was valued at US$ 454 million and US$ 797 million per 20-year construction cycle, respectively (American Forests, 2003; American Forests, 2004). Often the existing stormwater infrastructure is insufficient in processing all produced stormwater, further increasing the importance of this ‘green infrastructure’ in protecting water quality in urban areas.

1.3 The Process of Rainfall Interception

An important process by which forests provide stormwater benefits is called rainfall interception (e.g. Horton, 1919), that is, the part of rainfall that is intercepted by the tree canopy and evaporated directly back into the atmosphere (David et al., 2005). Rainfall interception, or interception loss, is traditionally derived from measurements of net precipitation, i.e. the portion of gross precipitation falling through gaps in the canopy as throughfall and stemflow (David et al., 2005).

Most studies have reported interception losses of 15 to 40 % per year in coniferous, and between 10 to 20 % in hardwoord forests (Crockford and Richardson 1990; Link et al., 2004; Llorens and Domingo, 2007), depending on climate and forest characteristics. Evergreen trees are capable of intercepting throughout the year compared to deciduous trees with leafless periods (Bryant et al., 2005; Xiao et al., 2000b). Climate and rainfall patterns play a major role in determining the importance of the process (Cappiella et al., 2005; David et al., 2005). McPherson et al. (2005) simulated the average annual interception of urban trees and arrived at 11.3 m^3 per tree in Bismarck, ND, compared to 1.4 m^3 in Glendale, AZ, where annual precipitation was less than 40 % of that of Bismarck (400 mm). These differences were among the most important factors affecting the total annual benefits from stormwater reduction in these cities, that is, US$ 496,227 in Bismarck and US$ 37,298 in Glendale.

The partitioning of rainfall into interception and net precipitation is well studied and great advances have been made in developing measurement techniques and models since the first studies conducted in the early 20th century by Horton (1919) among others. However, most studies have focused on rural forests while our understanding of the specific factors affecting the process in urban areas relies on simulated studies and more recently, research on individual tree crowns of few selected species (Asadian and Weiler, 2009; Xiao and McPherson, 2011; Xiao et al., 2000b). Urban forests differ in many ways from rural forests with regard to microclimate and tree architecture (Xiao et al., 1998, 2000b) and they hold a great potential in mitigating stormwater impacts by limiting the amount of throughfall generated.

Nevertheless, surprisingly little is known about how different species and their spatial arrangement affect runoff timing and volume at the scale of a single tree or a development parcel (Xiao et al., 2000a) and how this information could be used more efficiently in urban planning. There is a pressing need for more field observations and experimental measurements of the process of rainfall interception in urban areas (Asadian and Weiler, 2009).

1.4 Objectives

We intend to critically examine the research done on rainfall interception and throughfall in urban and rural areas, discussing the relevance of the latter to urban forests where appropriate. The most significant sources of variability affecting the spatial and temporal distribution of throughfall will be identified along with the main methods for measuring and modeling the variability.

Section 2: Rainfall Partitioning

2.1 Components of Rainfall

Gross precipitation is typically partitioned into throughfall, stemflow, and rainfall interception (Horton, 1919; Rutter et al., 1971) (Figure 1).

Throughfall is the portion of incident gross precipitation which penetrates or drips through a plant canopy (Levia and Frost, 2006). Two types of throughfall can be distinguished: the type that passes directly through the canopy without contacting any vegetative surface as *free throughfall* and the type that is initially intercepted and subsequently drips from the plant as *release throughfall* (Dunkerley, 2000). The latter is also commonly referred to as leaf drip (Xiao et al., 1998; 2000a). Throughfall is a major component in the interception process, accounting for approximately four-fifths of the incident gross precipitation for a wide range of species found within forests and other types of wooded ecosystems (eg. Carlyle-Moses et al., 2004; Lawson, 1967). As such, it is also one of the most important factors in estimating the importance of urban forests for water quality and quantity.

Stemflow is the portion of rainfall that flows down the branches and trunks of trees and shrubs (Levia and Frost, 2003). In spite of being a small component of net precipitation, stemflow can concentrate significant amounts of water and nutrients in the soil near the stem base (Eschner, 1967; Herwitz, 1982; Rutter, 1975).

Rainfall interception or interception loss is the portion of rainfall that never reaches the ground but is intercepted in the foliage and other plant surfaces until it evaporates (Levia and Frost, 2006). It is traditionally calculated as the difference between gross precipitation and net precipitation, i.e. throughfall and stemflow (David et al., 2005; Xiao et al., 1998). Another common term for describing rainfall interception is canopy storage capacity (Xiao et al., 2000b) which is commonly seen as a constant value characteristic of each species.

The accuracy of the interception calculation depends on the measurement accuracy of the previously mentioned components of rainfall (Xiao et al., 2000b). Thus, gross precipitation, throughfall, and stemflow need to be measured with precision to provide an accurate estimation of the actual interception loss (David et al., 2005).

2.2 Measurement Techniques

2.2.1 Gross Precipitation and Rainfall Characteristics

Gross precipitation is typically measured in a nearby clearing using funnels or rain gauges connected to a data logger or an automatic weather station (Valente et al., 1997). However, measurement of gross precipitation in forest clearings may be prone to errors due to the possible variability of rainfall in space, particularly during convective storms (David et al., 2005). David et al. (2005) recommend the measurement of gross precipitation above the forest canopy in the same location as the net precipitation measurements. However, measurements of rainfall above the canopy may also yield incorrect values as a result of air turbulence around the gauge (Valente et al., 1997). Thus, Roberts et al. (2004) suggest taking the measurements just above the canopy where the effects of wind may be smaller.

Apart from the magnitude of gross precipitation, the duration, intensity, and frequency of rainfall events play an important role in rainfall partitioning (David et al., 2005; 2006; Xiao et al. 2000a; Zeng et al., 2000). This information is commonly derived from measurements by a tipping-bucket rain gauge hooked to data logger with high temporal resolution (Valente et al., 1997).

2.2.2 Throughfall

Measurements of throughfall have been conducted in the field (e.g. Lloyd and Marques, 1988) and to a lesser extent in laboratory (Keim et al., 2006). Two main techniques in the field are *point measurements* and *area measurements* (Xiao et al., 1998). Point measurements are more commonly used (e.g. Bruijnzeel, 1990; Lloyd and Marques, 1988; Loescher et al., 2002; Valente et al., 1997) and are accomplished by using funnels or rain gauges directly beneath the canopy. The measurements are easy to perform, but are prone to measurement errors (Kimmins, 1973) due to the great spatial variability of throughfall. To overcome this issue, intensive sampling is typically needed using an array of funnel or trough gauges, placed randomly beneath the forest canopy (David et al., 2005). Splashing and the resulting overestimation of throughfall are commonly minimized by suspending the collector at some level above the ground surface (Levia and Frost, 2006).

Valente et al. (1997) recommend 20 to 30 funnel gauges to sample a forest plot of approximately 1,500 square meters, with 50 to 90 trees. In heterogeneous forests, such as tropical forests, the variability of throughfall is even greater, calling for particularly large number of samples (Bruijnzeel, 1990; Loescher et al., 2002). Even though some researchers have identified the number of gauges needed to sample throughfall under diverse vegetative cover, there is no standard protocol as to the number of gauges that must be used or the sampling technique utilized to get a representative sample of throughfall volume (Levia and Frost, 2006).

Furthermore, to obtain a better long-term statistical sample, David et al. (2005) recommend moving the gauges to new random positions after each reading. However, when rain gauges are repositioned, storm-to-storm variability in throughfall becomes harder to explain as canopy conditions no longer remain constant (Levia and Frost, 2006).

Area measurements (e.g. Calder and Rosier, 1976; Calder et al., 1986) using plastic sheets or troughs associated with tipping bucket or weighing type gauges average throughfall over a larger area, overcoming the issue of undercatch by capturing 100 percent of both throughfall and stemflow. However, possible problems include the adhesion of rainwater to the sheeting, splashing, and blockage of the collection gutter during large storms (Teklehaimanot et al., 1991) potentially causing large measurement errors. While overcoming the issue of sampling small-scale variability characteristic for point measurements, this method misses any information on the variation of net precipitation in space (David et al., 2005). Sheet gauges also tend to be problematic in the case of widely spaced trees (Ward and Robinson, 2000), forests with a dense understory, or in heterogeneous tropical forests (Roberts et al., 2004).

More recent methods include a system of polyvinyl chloride pipes hung beneath tree canopies for capturing throughfall by Asadian and Weiler (2009) and tablets placed under conventional throughfall collecting funnels that are weighed after rainfall by Dunkerley (2010).

2.2.3 Stemflow

Stemflow is usually measured directly from the stem surface using gutters sealed around the trunk leading to a collecting or measuring device (David et al., 2005). Like throughfall, stemflow is also very variable from tree to tree. Most studies have reported stemflow values ranging from 1 to 3 percent (Bryant, et al., 2005; Guevara-Escobar et al., 2007; Herbst et al., 2006). However, stemflow of up to 15 % of gross precipitation has been observed for an isolated evergreen oak tree during wintertime in an urban field site in California, characterized by Mediterranean climate with high winter precipitation (Xiao et al., 2000b). Thus, tree architecture plays a significant role in throughfall partitioning. Depending on climatic patterns, meteorological conditions, species composition, and tree architecture, stemflow can reach values as high as 20 % as found in evergreen broadleaved forests (Masukata et al., 1990) or even 45 % of gross precipitation in the case of Chihuahuan desert shrubs (Mauchamp and Janeau, 1993).

Some of the sampling problems characteristic of throughfall measurement apply to stemflow as well. However, these issues are typically perceived as negligible when measuring stemflow due to its minor role in the water balance of forests (e.g. Gash et al., 1995; Guevara-Escobar et al., 2007; Herbst et al., 2006; Hutjes et al., 1990; Lloyd et al., 1988; Valente et al., 1997).

Section 3: Variability in Throughfall

3.1. Spatial and Temporal Variability in Throughfall

The spatial distribution and timing of throughfall is extremely variable and depends on multiple factors related to climate and forest characteristics. A wide array of factors affect the quantity of throughfall, including species composition (Bouten et al., 1992; Bryant et al., 2005; Mahendrappa, 1989), meteorological conditions (Gómez et al., 2002; Huber and Iroumé, 2002), season (Herbst et al., 2006; Xiao et al., 1998), and canopy structure (Bouten et al., 1992; Crockford and Richardson, 2000; Xiao et al., 2000a; 2000b). Examining the sources of this variation is crucial for understanding the spatial distribution of throughfall and has not received enough attention in the scientific literature (Loescher et al., 2002).

3.2 Meteorological Factors

3.2.1 Climate

Studies of rainfall interception and throughfall have been conducted in various climates and ecoregions (Levia and Frost, 2006). Tropical regions (e.g. Dykes, 1997; Herwitz, 1987; Herwitz and Slye, 1992; Huber and Iroumé, 2001; Hutjes, 1990; Loescher et al., 2002) are characterized by larger amounts of throughfall compared to temperate (e.g. Goméz et al., 2002; Link et al., 2004; Llorens and Domingo, 2007; Price and Carlyle-Moses, 2003), semi-arid (e.g. Haworth and McPherson, 1995; Návar and Bryan, 1990), and boreal regions (e.g. Lankreijer et al., 1999). The differences are partly explained by the higher rainfall intensity and larger raindrop size which cause the canopy storage capacity to be reached sooner in tropical regions (Calder et al., 1986). Humidity, characteristically high in tropical and subtropical climates, also plays an important role in determining the rate of evaporation from the wet canopy during and after the storm (Gash, 1979). In addition, air temperature affects the rate of evaporation from canopies and can further increase interception losses in urban areas with generally higher temperatures (Asadian and Weiler, 2009).

3.2.2 Rainfall Patterns

Seasonal rainfall patterns and characteristics of a single rainfall event play an important role in the amount of throughfall produced. Rutter (1975) found that the largest evaporation losses occur in climates with a well-distributed rainfall pattern consisting of frequent, small storms rather than few large ones. Several studies of rainfall interception have highlighted the characteristics of rainfall events in explaining the partitioning of rainfall into net precipitation and rainfall interception (David et al., 2006; Gash, 1979; Xiao et al., 1998; 2000b). When the storage capacity of the canopy reaches its limit, throughfall begins (Rutter et al., 1971).

The duration and intensity of rainfall have been emphasized as the main meteorological factors affecting the process (David et al., 2005). However, many scientists have found that it is indeed the frequency of rewetting cycles that limits the total amount of rainfall intercepted and evaporated (David et al., 2006; Xiao et al. 2000a; Zeng et al., 2000). Thus, the canopy storage capacity is replenished if the foliage has time to dry in between storms, allowing more rainfall to be intercepted during the next storm. While some water is evaporated during the rainfall, most canopy drying takes place after the rain event (Link et al., 2004). Gash (1979) identified two major factors that control the evaporation of intercepted rainfall and based his analytical model of these findings: 1) the duration of canopy saturation during rainfall and the evaporation rate during this time, and; 2) the canopy saturation capacity (i.e. canopy storage capacity) and the number of times this storage is emptied by evaporation after the rainfall.

3.2.3 Wind Speed and Direction

The spatial variability of throughfall is increased during rainfall events with high wind speeds (David et al., 2005). Wind increases leaf-drip during and after the cessation of rainfall (Xiao et al., 1998; 2000a). David et al. (2006) found a distinct non-random distribution of ground-level rainfall characterized by larger amounts of rainwater upwind beneath the crown and rain-shadows downwind. The presence of wind may also increase the interception loss by enhancing evaporation from the canopy (Xiao et al., 2000b). The surface temperature of a wet tree crown is one of the factors affecting evaporation and it depends greatly on the available energy and wind speed. Pereira et al. (2009) found that isolated, saturated tree canopies behave as wet bulbs allowing the estimation of interception loss from a simple diffusion equation for water vapor.

The complex phenomena mentioned above affect the partitioning of rainfall into interception and net precipitation and the spatial and temporal variability of throughfall. To account for this variation, the effects of wind have been addressed in various ways in the models simulating rainfall interception (Muzylo et al., 2009). In their review of throughfall variability, Levia and Frost (2006) highlight wind speed and direction as some of the key areas where current knowledge remains weak.

3.3 Biological Factors

3.3.1 Canopy Cover and Leaf Area Index

Canopy cover and leaf area index (LAI) have been adapted as two of the most prominent indicators of ecological function in most forest-related research (Buckley et al., 1999). As a matter of fact, they also hold a special importance in interception modeling, judged by their appearance in most available models for estimating the process (Muzylo et al., 2009). Canopy cover is typically defined as the fraction of forest floor (or any surface) covered by the vertical projection of the tree crowns (Jennings et al., 1999). Leaf area index (LAI) is the ratio of one-sided leaf area to ground area (McPherson, 1998). The purpose of this section is to review the use of canopy cover and LAI in both urban and rural studies of rainfall interception.

A review by Muzylo et al. (2009) of rainfall interception models revealed that 7/15 of the reviewed models included canopy cover and 6/15 relied on LAI or other plant area indices. Three out of 15 models included both canopy cover and LAI. The two parameters seem to have been fairly equal in importance throughout the reviewed history of modeling. However, urban studies of rainfall interception seem to favor LAI (Xiao and McPherson, 2011; Xiao et al., 2000b). The popularity of LAI in the urban literature may relate to the strong focus on crown-level research. Canopy cover has been a more popular predictor of the process in the history of rainfall interception research, possibly owing to the lower costs from equipment relative to LAI and the possibilities offered by remote sensing.

Xiao et al. (2007) found that rainfall interception increased with tree canopy coverage and was further related to a reduction in annual stormwater runoff. Upon discovering that models developed for rural forests overestimated rainfall interception in sparse forests, Gash et al. (1995) and Valente et al. (1997) modified the models with an assumption that evaporation from the wet canopy decreases with canopy cover fraction. The modified Gash (Gash et al.,1995) and Rutter models (Valente et al., 1997) have been successfully used in various climate zones (Bryant et al., 2005; Germer et al., 2006; Lankreijer et al., 1999) characterized by sparse canopies.

When David et al. (2006) measured interception loss per crown-projected area for an isolated evergreen oak tree, the fraction of canopy cover was not found significant. This finding may partly explain the trend of favoring LAI in urban studies of open-grown trees. Several researchers have highlighted the importance of LAI in determining canopy storage capacity in both urban and rural areas (Keim et al., 2006; van Dijk and Bruijinzeel, 2001; Xiao et al, 1998; Xiao et al., 2000). Keim et al (2006) found that coniferous trees with higher leaf area retained more water per leaf area than those with lower LAI.

However, when studying the seasonal differences in a deciduous multi-species forest in Japan, Deguchi et al. (2006) found little variation in interception (14.3-17.6 %) even though LAI ranged significantly (1.65-4.31) during the study period. Bellot (1998) found a decreasing trend in throughfall generation of a Mediterranean holm oak forest as LAI increased but the correlation was not statistically significant. One explanation for the varying results may be the measurement technique used, as some of the most common instruments for measuring LAI have previously been found to underestimate the seasonal changes in vegetation (McPherson and Peper, 1998).

Canopy cover and LAI have been favored as input parameters for rainfall interception models historically. Nevertheless, both have yielded inconsistent results in past studies, leaving no general consensus among researchers as to which one of these indicators provides the best estimate of rainfall interception. Canopy cover may not perform as well when moving from stand-scale to the level individual tree crowns while the prediction power of LAI may be sensitive to the method of measurement.

3.3.2 Tree Architecture

Canopy cover and LAI alone do not explain the partitioning of gross precipitation into throughfall, stemflow, and rainfall interception or the spatial variability of throughfall. For a more thorough understanding of the process we must consider the specific architecture of each species. Tree architecture is composed of characteristics such as branching structure, canopy density, leaf texture and angle, and bark texture (Xiao et al., 2000a), and depends on the species and environmental factors.

Xiao et al. (2000a) noted that species with smooth bark surfaces and vertically oriented branches have greater rates of stemflow than species with rough bark and horizontally oriented branches. However, there is still no clear consensus as to where the largest volumes of throughfall occur in relation to the edge of the crown, i.e. drip-line (Levia and Frost, 2006); whether the canopy acts as an umbrella concentrating most of the of throughfall around the drip-line (Eschner, 1967; Shuttleworth, 1988; Stout and McMahon, 1961; Lloyd and Marques, 1988; Ward and Robinson, 2000), or as a funnel channeling the water near the stem (Herwitz, 1987; Ford and Deans, 1978). For example, in a *P. sitchensis* plantation, throughfall was concentrated near the tree trunk (Ford and Deans, 1978). In forest consisting of *Picea mariana* however, Carleton and Kavanagh (1990) found the largest throughfall inputs under the mid-portion of the crown, between the stem and drip-line. Beier et al. (1993) on the other hand found that the flux of throughfall water was higher away from the stems in a *P. abies* forest.

The above studies clearly show the great variation in throughfall distribution even within the same genus. The results may also be an outcome of the positioning of sampling points below the tree crown. Some studies have found a complete lack of relationship between throughfall and the distance from the stem (Carlyle-Moses et al., 2004; Návar and Bryan, 1990; Loustau et al., 1992).

Tree architecture not only varies among species but also according to tree spacing. That is, the phenotypes of the same tree species can differ significantly according to the availability and competition over light and other resources. This difference is especially noticeable when comparing two individuals of the same species growing in a forest and an open park. Isolated trees have been found to increase the spatial variability of throughfall by concentrating leafdrip to certain points in the ground (David et al., 2006; Gómez et al., 2002; Guevara-Escobar, 2007; King and Harrison, 1998). Likewise, prominent trees in forests (Herwitz and Slye, 1995) and especially forest edges (Darnhofer et al., 1989) tend to cause a clearly non-random distribution of throughfall around the canopy. Teklehaimanot et al. (1991) found an increase in interception loss when tree spacing increased. The authors attributed the increased evaporation to the differences in the boundary layer conductance among different spacing treatments.

3.3.3 Seasonal Changes

The spatial and temporal variability of throughfall is highly dependent on the seasonal changes in vegetation. Functional vegetation groups formed by evergreen and deciduous species have been found to affect the microclimate of a forest even more than LAI (Peters and McFadden, 2010). The seasonal changes in the amount of foliage also affect the process of rainfall interception though variation in canopy storage capacity. Many studies have reported interception losses of 20-40 percent in coniferous forests and between 10-20 percent in deciduous forests (Crockford and Richardson, 1990; Link et al., 2004; Llorens et al., 1997; Llorens and Domingo, 2007). This variation is partly explained by biological differences in species. For example, Barbour et al. (1980) established that coniferous forests typically have approximately 1.5 times higher LAI than deciduous forests.

The relative importance of rainfall interception across seasons is also dependent on climatic factors. In climates where most precipitation occurs during winter, evergreen trees can have a major importance in rainfall interception while deciduous trees can have a significant role in areas with summer precipitation (Xiao et al., 1998). Cantu-Silva and Gonzalez Rodriguez (2001) studied rainfall interception in different types of forest communities in northeastern Mexico and found highest interception losses in pine-oak forests (23 %) compared to pure pine (19 %) and oak (14 %) stands. A combination of different functional groups can thus result in higher percentages of rainfall interception in certain climates.

3.4 Factors Specific to Urban Areas

3.4.1 Rainfall Patterns and Microclimate

Urban and rural areas differ in several ways with regard to microclimate and forest structure.

The urban heat island effect (Arnfield, 2003) particularly in larger cities coupled with air pollution can cause more frequent rainfall (Heino, 1978; Kotola and Nurminen, 2003), further increasing the importance of rainfall interception. Moreover, the largest interception losses occur with frequent, low-intensity storms (David et al., 2006; Rutter, 1975; Xiao et al. 2000a; Zeng et al., 2000) that may be the most harmful for water quality in urban streams due to frequently washing off the pollutant-load accumulated on different surfaces (Xiao et al., 1998).

Large metropolitans are characterized by open-grown trees growing in parks and along streets. The microclimate around these trees can vary more rapidly due to the lack of other trees that stabilize the effects of extreme temperatures and wind (McPherson, 1998). These factors may affect evaporation and leafdrip, and expose trees to potential storm damage (Hauer et al., 1993; McPherson, 1998). On the other hand, Xiao et al. (2000b) found that the rain shadow caused by adjacent trees and heat storage inside the tree crowns did not influence interception and evaporation processes in two open-grown trees in urban areas (Xiao et al., 2000b).

3.4.2 Vegetation Structure

Urban forests are generally characterized by a much smaller percentage of canopy cover compared to rural forests (McPherson, 1998). Many studies conducted in rural forests have found that evaporation decreases in linear proportion to the decrease in canopy cover fraction (Gash et al., 1995; Valente et al., 1997), thus increasing throughfall. However, the assumption of lower canopy cover does not always hold true for cities. While large, densely built metropolitans might have a relatively low percentage of canopy cover formed by more street and park trees, cities with lower densities may harbor significant proportions of forest-like vegetation within the city structure. In the latter cases, the canopy cover of the urban ‘forest stand’, e.g. 49 % in Charlotte, NC (American Forests, 2003), may be comparable to that of a sparse rural forest, e.g. 45 % in a Maritime pine plantation forest in France (Gash et al., 1995).

Compared to rural forests, urban forests typically possess a much more diverse mix of species with varying phenological patterns (McPherson, 1998). The presence of a large number of species, both evergreen and deciduous, may allow for year-round rainfall interception compared to forests formed by fewer species. One source of the added diversity is the introduction of exotic ornamental species in public green areas and private yards and gardens.

Fewer trees per unit area decrease competition over light and other resources, allowing for a much larger tree size judged by DBH (diameter at breast height), canopy width, and other tree architectural parameters (McPherson, 1998; Nowak, 1996; Xiao et al, 2000a). Xiao and McPherson (2011) and Xiao et al. (2000b) studied three open-grown trees of different species growing in California and found rainfall interception rates between 14 and 27 % per tree. The main factor influencing the differences was the plant functional group; the highest interception losses (27 %) were associated with an evergreen oak (Xiao et al., 2000b) and lemon (Xiao and McPherson, 2011) while the lowest rates (14-15 %) were produced by a deciduous sweet gum (Xiao and McPherson, 2011) and pear (Xiao et al., 2000b).

Asadian and Weiler (2009) studied two coniferous trees growing in urban settings, a Douglas-fir and western red cedar, and found interception losses of 49 and 61 %, respectively. These values are significantly higher than those found in open-grown broadleaved trees by Xiao et al. (2000b) and Xiao and McPherson (2011). Coniferous forests typically have approximately a much higher LAI than broadleaved forests, most likely explaining these differences (Barbour et al., 1980).

3.4.3 Tree Condition

From an ecological point of view, urban forests are fundamentally different from natural rural forests in the sense that they encounter constant anthropogenic disturbances. These disturbances may affect the rate of interception, among other processes.

An extreme are street trees that are subject to by pollution, changes in water availability (e.g. Jim, 1998), soil compaction, mechanical damage, and diseases and pests (e.g. Nowak et al., 2001). These stress factors may decrease the vitality of urban trees, affecting canopy storage capacity. Asadian and Weiler (2009) found an urban open-grown Douglas-fir, growing close to a street (DBH = 68 cm, height = 39 m), to intercept less during all measured rain events compared to an individual (DBH 78 cm, height = 35 m) growing further away from the main street, close to a parking lot. Regardless of the variability in tree size, Asadian and Weiler (2009) explained the observed lower interception rates by the poorer condition of the street tree. However, poor health did not yield lower interception rates for all studied individuals across all events, suggesting that tree vitality may be hard to assess objectively.

3.4.4 People in the Forest

The main threat to ecological functions, such as rainfall interception, is the conversion of land surfaces to impervious cover (Wang et al., 2008). The realization of the benefits provided by vegetation in cities has raised interest among researchers towards the quiet managers of the resource: private residents (Byrne and Grewal, 2008; Larsen and Harlan, 2006).

Private residents may have a significant influence on urban forests through the vegetation growing in their yards. People's behavior is known to affect the quantity and quality of vegetation in private residential yards (Larsen and Harlan, 2006). Among other factors, behavior guided by landscape preferences that guide people to choose managed, green lawns over shrubby, shady forests in their front yards. In yards and private gardens, flowering, exotic species are typically valued over natural vegetation. Large trees may also be considered as a safety hazard in hurricane-prone regions and close to buildings and power lines, justifying their removal.

People's landscape preferences have been found to vary greatly with different demographic groups (Stamps, 1999) and people's backgrounds (Yu, 1994). Furthermore, in Phoenix, AZ, Larsen and Harlan (2006) noted that residents' socioeconomic status correlated with the way people managed the visible parts of their yard, perhaps indicating some pressure from neighbors. Backyards, on the other hand, were found to reflect people's individual fantasies and interests. Thus, backyards within the same neighborhood may harbor very different types of vegetation compared to front yards. These patterns may further affect the amount of throughfall produced in the residential urban forests. Throughfall variability in urban areas is a function of complex socioeconomic interactions that have barely been touched upon.

Section 4: Conclusions

Rainfall interception has the potential to significantly decrease the amount throughfall reaching the ground and becoming stormwater runoff. The process has received much attention in the literature but most studies have focused of rural forests with little attention given to the factors affecting rainfall interception and throughfall in urban areas.

Throughfall is a critical component of the hydrological cycle of urban areas and it is characterized by large temporal and spatial variability owing to meteorological and biological factors. The most important factors driving the generation of throughfall include meteorological factors, rainfall patterns, and vegetation characteristics including canopy cover, LAI, species, and canopy architecture. Both meteorological and biological drivers seem to be prone to increasing variability in urban areas (Kotola and Nurminen, 2003; McPherson, 1998; Nowak, 1996), calling for more research on the drivers of throughfall generation in urban forests.

One potentially significant reason for the high variability in urban forests is related to the heterogeneous group of residents managing a significant proportion of the urban canopy. This aspect is completely unexplored in the field of rainfall interception regardless of previous research that has found residents' landscape preferences to determine the vegetation structure in residential yards. Residents' behavior may have a significant effect on the structure of urban forests and the related capacity to regulate throughfall and potential stormwater runoff.

Past literature has shown no consensus on the most important drivers of throughfall variability (Levia and Frost, 2006; Loescher et al. 2002) and our understanding remains even more limited in urban areas. Examining the specific factors affecting the variability of throughfall in these settings is crucial for understanding the true value of urban vegetation in reducing stormwater damages.

Chapter 1 Figures:

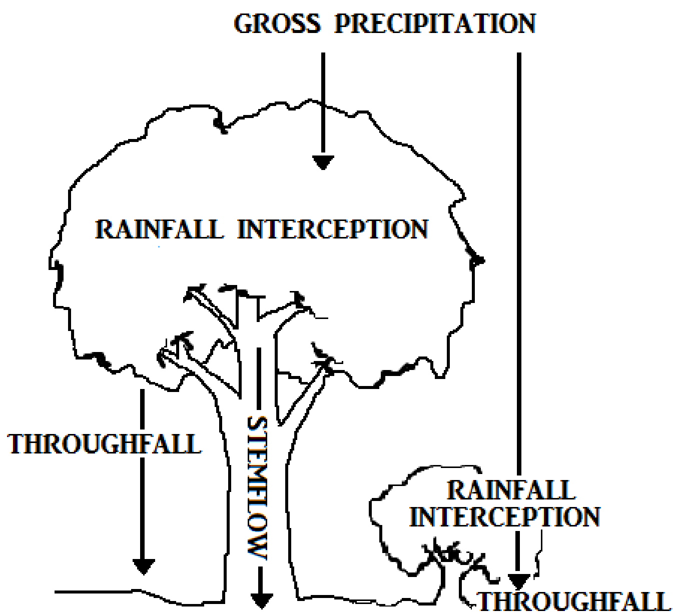

Figure 1. Partitioning of gross precipitation into throughfall, stemflow, and rainfall interception (modified from Levia and Frost, 2006).

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Chapter 2: Urban Residential Forests in Regulating Throughfall and Potential Stormwater Runoff – Case Study of Raleigh, NC.

1. Introduction

Stormwater runoff caused by impervious surfaces is the main cause of poor water quality, flooding, and deteriorating stream health in cities (Cappiella et al., 2005; Cunningham et al., 2009; Weijters et al., 2009). Urban forests have a great potential for reducing stormwater damages by regulating the amount of throughfall reaching the ground via rainfall interception (Asadian and Weiler, 2009; McPherson, 1998; Xiao et al., 1998, 2000b). Rainfall interception is the proportion of rainfall that is intercepted by plant surfaces and evaporated directly back into the atmosphere (David et al., 2005). Most studies have reported interception losses of 10 to 40 % of gross precipitation, depending on meteorological factors and the type of vegetation (Crockford and Richardson, 1990; Llorens et al., 1997; Llorens and Domingo, 2007; Link et al. 2004). Because of rainfall interception, throughfall is produced more gradually allowing more water to infiltrate the soil, reducing peaks in stormwater runoff (David et al., 2005; McPherson, 1998).

Regardless of the great potential in reducing the adverse impacts of stormwater runoff where it is most needed, rainfall interception has been largely overlooked in urban areas as most research has focused in rural forests. Urban forests differ in many ways from rural forests with regard to microclimate and tree architecture (Xiao et al., 1998, 2000b). In addition, the constant anthropogenic influence on urban forests presents higher probability of mechanical damage or stress caused by pollution, pests, and water availability (Asadian and Weiler, 2009; McPherson, 1998). Thus, a common perception in the field of environmental studies has been that urban forests may not fulfill the same functions as rural forests. More recently, however, it has been suggested that urban trees may in fact intercept higher amounts of rainfall compared to rural forests. Wider crowns and higher evaporation rates caused by wind and elevated temperatures have been found to produce lower throughfall magnitudes, producing up to 60 % less throughfall under individual tree crowns growing in urban areas (Asadian and Weiler, 2009; Xiao and McPherson, 2011; Xiao et al., 2000b).

The amount of rainfall intercepted depends on the characteristics of both rainfall and vegetation in an area. For instance, the intensity and duration of rainfall and the frequency of storms have been highlighted as the main factors determining the efficiency of this process (David et al., 2005; David et al., 2006; Gash, 1979; Xiao et al. 2000a; Zeng et al., 2000). Certain vegetative characteristics such as canopy storage capacity (i.e. the amount of water stored on foliage when the canopy is saturated) interact with rainfall patterns as well (Rutter et al., 1971). Storms below canopy storage capacity produce less throughfall than storms exceeding canopy storage capacity. Less throughfall is produced when the canopy has sufficiently time to dry in between storms (Gash, 1979).

The functional type of vegetation greatly influences canopy storage capacity and the amount of rainfall intercepted. Conifers have been found to have higher leaf area index (LAI) than deciduous trees (Barbour et al., 1980). Interception losses of 20-40 % have been reported in coniferous forests while 10-20 % have been found in broadleaved forests (Crockford and Richardson, 1990; Link et al., 2004; Llorens et al., 1997; Llorens and Domingo, 2007). Seasonal changes in canopies also affect the amount of throughfall reduced via rainfall interception. Evergreen trees are capable of intercepting for a larger part of the year than deciduous trees and are thus especially important in regions with winter precipitation (Xiao et al., 1998).

Several models have been developed for estimating rainfall interception (Muzylo et al., 2009). Most models include one or more vegetation variables, with the most common metrics being canopy cover and LAI. To date, canopy cover has been more popular in predicting rainfall interception probably due to being relatively easy to measure (Bryant et al., 2005; Gash, 1979; Gash et al., 1995). Some researchers however stress the importance of LAI in estimating canopy storage capacity and the variable has been preferred in urban areas for modeling rainfall interception of individual tree crowns (van Dijk and Bruijnzeel, 2001; Xiao et al., 2000b). LAI may be a better indicator of rainfall interception at the crown-level while issues may arise for measurements in heterogeneous canopies, typical in urban forests.

Another variable that may be influential in modeling throughfall in urban systems is the Shannon diversity index (Shannon, 1948; ref: McElhinny et al., 2005). Although the most popular use of this index has been to estimate species diversity in forests, it is similarly useful in quantifying the vertical structural complexity of vegetation. In fact, Calder (1996) found that more canopy layers allow more interception through the gradual wetting of the canopy.

Landscape heterogeneity, characteristic of urban systems, is largely a sum of the way people manage their individual, privately-owned plots of land. Residents manage their yards according to landscape preferences that are reflected in vegetation structure. These preferences have been suggested to depend on cultural norms (Stamps, 1999; Yu, 1994) and the type of neighborhood people live in (Nassauer et al., 2009). The perceived pressure from neighbors to conform to the style of the neighborhood may result in differences in vegetation structure between front yards and more concealed backyards (Larsen and Harlan, 2006; Nassauer et al., 2009). These factors need to be considered in studies of urban rainfall interception and throughfall in order to truly understand the factors affecting stormwater benefits provided by urban trees.

Our first goal was to quantify the amount of throughfall reduced by an urban residential forest managed by multiple residents. Secondly, we set out to determine the best descriptors of vegetation characteristics for estimating interception. Finally we aimed to evaluate whether individual resident’s landscape designs had an impact on the generation of throughfall. These results will help us understand the value of urban forests for throughfall regulation and the ways in which residents’ landscape choices affect the amount of throughfall produced. Our findings will inform future research on measuring and modeling rainfall interception and throughfall.

2. Materials and Methods

2.1 Study Area

The City of Raleigh, North Carolina, is one of the fastest growing regions in the USA; the population has grown by 46.3 % from year 2000 to 403,892 people in year 2010 (United States Census Bureau, 2011). The city has maintained a high tree cover of 55 % (Bigsby et al., unpublished data) owing to the gradual development from agricultural areas to low-intensity residential areas that allow the existence of forest-like vegetation in urban areas. The high canopy cover allows for significant amounts of rainfall interception, making Raleigh an ideal city for studying the potential stormwater benefits provided by urban forests.

According to Raleigh Department of City Planning (http://www.raleighnc.gov/cp), single-family residential areas accounted for 34.1 % of land surface in 2007, making it the single largest land use type – and a significant holder of the valuable urban forest resource in Raleigh. Development is also spreading rapidly in the region. As other sprawling cities, Raleigh will most likely experience a considerable growth in residential land use in the future. Thus, the relative importance of residents' landscape choices on stormwater regulation may increase in the future in Raleigh and other similar regions.

The experiment took place in the Beaverdam Creek residential watershed, located in Raleigh (latitude: N35° 48'22"; longitude W78° 40'17", Figure 1). The watershed of approximately 8 km^2 is characterized by relatively high canopy coverage, dispersed building pattern, and large lot size. The study area was chosen to represent a typical low-intensity residential area in the region. Being a watershed, it also provides insight on how residents may be contributing to the health of the local urban stream, the Beaverdam creek. The average elevation in the study area is below 80 m above sea level (USGS, 2009).

Forests in the residential watershed comprise a mix of deciduous oaks and pines with a characteristically dense understory of shrubs and vines. Exotic ornamental species are also common in the watershed.

The region is influenced by humid subtropical climate, thus belonging to the category ‘Cfa’ in the Köppen classification system (McKnight and Hess, 2000). The climate is characterized by moderate spring and fall temperatures, warm to hot summers, and mild winters. Average summertime temperatures range between 19-34 °C with highs around 38 °C (NOAA, 2011). Winter averages fall typically within 8-12 °C with lows commonly above or slightly below the freezing point.

Precipitation occurs throughout the year but large storms are especially common during the summer (NOAA, 2011). Between years 1981 and 2010, average annual precipitation was 1,096 mm and monthly averages ranged between 74 mm in April and 120 mm in July (Figure 2). The relative humidity is especially high between late summer and fall (Southeast Regional Climate Center, 2007). According to NOAA (2011) the average wintertime snowfall in Raleigh is 152 mm.

2.2 Experimental Design

We randomly picked residential yards with varying canopy cover and vegetation structure at close proximity to Beaverdam Creek (Figure 3). We approached residents in July 2010 and found sixteen yards for measuring gross precipitation and throughfall. Nine of the yards were owned by private residents and the remaining seven were rental properties, collaboratively managed by the landlord and tenants.

We laid a grid of 10 by 10 meters over each yard, resulting in a sampling density of one measuring point per 100 m^2. Each yard had 4 to 35 measuring points according to the size of the yard, with a total of 207 points. We used buckets of 19 liters in volume with a diameter of 0.29 m to measure throughfall and gross precipitation for the 207 measuring points. We stabilized the buckets with metal stakes to decrease the probability of buckets getting knocked over. However, occasionally buckets were knocked over by wind, animals, people, and the flooding of a stream. Miscommunication between tenants and the landlord led to the removal of 28 measuring points located in six different yards on October 22, 2010. These yards (5, 7, 8, 13, 14 and 15; Figure 3) were located in one neighborhood with relatively low canopy cover. We also respected homeowners' wishes when setting up the study by excluding driveways and other frequently used areas close to buildings from the effective study area.

2.3 Measurements and Calculations

2.3.1 Components of Rainfall

We measured throughfall and gross precipitation for twenty storms recorded between July 28 and November 17, 2010. We conducted the measurements on the day following the storm. Thus, the date of the storm refers to the date when data was collected, regardless of when the storm started.

We measured the volume of throughfall using a 2-liter container allowing for measurement accuracy of approximately 0.2 mm. The actual measurement accuracy of field measurements depends on multiple factors, including potential bias caused by high winds, animals occasionally knocking over buckets, or evaporation of water from the buckets. Because the climate in Raleigh is characterized by high humidity, especially during the nighttime, it is unlikely that there were significant evaporation losses before we took our measurements (Appendix A: Figure 1).

We identified six control measuring points under open sky for collecting gross precipitation in yards 2, 3, 6, 9, 12, and 16 (Appendix B: Table 1). The strong correlation (r^2=0.997) among measurements from control points indicated little bias caused by adjacent trees and buildings in the yards or the ~ 750 m distance between the northern and southern groupings of yards (Figure 3; Appendix B: Figure 1). Thus, data collected in these yards were applicable to forested yards, lacking open areas, in the same neighborhood.

We assumed stemflow of 0.5 to 2 % of gross precipitation based on the work by Bryant et al.

(2005) in rural forests of similar plant communities, located in the southeastern US. Guevara-Escobar et al (2006) found 2 % stemflow under an isolated urban *Ficus* tree and Xiao et al. (1998) simulated stemflow of 0.6 % for deciduous urban forests in California, agreeing well with our estimates.

We calculated rainfall interception from a simple mass balance equation often used to describe rainfall partitioning (Crockford and Richardson, 2000; Horton, 1919; Xiao et al., 2000b):

$$I = P - TH - ST \qquad (1)$$

I is rainfall interception, P, TH, and ST stand for gross precipitation, throughfall, and stemflow, respectively.

2.3.2 Canopy Cover

For each yard, we measured canopy cover on two occasions to account for the seasonal changes in vegetation. Measurements were taken between October 1 and October 4, 2010 and again between December 2 and December 17, 2010. We used a Spherical Densiometer (Lemmon, 1956) for measuring canopy cover.

2.3.3 Leaf Area Index

For each yard, we measured photosynthetically active radiation (PAR) for calculating LAI by using a Sunfleck PAR Ceptometer (Decagon Pullman, WA) on three occasions throughout the study period: between August 27 and September 1, 2010; between October 18 and October 29, 2010; and on November 28, 2010.

We measured PAR below (Q_i) and above (Q_0) the canopy under clear skies. Measurements were carried out between 11:00 and 15:00 to avoid errors caused by tall trees blocking the radiation which may happen when the zenith angle of the sun departs greatly from 0°

(directly overhead). We took the above canopy readings in a football field within a distance of 700 meters from each measuring point and repeated them at least twice in a period of three hours. We obtained the actual LAI values from the following equation:

$$LAI = - \ln (Q_i/Q_o)k^{-1} \tag{2}$$

The light-extinction coefficient (k) can be calculated from the following equation when leaf angle distribution is assumed to be spherical:

$$k = 1/ (2 \cos \theta) \tag{3}$$

The zenith angle of the sun θ is calculated from:

$$\theta = \arccos (\sin L \sin D + \cos L \cos D \cos 0.2618(t-t_o)) \tag{4}$$

L is latitude, D is the solar declination, t is the time (hours), and t_o is the time of solar noon. The constant 0.2618 converts hours to radians.

The Beer-Lambert law assumes that foliage is randomly distributed in space and that there is a spherical distribution among leaf inclination angles (Jarvis and Leverenz, 1983). Violations of this assumption may yield underestimations of LAI caused by bias from direct sunlight penetrating the canopy. The uneven canopy cover, characteristic of urban forests, thus complicates the measurement of LAI at the level of a measuring point. We took several measurements above the opening of each bucket and each yard included at least four measuring points. Thus, the averaged values within and across yards should provide reliable estimates of LAI.

We further increased the temporal resolution of the measured PAR data with data from Lake Wheeler Road weather station (Latitude: 35.72816; Longitude: -78.67981, 10,000 m south from the northernmost measuring point) after assuring the comparability of the two datasets via regression analyses. We created a regression plot of the weather station data and our own above canopy measurements from the same time interval and used the curve obtained from the regression plot to interpolate Q_0 for each measurement of Q_i.

2.3.4 Vertical Structural Complexity

We measured vertical structural complexity (VSC) twice during the study to evaluate the vertical arrangement and layering of shrubs and trees above each of our measuring points. First measurements were taken between September 24 and October 7 and second measurements between December 9 and December 19. We visualized a rectangle of 27 m^3 (3*3*3 m) around each bucket and estimated the fraction of vegetation (C) within this 'box'. The assessment was repeated vertically throughout the canopy.

The measurements were repeated towards the end of the study period to account for seasonal shifts in leaf area or changes induces by natural thinning of plants, storm damages, mechanical damages, or pruning. Minor changes in vegetation structure may not be detectable via visual estimation which becomes more challenging in dense forests consisting of multiple canopy layers. To decrease bias caused by subjective observations, it is essential that one person conducts the measurements each time.

We calculated the vertical structural complexity index (VSC) using the Shannon-Weiner equation (Shannon, 1948; ref: McElhinny et al, 2005):

$$VSC = \sum_{i=1}^{n} \left(\frac{1}{C_i} \Big/ \ln\left(\frac{1}{C_i}\right) \right) \tag{5}$$

2.3.5 Other Vegetation Parameters

We also measured the quantity, distance and direction of trees, shrub masses, and nearest buildings from the measuring point. These variables were measured within a plot of six meters in radius (~113 m^2). When no trees or shrubs were growing within the plot, we measured the nearest tree or shrub outside the plot. In addition, we estimated the percentage cover of evergreen, deciduous, coniferous, and broadleaved tree and shrub cover within the plot around each measuring point. We considered trees with a shrubby appearance as shrubs when they had a lower diameter at breast height (DBH) than 2.5 cm or more than six stems.

2.3.6 Statistical Analyses

We used SAS 9.1 (SAS® 9.1 Software) and JMP 8 (JMP® 8 Software) for calculating descriptive statistics and restricted maximum likelihood (REML) correlations, for performing ANOVA tests, for selecting a linear regression model including influential variables, and for visualizing the results.

Storms were classified into those with 24 or more rainless hours preceding the time of measurement (dry canopy) and those with less than 24 hours (wet canopy). We created a dummy variable, the dryness index, to test for the importance of the initial dryness of the canopy on throughfall.

To assess the seasonal changes in vegetation and throughfall, we divided the data into storms during leaf-on and leaf-off periods. The threshold for the leaf-off period was set to November 7 when the first temperatures below freezing-point occurred (NOAA, 2011).

Variables influencing throughfall were selected for a linear model by using the forward stepwise selection method at $\alpha = 0.05$. We adopted Mallow's Cp, adjusted R-squared, and root mean square error (RMSE) as the main selection criteria for selecting influential variables.

We conducted ANOVA analyses to test for across and within yard variability in throughfall. Tukey's Studentized Range (HSD) tests (α=0.05) were used to test for significant differences among yards. Pooled T-tests were used to test for significant differences between front and backyards.

3. Results

3.1 Throughfall Regulation

The 20 measured storms between July 28 and November 17, 2010, delivered 466.9 mm of gross precipitation to the study area (Appendix A: Table 1). Storm magnitude ranged from 0.7 mm (StdErr=0.02) on August 23 to 98.3 mm (StdErr=0.12) on September 30. Eighty percent of measured gross precipitation occurred between late July and late September, agreeing well with the long time precipitation averages in Raleigh (Figure 2). No snow was recorded during the study period.

Throughfall accounted for 418.9 mm or 89.7 % (StdErr=0.005) of gross precipitation. Assuming stemflow from 0.5 to 2 %, estimated rainfall interception was 9.8 to 8.3 % (Appendix A: Table 1). Thus, 8.3-9.8 % less throughfall was produced owing to the urban vegetation in the study area.

3.2 Vegetation Characteristics

Table 1 summarizes average vegetation characteristics at the study site. Average canopy cover in the study site yards was 66.8 % (StdErr=0.543) which can be considered very high for urban areas. However, as buildings and driveways were excluded from the efficient study area, the resulting canopy coverage should be considered as an estimate of the canopy-level coverage of a low-intensity residential area.

Average LAI during the study period was 2.0 (StdErr=0.025). Average vertical structural complexity index was 34.6 (StdErr=0.451) and an average of 6 (StdErr=0.100) trees were found on a plot of 113m^2. The mean percentages of coniferous and evergreen trees were 22.5 % (StdErr=0.615) and 27.8 % (StdErr=0.678), respectively. The shrub canopy comprised of 99.3 % (StdErr=0.096) broadleaved shrubs, 49.9 % (StdErr=0.690) of which were evergreen.

We observed some seasonal variability in vegetation between the leaf-on (July 28-November

5) and leaf-off (November 7-17) periods although the differences remained relatively small (Appendix D: Table 1). Average canopy coverage in the study site during leaf-on and leaf-off was 68.5 % (StdErr=0.580) and 54.9 % (StdErr=1.395), respectively. LAI ranged on average from 2.1 (StdErr=0.027) during leaf-on to 1.1 (Stderr=0.035) during leaf-off. The vertical structural complexity of vegetation increased towards the end of the study period, from 33.8 (StdErr=0.470) to 40.4 (StdErr=1.490). No significant changes in throughfall were observed due to relatively small changes in vegetation.

3.3 Variables Explaining Throughfall

Canopy cover had the strongest correlation with the percentage of throughfall of gross precipitation (R^2=-0.32), followed by VSC index (R^2=-0.24), the percentage of coniferous (R^2=-0.20) and evergreen (R^2=-0.19) trees, and LAI (R^2=-0.16) (Appendix C: Table 1). The remaining variables, i.e. the percentage of evergreen and coniferous shrubs, the distance to trees and buildings, and the number of trees had either a negligible or no influence on the amount of throughfall generated.

We generated a linear empirical model including the most influential parameters for estimating throughfall:

$$TH = 4.47 + 0.93P - 0.05CC - 0.002\,((P-25.52)\,(CC-66.85)) - 0.01CON - 1.12DRY \qquad (6)$$

TH refers to throughfall, *P* stands for gross precipitation, *CC* and *CON* refer to the percentages of canopy cover and coniferous trees, respectively, and *DRY* is an index controlling for the initial canopy wetness before storm. VSC index (p=0.0653), leaf area index (p=0.7014), the percentage of evergreen trees (p=0.9052) were not influential at the 0.05 significance level.

The linear model confirmed that gross precipitation (p<.0000) accounted for most variability in throughfall. In addition, the estimate of 0.93 for gross precipitation indicates that a significant proportion of rainfall was reduced by vegetation. All vegetation variables had a negative relationship with throughfall, as could be expected. Every additional percentage unit of canopy cover ($p<.0001$) decreased throughfall by 0.05 mm and every unit of coniferous trees ($p=0.0305$) decreased a further 0.01 mm. The shared influence of canopy cover and gross precipitation ($p<.0001$) was smaller, - 0.002 mm.

The canopy dryness index ($p=0.0001$) greatly affected throughfall as 1.1 mm less throughfall was produced when the storm was preceded by one or more rainless days (Appendix A: Table 1). In other words, a wet canopy produced 1.1 mm more throughfall than a dry one. A sensitivity analysis of the model revealed that at small storm magnitudes the model was especially sensitive to changes in the initial dryness of the canopy.

Figure 4 shows the actual vs. predicted throughfall using the described model. The empirical model explained 94 % of the variability in throughfall ($R^2=0.9419$, $p=0.0001$, RMSE=6.9903). The addition of vegetation variables increased the explained variability and decreased the RMSE albeit the improvement was relatively low compared to storm magnitude alone ($R^2=0.9366$, $p=0.0001$, RMSE=7.3033).

As seen in Figure 4, residuals show an increasing trend towards larger values indicating heteroscedasticity i.e. uneven variabilities among different storm magnitudes. Thereby, the variability in throughfall increases as storm magnitude increases.

3.4 Throughfall Regulation at Yard-level

The 16 yards presented significant variability in vegetation characteristics. Average canopy cover at yard-level had a great variability from 30.9 % (Yard 16, StdErr=3.029) to 88.9 % (Yard 10, StdErr=0.557) (Table 1). LAI varied from 1.1 (Yard 6, StdErr=0.102, yard 9, StdErr=0.107, yard 16, StdErr=0.091) to 3.2 (Yard 1, StdErr=0.070). The highest vertical structural complexity was found in yard 4 with the score 52.2 (StdErr=1.218) and lowest complexity occurred once again in yard 16, with the score 12.5 (StdErr=0.776). The largest amount of coniferous and evergreen tree cover was found in yards 1, 4, and 10 with 43 % (StdErr=1.552), 44.2 % (StdErr=1.594), and 50.8 % (StdErr=1.704) coniferous trees, and

45.0 % (StdErr=1.622), 50.8 % (StdErr=1.669), and 60.4 % (StdErr=1.987) evergreen trees, respectively.

Significant differences were observed among the average percentage of throughfall generated in yards (ANOVA, $\alpha = 0.05$). The range in throughfall between yards was 84.0 % to 98.2 % of gross precipitation with lowest and highest values found in yards 4 and 7, with 80.2 % and 63.0 % canopy cover, respectively.

As hypothesized, significant differences in throughfall and vegetation characteristics were also found between front and backyards (ANOVA; $\alpha = 0.05$; Figure 5). Lower percent canopy cover (-12.2 %) and leaf area index (-0.8) were measured in front yards compared to backyards. The amounts of evergreen trees (-10.7 %) and coniferous trees (-10.7 %) were also lower in front yards compared to backyards. Finally, the percentage of throughfall was found to be 3.1 % higher in front yards compared to backyards.

4. Discussion

4.1 Throughfall Regulation by Urban Forests

4.1.1 Rainfall Partitioning

Our first goal was to find out how much throughfall was reduced by the urban forest located in a residential area in Raleigh between late summer and early winter. On average, throughfall was found to account for 89.7 % of gross precipitation. In other words, the primarily deciduous broadleaved urban forest with an average canopy cover of 66.8 % reduced throughfall by 8.3-9.8 % via rainfall interception, assuming 2-0.5 % stemflow.

4.1.2 Comparisons among Urban Forests

Previous urban studies have reported throughfall percentages ranging between 38.1-93.4 %

of gross precipitation (Table 2). The wide range of throughfall values is mostly explained by the different scales of these studies as some researchers have focused on individual trees (crown-level) whereas others have considered the entire canopy (stand-level). The direct comparison between results obtained at crown-level and stand-level would be faulty as the proportion of direct throughfall is naturally much lower when limiting the area of interest under the drip-line of a single tree crown as opposed to the level of the entire canopy. Thus we will compare our findings with other stand-scale studies conducted in urban areas.

In the Mediterranean climate of Sacramento, CA, Xiao et al. (1998) found throughfall percentages between 86.4 and 93.4 % of gross precipitation, comparing well with our findings of 89.7 %. Xiao et al. (1998) noted that less throughfall (86.4 %) was generated in the 'suburban sector' dominated by broadleaved evergreen trees compared to the 'city sector' dominated by broadleaved deciduous trees (93.3 %). Apart from maintaining foliage throughout the rainy winter seasons, evergreen trees also tend to have higher LAI than do deciduous trees (Xiao et al., 1998). Thus, the differences between the two land use sectors were related to dominant vegetation types and the seasonal rainfall patterns characteristic of the region. In our study, the role of evergreen trees in the amount of rainfall intercepted was not significant, possibly due to the shorter duration of our study, showing little seasonal variability in the foliage. We believe that a study extending across seasons might reveal the differences between evergreen and deciduous trees in regulating throughfall.

Wang et al. (2008, Table 2) found that rainfall interception accounted for 18.4 % of gross precipitation, resulting in net precipitation, i.e. throughfall and stemflow, of 81.6 % (Table 2). These results were simulated using the model UFORE-Hydro (currently iTree-Hydro) in an urban watershed dominated by deciduous vegetation (22 % of watershed), located in the humid subtropical climate. Our study site in similar climate had higher net precipitation of 90.2-91.7 % (assuming stemflow of 0.5-2 %) regardless of the considerably higher canopy cover of 66.8 % (StdErr=0.543). It should be noted however that our measurements of canopy coverage were done at the canopy-level in the field whereas Wang et al. (2008) estimated theirs from land cover data. As such, the unexpected similarities in net precipitation may reflect differences in measurement techniques. In addition, simulations produced by models such as UFORE-Hydro may not be equivalent to actual observations.

4.1.3 Urban vs. Rural Forests

Comparing our findings with rural forests within the same humid subtropical climate zone helps us understand the relative importance of urban forests in reducing throughfall. Thereby, similar vegetation structure, assessed through canopy cover, functional groups, and LAI among other variables, should yield similar throughfall percentages. Regardless of having relatively high canopy cover of 66.8 %, the urban residential forest in this study produced 7.7 % more throughfall than a broadleaved deciduous rural forest (TH = 82.0 %) in the same climate zone with lower canopy cover of 52 % (Bryant et al., 2005; Table 2).

For more detailed comparisons with rural forests with regard to vegetation structure, we will focus on subpopulations i.e. yards with similar canopy cover and functional vegetation groups. Yard 2 with 53.7 % (StdErr=0.523) of primarily deciduous canopy cover produced 93.3 % of throughfall which is 11.3 % more than the similar deciduous rural forest (Bryant et al., 2005). Bryant et al. (2005) found a rural mixed stand with canopy cover of 74 % to produce 80.9 % of throughfall. Yard 13 with similar vegetation structure produced 88.1 % of throughfall, that is, 7.2 % more throughfall than the mixed rural forest. These results suggest that urban forests may produce more throughfall compared to rural forests but the differences seem relatively small according to our results.

In a study of a rural deciduous broadleaved forest in Japan, Deguchi et al. (2006) measured 77.1 % of throughfall (Table 2). LAI was reported to be 3.1 during the study period, thus higher than the average of 2.0 (StdErr=0.025) found at our urban study site. Yard 14 with LAI of 2.1 (StdErr=0.196) consisting predominantly of deciduous vegetation produced 89.2 % of throughfall. Yard 8 with relatively low evergreen cover and LAI of 2.8 (StdErr=0.209) produced 98.1 % which is considerably higher than that of the rural forest (Deguchi et al., 2006). Considering the lower LAI in the urban forest stands, however, it is difficult to determine whether the observed differences in throughfall are actual differences or caused by differences in vegetation structure. The relatively small number of measuring points located in yards 8 and 14 and the heterogeneous vegetation structure in these yards should also be considered in these comparisons. The high variability in vegetation cover and characteristics of urban forests (McPherson, 1998) complicates comparisons with rural stands that characteristically possess more even vegetation structure.

4.2 Factors Controlling the Performance of Vegetation

We found some seasonal changes in vegetation structure but the changes were relatively small due to the restricted study period from late July to mid-November, 2010. The average percentage of throughfall from gross precipitation decreased moderately towards the end of the study. We believe this effect to be the cause of seasonal rainfall patterns and meteorological conditions that may obscure changes caused by decreasing leaf area. Falls and winters in the study area are characterized by smaller storms that occur generally at longer intervals compared to larger storms coupled with higher relative humidity during summers (Appendix A: Figure 1; Table 1). These seasonal changes greatly affect the initial wetness of the canopy and the rate of evaporation from the wet canopy (Gash, 1979; Rutter et al., 1971), and consequently, the total percentage of throughfall of gross precipitation.

The strong linear relationship found between gross precipitation and throughfall shows that the amount of throughfall produced depends profoundly on storm magnitude. Thus, the performance of vegetation in reducing throughfall is determined by the magnitude of the incident storm. It is a well-known fact that storms below canopy storage capacity (S) produce less throughfall than storms above S (Gash, 1979; Rutter et al., 1971; Xiao et al., 2000b).

The frequency of re-wetting cycles has been highlighted as the most important factor determining the amount of rainfall intercepted (David et al., 2006; Zeng et al., 2000) due to affecting the initial wetness of the canopy. Indeed, we also found that the initial wetness of the canopy, determined by the time passed from the previous storm, was one of the most influential predictors of throughfall generation ($p=0.0001$). Specifically, a dry canopy in the beginning of a storm produced on average 1.1 mm less throughfall compared to a wet canopy.

4.3 Influential Vegetation Variables

We aimed to establish the most influential vegetation variables affecting the generation of throughfall in the urban residential yards of various levels of canopy cover and different vegetation types. Our results indicate that canopy cover is the single most important vegetation variable in explaining the percentage of throughfall of gross precipitation and was therefore included in the linear model estimating throughfall ($p<.0001$). However, the influence was moderate as every additional unit of canopy cover (range 0-100 %) decreased throughfall by 0.05 mm.

The percentage of coniferous trees was selected for the linear model ($p=0.0305$) whereas the percentage of evergreen trees was not found influential in predicting throughfall ($\alpha=0.05$). We believe that the relatively short study period may have obscured the seasonal changes one expects to see in dominantly deciduous vegetation, thus downplaying the importance of evergreen vegetation in predicting throughfall at wintertime.

Vertical structural complexity index had the second highest correlation with the percentage of throughfall of gross precipitation but nor VSC ($p=0.0653$) or leaf area index ($p=0.7014$) were found influential in this study according to our regression analyses. The remaining variables, i.e. the percentage of evergreen and coniferous shrubs, the distance to trees and buildings, and the number of trees had either a negligible or no influence on the amount of throughfall generated.

Our results indicated that canopy cover is a more influential variable in predicting throughfall than LAI. Canopy cover may be a more robust predictor compared to LAI whose accurate measurement is especially challenging in urban forests with high within-stand heterogeneity. The successful use of LAI in studies of isolated urban trees (Xiao and McPherson, 2011;

Xiao et al., 2000b) suggests that LAI may provide a better estimate of throughfall production at the crown-level compared to stand-level studies. Some previous studies in rural forests have also found that significant changes in LAI did not result in expected changes in throughfall proportion (Bellot, 1998; Deguchi et al., 2006) agreeing with our findings.

We tested the performance of VSC index for estimating throughfall in this study. Even though the VSC index was not selected for the model, we found that the variable had a stronger correlation with the percentage of throughfall than LAI, a previously established variable for predicting throughfall. This is an interesting finding and should be further researched in order to determine whether VSC may even explain more variability in throughfall at the stand-scale than LAI. In addition, vertical structural complexity was the only vegetation characteristic found to increase towards the end of the study period, possibly indicating that the distribution of canopy layers became more even as leaf area decreased. Such characteristics of the canopy are not explained by any other variable previously used in studies of rainfall interception or throughfall.

Measurements based on visual estimation are prone to subjectivity that potentially causes bias in the results. The uncertainty is greatly emphasized if the person collecting data lacks experience of the method, possibly yielding inconsistent measurements for the same measuring point. In the worst case, measurements obtained from the same location at different points in time may not reflect actual changes in vegetation structure. To overcome this issue, measurements should always be taken from the same direction in relation to the measuring point and recorded each time by the same person. According to our experience, the visual estimation of VSC became more challenging in dense forests where it is difficult to obtain a full view of the vertical arrangement of branches. Thus, this method may be more successful in sparse forests such as managed urban parks.

4.4 Landscape Preferences and Throughfall

Our final goal was to evaluate the significance of people’s landscape choices in determining the amount of throughfall, i.e. potential stormwater runoff, produced in the study area. The 16 yards representing low-intensity residential areas in Raleigh differed significantly with regard to canopy cover, LAI, the quantity of trees, and the percentage of coniferous and evergreen trees. Differences were also found between front and backyards as more remote backyards typically had higher canopy cover and LAI, and a higher proportion of evergreen and coniferous trees. The differences in vegetation structure between front and backyards resulted in moderate reductions (3.1 %) in throughfall in backyards.

Landscape preferences have been suggested as the main driver of vegetation structure in residential areas (Larsen and Harlan, 2006). These preferences have been found to guide the management choices between front and backyards. In this study, front yards facing the street were typically kept relatively open with few, often planted, trees and shrubs, and managed lawn. The preferred design for front yards may reflect the type of neighborhood in question. Front yards in a neighborhood tend to resemble one other and departing from common standards may be perceived negatively by neighbors (Nassauer et al., 2009; Zmyslony and Gagnon, 2000). In hurricane-prone regions such as Raleigh, open yards may also be preferred to protect houses from storm damages caused by falling trees.

The more remote backyards often consisted of more forest-like plant assemblages, mixed with planted exotic species. Management of backyards has been found to reflect people's personal preferences to a greater extent than front yards do (Larsen and Harlan, 2006). One home-owner mentioned removing unwanted shrub cover by the adjacent, sloped stream bank because the vegetation was considered to look unattractive and to complicate walking across the site. These factors may have considerable local effects on the potential of vegetation in reducing throughfall. Although we did not collect qualitative data on landscape preferences we were able to show that there were significant differences between front and back yard landscaping patterns, reflecting the quantity of throughfall.

4.5 Management Strategies for Regulating Throughfall

An actual example of successful vegetation structure for regulating throughfall is provided by yards 4 and 10. The specific vegetation characteristics in these yards include canopy cover of 80.2 % and 86.2 %, respectively. Of this, 50.8 %, and 60.4 % were formed by evergreen canopy, with a contribution of 44.2 % and 50.8 % from coniferous trees, respectively. Relatively high LAI values of 2.2 and 2.3 were measured in these yards. High vertical structural complexity was found in the canopy, described by the indices of 52.2 and 41.6 for yards 4 and 10. In addition, 48.0-59.8 % of evergreen shrub cover was recorded in yards 4 and 10, further increasing the structural complexity of vegetation. These yards produced 84.0 and 85.2 % of throughfall, compared to the average of 89.7 % in the whole study area.

Based on a linear model developed in this study a typical fall storm of 9 mm (average of October-November, 2010), falling on initially dry canopy coverage of 67 % with 23 % coniferous tree cover (study area average), would bring 7 mm of throughfall i.e. 81 % of gross precipitation. Increasing forest cover to 85 % (+18 %) and the share of coniferous trees to 50 % (+22%) would produce 74 % of throughfall, that is, 7 % less than the urban forest currently in the study area. A considerably larger storm of 55 mm would produce 91 % of throughfall under the current conditions and 88 % in the alternative, more forested scenario, reducing throughfall by 3.5 %. Thus, at the landscape-level, increasing forest cover and the amount of coniferous trees would offer moderate additional reductions in throughfall. The benefits will be smaller during large storms that are common in Raleigh especially during the summer.

Increasing throughfall regulation by urban residential forests may offer a valuable reduction in stormwater runoff in urban areas. Urban residents may contribute by enhancing beneficial forest characteristics for throughfall regulation i.e. canopy cover and the amount of coniferous trees in their own yards. People who prefer open front yards may leave forest-like vegetation in more remote sections of backyards. The reductions can be further enhanced by promoting multiple canopy layers of preferably evergreen shrub cover beneath the tree canopy. Targeted stormwater management may be gained by promoting intercepting vegetation especially over impervious surfaces, where most stormwater runoff is generated, and close to streams where the damages caused by stormwater runoff are the most severe.

Chapter 2 Tables and Figures:

Table 1. Average vegetation characteristics and the percentage of throughfall (TH) of gross precipitation across study period by yard.

Yard ([a])	**LAI**	**VSC**	**# Trees**	**Conifer trees**	**Conifer shrubs**	**Evergreen trees**	**Evergreen shrubs**	**Canopy cover**	**TH, %[b]**
				Percentage					
1 (22)	3.2	44.2	6	43.0	0.0	45.0	67.5	88.9	89.1
2 (30)	1.6	23.9	5	9.9	0.0	9.9	46.9	53.7	91.3
3 (19)	1.7	31.4	6	0.2	0.0	0.7	44.9	61.8	90.0
4 (35)	2.2	52.2	6	44.2	0.0	50.8	48.0	80.2	84.0
5 (5)	0.6	13.9	4	0.0	0.0	18.2	87.4	41.2	94.9
6 (8)	1.1	28.9	6	34.9	0.0	35.3	46.3	54.0	95.4
7 (5)	1.6	38.0	8	0.0	0.0	15.7	54.3	63.0	98.2
8 (4)	2.8	32.1	7	7.5	0.0	12.5	60.0	68.0	98.1
9 (6)	1.1	24.9	6	15.3	0.0	26.7	44.8	43.2	92.3
10 (15)	2.3	41.6	5	50.8	3.8	60.4	59.7	86.2	85.2
11 (15)	1.5	41.2	6	0.0	2.0	2.3	17.1	61.3	92.6
12 (16)	2.0	32.9	5	17.9	0.0	30.8	70.1	69.2	86.8
13 (8)	2.2	20.2	6	19.8	0.0	19.8	31.7	70.4	88.1
14 (4)	2.1	31.3	6	0.0	0.0	0.0	0.0	67.9	89.2
15 (4)	1.8	19.4	9	22.5	0.0	24.3	33.0	58.4	97.1
16 (11)	1.1	12.5	7	18.3	5.6	43.3	55.2	30.9	90.6
Mean	2.0	34.6	6	22.5	0.7	27.8	49.9	66.8	89.7

a) Number of measuring points per yard
b) Percentage of gross precipitation

Table 2. Relevant urban and rural studies

Land use (scale)	Climate (species/functional type)	Canopy cover, %	LAI	P, mm	TH, %	I, %	Author
Urban (stand)	Humid subtropical (broad-leaved deciduous)	66.8	2.0	466.9	89.7	9.8-8.3	This study
Urban (stand)	Humid subtropical (deciduous)	22.0 [a]	4.3	1029	na	18.4	Wang et al., 2008
Urban (stand)	Mediterranean (broad-leaved deciduous [b])	na	na	393.2	93.4	6.0	Xiao et al., 1998
Urban (stand)	Mediterranean (broad-leaved evergreen [b])	na	na	433.2	86.4	13.0	Xiao et al., 1998
Urban (crown)	Mild oceanic (*Pseudotsuga menziesii)*	na	na	377.0	50.1	49.1	Asadian and Weiler, 2009
Urban (crown)	Mild oceanic (*Thuja plicata*)	na	na	377.0	46.2	60.9	Asadian and Weiler, 2009
Urban (crown)	Semiarid (*Ficus benjamina*)	na	na	152.0	38.1	59.5	Guevara-Escobar et al., 2007
Urban (crown)	Mediterranean (*Pyrus calleryana*)	na	7.0	441.0	77.0	15.0	Xiao et al., 2000b
Urban (crown)	Mediterranean (*Quercus suber*)	na	3.4	700.0	58.0	27.0	Xiao et al., 2000b
Urban (crown)	Mediterranean (*Jacaranda mimosifolia*)	na	na	570.0	na	15.3	Xiao and McPherson, 2002
Urban (crown)	Mediterranean (*Tristania conferta*)	na	na	570.0	na	66.5	Xiao and McPherson, 2002
Urban (crown)	Mediterranean (*Ginkgo biloba*)	na	5.2	728.2	73.8	25.2	Xiao and McPherson, 2011
Urban (crown)	Mediterranean (*Liquidambar styraciflua*)	na	4.7	728.2	81.6	14.3	Xiao and McPherson, 2011
Urban (crown)	Mediterranean (*Citrus limon*)	na	3.0	728.2	70.9	27.0	Xiao and McPherson, 2011
Rural (stand)	Humid subtropical (mixed hardwood-conifer)	74.0	na	684.9	80.9	18.6	Bryant et al., 2005
Rural (stand)	Humid subtropical (deciduous broadleaved)	52.0	na	724.8	82.0	17.4	Bryant et al., 2005
Rural (stand)	Humid subtropical (deciduous broad-leaved)	na	3.1	3857.2	77.1	16.8	Deguchi et al. 2006
Rural (stand)	Humid subtropical	na	na	4934.8	90.0	10.0	Lin et al., 2000

a) Calculated based on the 5 % of tree cover on impervious and 17 % or tree cover on pervious land cover reported by Wang et al. (2008)
b) Dominance by leaf surface area
c) Only street and park trees (40 % of total canopy)

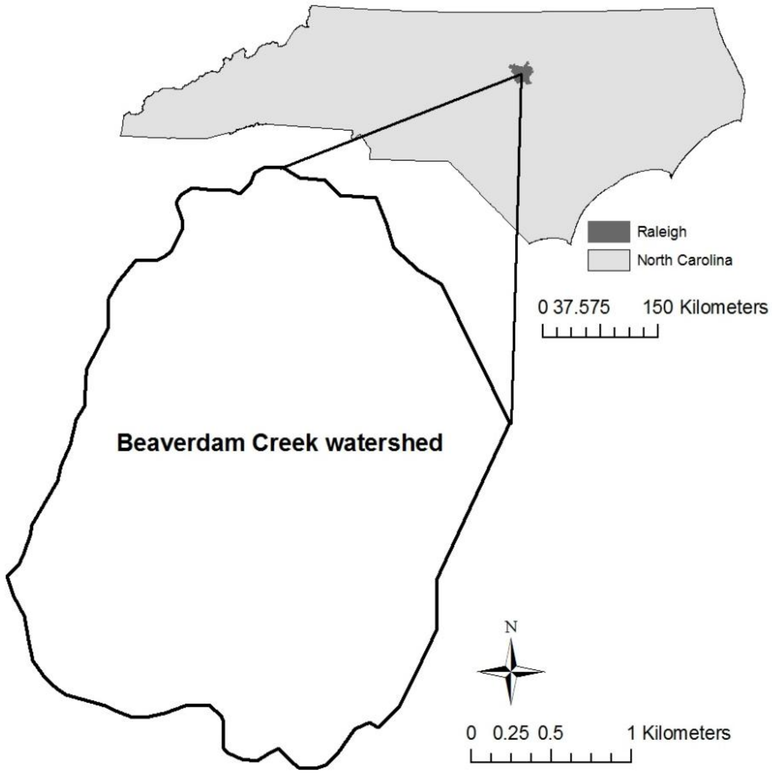

Figure 1. Beaverdam Creek watershed Raleigh, North Carolina, USA

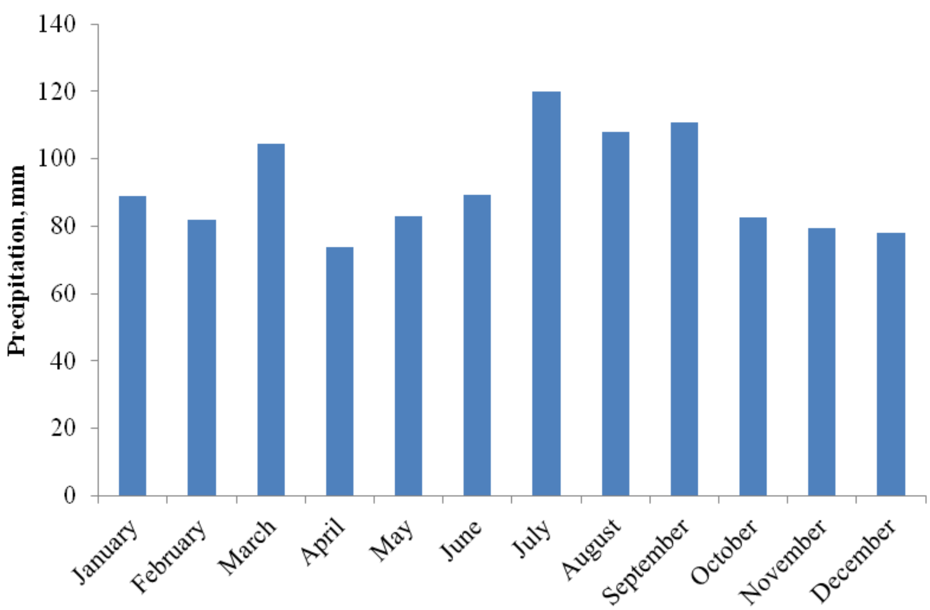

Figure 2. Monthly precipitation averages in Raleigh (1981-2010) Source: NOAA, 2011

Figure 3. Study area with 16 residential yards at a close proximity to Beaverdam Creek (left); Close-up of yards 1-4 with measuring points (middle); Measuring point under a Dogwood (right). Data sources: Wake Government

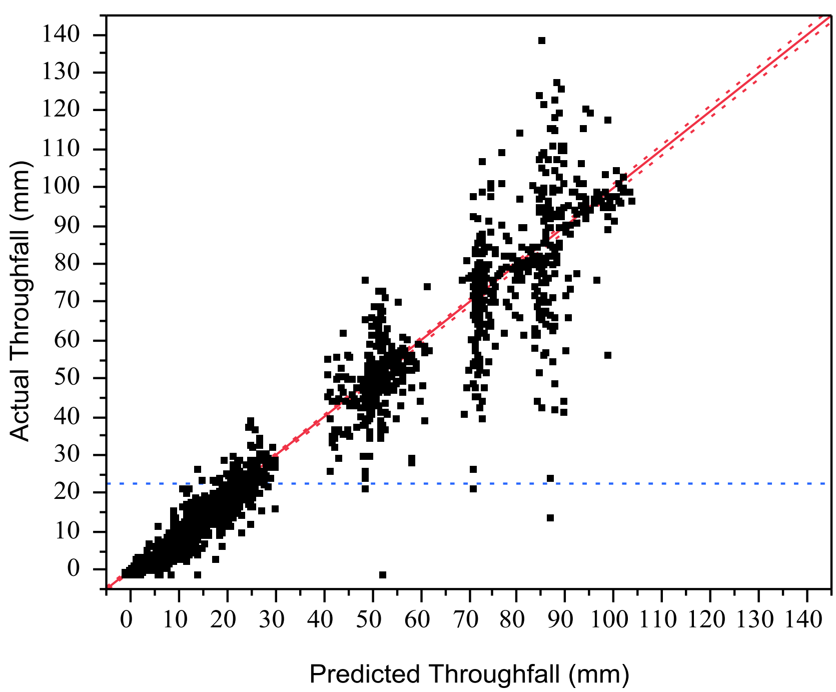

Figure 4. Actual vs. Predicted throughfall (p<.0001, Adjusted R2=0.9431, RMSE=6.8972) for a model including vegetation parameters. Dashed red line indicates 1:1. Dashed blue line shows the mean of response (22.8 mm).

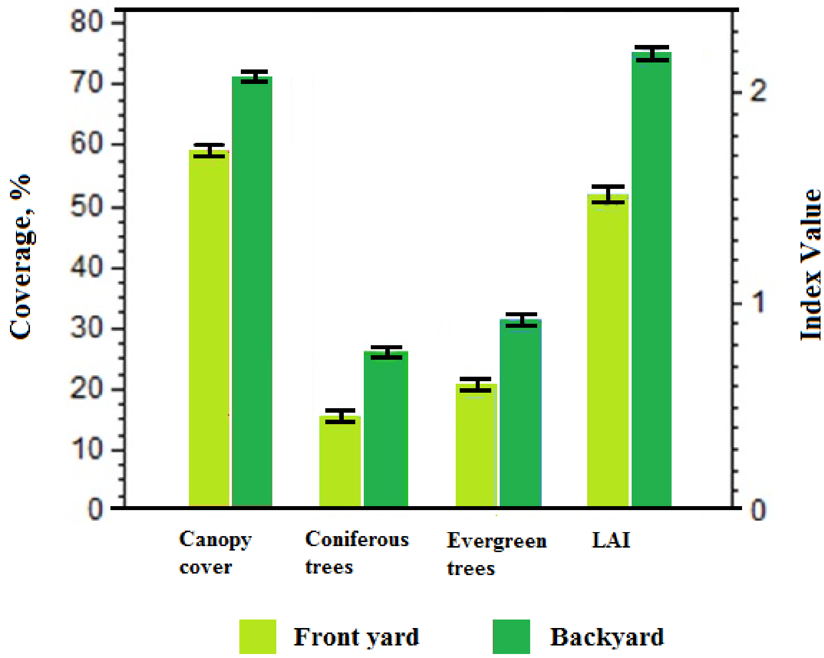

Figure 5. Significant differences in the percentage of canopy cover, coniferous trees, and evergreen trees (Y-axis, left), and LAI (Y-axis, right) between front and backyards (standard errors displayed)

Section 5: Conclusions

Our results from a low-intensity residential area in the humid subtropical climate indicate that vegetation may have a significant influence on the regulation of throughfall and potential stormwater runoff and that residents can considerably affect the process.

The performance of vegetation in reducing throughfall depends profoundly on the magnitude of the incident storm and the frequency of storms. Canopy cover was found to be more influential in predicting throughfall than LAI, possibly relating to the difficulties in measuring LAI accurately in heterogeneous urban forests. This assumption along with the usefulness of VSC index in throughfall prediction should be further tested.

Our results suggest that urban forests may produce more throughfall than rural forests with similar vegetation characteristics. This may be caused by the higher heterogeneity found in urban forests compared to more evenly distributed canopies in rural forests. Comparative studies in the same climate zone are needed to establish the magnitude and actual causes of differences between urban and rural forests with regard to throughfall.

Significant variability was found among yards and between front and backyards, suggesting that residents' landscape preferences in fact influence the amount of throughfall generated. Increasing forest cover and the amount of coniferous trees would provide a moderate reduction in throughfall and potential stormwater runoff. Residents should be encouraged to promote forest-like vegetation at least in more remote sections of yards. The benefits of increased throughfall regulation are most significant over impervious surfaces and close to urban streams.

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APPENDICES

APPENDIX A

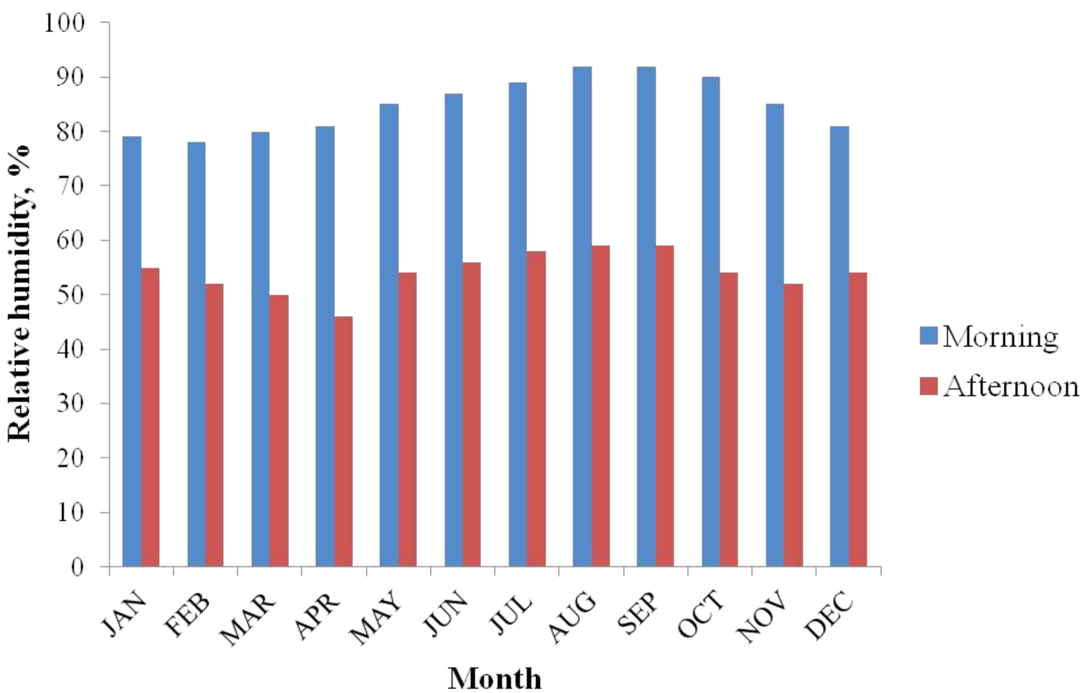

Figure 1. Mean annual relative morning and afternoon humidity (%) in Raleigh (Source: Southeast Regional Climate Center, 2007)

Table 1. Average gross precipitation (P), throughfall (TH), percentage of TH and rainfall interception (I) of P, and dryness index (DRY, 1 = 0 days from previous storm; 2 = one or more days from previous storm) across storms

Storm #	**Date**	**P (mm)**	***StdErr***	**TH (mm)**	***StdErr***	**TH (%)**	**I (%[a])**	**DRY**
1	07/28/10	10.3	0.00	7.6	0.48	73.6	25.9-24.4	2
2	07/29/10	56.3	0.46	52.7	1.01	93.6	5.9-4.4	1
3	08/01/10	6.6	0.10	4.8	0.25	73.1	26.4-24.9	1
4	08/05/10	24.6	0.08	23.7	0.42	96.2	3.3-1.8	1
5	08/06/10	28.2	0.00	27.4	0.62	97.0	2.5-1.0	1
6	08/12/10	2.6	0.06	1.8	0.09	70.8	28.7-27.2	2
7	08/19/10	22.2	0.14	18.7	0.34	84.4	15.1-13.6	2
8	08/20/10	14.8	0.21	14.5	0.32	98.1	1.4-(-0.1)	1
9	08/23/10	0.7	0.02	0.4	0.06	57.1	42.4-40.9	2
10	08/24/10	54.3	0.31	50.0	0.73	92.1	7.4-5.9	1
11	09/12/10	2.3	0.05	1.2	0.06	54.5	45.0-43.5	2
12	09/28/10	82.0	0.06	74.4	0.98	90.7	8.8-7.3	2
13	09/30/10	98.3	0.12	90.1	1.30	91.6	7.9-6.4	2
14	10/15/10	11.1	0.02	10.0	0.16	90.0	9.5-8.0	2
15	10/21/10	1.8	0.01	0.9	0.04	50.0	49.5-48.0	2
16	10/27/10	16.7	0.08	14.0	0.30	83.9	15.6-14.1	2
17	10/28/10	6.5	0.06	5.1	0.14	78.2	21.3-19.8	1
18	11/05/10	14.4	0.02	11.8	0.21	82.4	17.1-15.6	2
19	11/07/10	2.8	0.02	1.6	0.06	58.4	41.1-39.6	2
20	11/17/10	10.5	0.04	8.1	0.15	77.2	22.3-20.8	2
	Total	**466.9**		**418.9**				
	Average	**23.3**		**20.9**		**89.7**	**9.8-8.3**	

a) Assuming 0.5-2 % stemflow

APPENDIX B

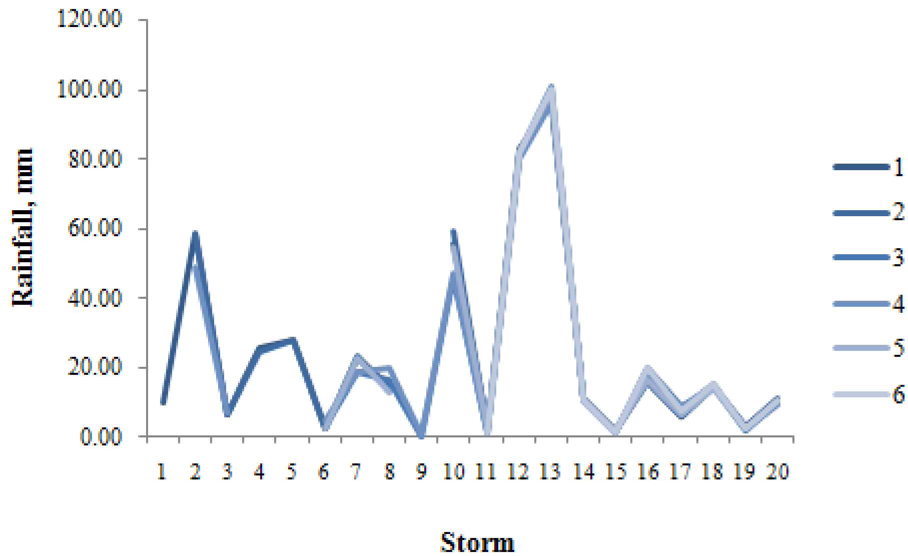

Figure 1. Correlation between control measuring points

Table 1. Control points for measuring gross precipitation, canopy cover, distance to the nearest building, and location (yard).

Control	Canopy cover, %	Distance to bldg, m	Location, yard #
1	6.2	>10	2
2	8.8	>10	3
3	15.9	>10	6
4	0.1	8.8	9
5	8.0	7.5	12
6	6.5	>10	16

APPENDIX C

Table 1. Correlation coefficients between the percentage throughfall of gross precipitation and vegetation parameters for the following storm classes: below or equal to canopy storage capacity (S); above S; preceded by a storm (wet canopy); not preceded by storms (dry canopy); during leaf on period; and during leaf off period.

Variable	**Storms ≤ S**	**Storms >S**	**Wet canopy**	**Dry canopy**	**Leaf on (07/28-11/05)**	**Leaf off (11/07 -17)**	**All**
Canopy cover	-0.53	-0.32	-0.25	-0.36	-0.32	-0.55	-0.32
Leaf area index	-0.49	-0.15	-0.15	-0.18	-0.20	-0.22	-0.16
VSC index	-0.41	-0.24	-0.17	-0.25	-0.21	-0.36	-0.24
% Coniferous trees	-0.05	-0.21	-0.19	-0.21	-0.18	-0.31	-0.20
% Coniferous shrubs	. [a]	-0.06	-0.11	-0.04	-0.06	-0.03	-0.05
% Evergreen trees	-0.03	-0.20	-0.20	-0.19	-0.18	-0.27	-0.19
% Evergreen shrubs	-0.22	-0.10	-0.14	-0.09	-0.10	-0.12	-0.10
Distance to trees, m	-0.10	-0.01	-0.00	-0.01	-0.00	-0.05	-0.01
Distance to building, m	0.25	-0.01	0.01	-0.01	-0.01	0.06	-0.01
Number of trees	0.23	0.03	0.03	0.04	0.03	0.08	0.04

[a] Due to the addition of yards 10, 11, and 16 (with coniferous shrub cover) after August 23, no data on coniferous shrubs is available for storms ≤ S

APPENDIX D

Table 1. Seasonal changes in thepercentage of throughfall of P and vegetation characteristics across yards by leaf on (L_{on}: 07/28-11/05) and leaf off period (L_{off}: 11/07-17)

	Throughfall, %			Canopy cover, %			LAI			VSC index		
Yard	L_{on}	L_{off}	Mean	L_{on}	L_{off}	Mean	L_{on}	L_{off}	Mean	L_{on}	L_{off}	Mean
1	89.8	67.6	89.1	90.8	75.4	88.9	3.5	1.5	3.2	42.4	57.4	44.2
2	91.6	80.7	91.3	53.4	55.5	53.7	1.7	0.9	1.6	23.7	24.7	23.9
3	90.2	85.9	90.0	64.9	39.8	61.8	1.9	0.9	1.7	29.9	42.8	31.4
4	85.1	58.7	84.0	82.7	67.1	80.2	2.4	1.3	2.2	52.9	48.8	52.2
5	94.9	80.0[a]	94.9	41.2	41.5[a]	41.2	0.6	0.5[a]	0.6	13.9	13.3[a]	13.9
6	95.9	82.6	95.4	55.7	40.7	54.0	1.1	0.8	1.1	26.7	45.5	28.9
7	98.2	85.0[a]	98.2	63.0	62.8[a]	63.0	1.6	1.3[a]	1.6	38.0	38.1[a]	38.0
8	98.1	68.[a]	98.1	68.0	68.0[a]	68.0	2.8	1.9[a]	2.8	32.1	32.1[a]	32.1
9	92.4	89.2	92.3	43.8	38.7	43.2	1.1	0.8	1.1	23.5	34.7	24.9
10	86.1	56.2	85.2	87.5	76.6	86.2	2.4	1.6	2.3	41.1	45.3	41.6
11	93.2	78.3	92.6	65.2	38.2	61.3	1.7	0.5	1.5	41.2	41.0	41.2
12	87.4	71.3	86.8	71.9	54.1	69.2	2.2	1.1	2.0	31.9	38.3	32.9
13	88.1	59.4[a]	88.1	70.4	69.9[a]	70.4	2.2	1.7[a]	2.2	20.2	21.0[a]	20.2
14	89.6	71.0	89.2	69.3	52.3	67.9	2.2	1.0	2.1	28.5	61.7	31.3
15	97.1	62.5[a]	97.1	58.4	58.4[a]	58.4	1.8	1.3[a]	1.8	19.4	19.4[a]	19.4
16	90.6	90.9	90.6	34.9	15.0	30.9	1.0	1.1	1.1	12.5	12.4	12.5
Mean	**90.0**	**73.1**	**89.7**	**68.5**	**54.9**	**66.8**	**2.1**	**1.1**	**2.0**	**33.8**	**40.4**	**34.6**

a) Situation on 10/21/10 before the removal of measuring points located in yards 5, 7, 8, 13, 14, and 15 on 10/22/2010.

Table 2. Significant differences in vegetation characteristics and mean observed throughfall (% of gross precipitation) between front and back yards ($\alpha = 0.05$)

	Front yard		**Backyard**		**Difference**		
	Mean	*StdDev*	*Mean*	*StdDev*	*Mean*	*StdDev*	**Prob> t**
Canopy cover, %	59.115	29.100	71.302	28.273	-12.190	28.578	<0.0001
LAI	1.524	1.248	2.200	1.307	-0.772	1.286	<0.0001
Evergreen trees, %	20.975	36.006	31.663	36.123	-10.690	36.080	<0.0001
Coniferous trees, %	15.715	31.602	26.450	33.247	-10.730	32.655	<0.0001
Throughfall, %	81.102	32.776	77.879	29.217	3.223	30.376	0.0064

APPENDIX E

Table 1. Details about urban and rural studies discussed

Land use sector	Stand/ crown	Location	Climate	Annual P, mm	Species	Canopy cover, %	LAI	P, mm	TH, %	I, %	ST, %	Measured (m)/ simulated (s)	Author
Urban (residential)	Stand	Raleigh, NC	Humid subtropical	1096	Broad-leaved deciduous	66.8	2.0	466.9	89.7	9.8-8.3	0.5-2.0	m	This study
Urban	Stand	Baltimore, MD	Humid subtropical	1100	Deciduous	22 a)	4.3	1029	na	18.4	na	s	Wang et al., 2008
Urban	Stand	Sacramento, CA	Mediterranean	455	Broad-leaved deciduous b)	na	na	393.2	93.4	6.0	0.6	s	Xiao et al., 1998
Urban (suburban)	Stand	Sacramento, CA	Mediterranean	455	Broad-leaved evergreen b)	na	na	433.2	86.4	13.0	0.6	s	Xiao et al., 1998
Urban (street, park)	Crown	British Columbia, Canada	Mild oceanic	1200 - 3000	*Pseudotsuga menziesii*	na	na	377.0	50.1	49.1	na	m	Asadian and Weiler, 2009
Urban (street, park)	Crown	British Columbia, Canada	Mild oceanic	1200 - 3001	*Thuja plicata*	na	na	377.0	46.2	60.9	na	m	Asadian and Weiler, 2009
Urban	Crown	Queretaro City, Mexico	Semiarid	548	*Ficus benjamina*	na	na	152.0	38.1	59.5	2.4	m	Guevara-Escobar et al., 2007
Urban (field site)	Crown	Central Valley, CA	Mediterranean	446	*Pyrus calleryana*	na	7.0	441.0	77.0	15.0	8.0	m	Xiao et al., 2000b
Urban (field site)	Crown	Central Valley, CA	Mediterranean	446	*Quercus suber*	na	3.4	700.0	58.0	27.0	15.0	m	Xiao et al., 2000b
Urban	Crown	Santa Monica, CA	Mediterranean	569.5	*Jacaranda mimosifolia*	na	na	570.0	na	15.3	na	s	Xiao and McPherson, 2002
Urban	Crown	Santa Monica, CA	Mediterranean	569.5	*Tristania conferta*	na	na	570.0	na	66.5	na	s	Xiao and McPherson, 2002
Urban (residential)	Crown	Oakland, CA	Mediterranean	582.7	*Ginkgo biloba*	na	5.2	728.2	73.8	25.2	1.0	m	Xiao and McPherson, 2011
Urban (residential)	Crown	Oakland, CA	Mediterranean	582.7	*Liquidambar styraciflua*	na	4.7	728.2	81.6	14.3	4.1	m	Xiao and McPherson, 2011
Urban (residential)	Crown	Oakland, CA	Mediterranean	582.7	*Citrus limon*	na	3.0	728.2	70.9	27.0	2.1	m	Xiao and McPherson, 2011
Rural	Stand	Fort Benning, GA	Humid subtropical	830	Mixed forest	74	na	684.9	80.9	18.6	0.5	m	Bryant et al., 2005
Rural	Stand	Fort Benning, GA	Humid subtropical	830	Upland hardwood	52	na	724.8	82.0	17.4	0.5	m	Bryant et al., 2005
Rural	Stand	Aichi Prefecture, Japan	Humid subtropical	1498.4	Deciduous broad-leaved	na	3.1	3857.2	77.1	16.8	6.0	m	Deguchi et al. 2006
Rural	Stand	Northeastern Taiwan	Humid subtropical	2900-6000	Mixed evergreen forest	na	na	4934.8	90.0	10.0	0.0	m	Lin et al., 2000

a) Calculated based on the 5 % of tree cover on impervious and 17 % of tree cover on pervious land cover reported by Wang et al. (2008)
b) Dominance by leaf surface area
c) Only street and park trees (40 % of total canopy)