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Research Paper

The role of the residential urban forest in regulating throughfall: A case study in Raleigh, North Carolina, USA

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HIGHLIGHTS

- Urban residential forest reduced potential stormwater runoff by 9.1–21.4%.
- Throughfall amounts ranged greatly among yards with 41.5–88.3% canopy cover.
- Variability found in vegetation and throughfall between private and rented yards.
- Differences also found between front and backyards.
- Canopy cover ($p < 0.0001$) and coniferous trees ($p = 0.017$) influential variables.

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ABSTRACT

Overwhelming stormwater volumes, associated with deteriorating water quality and severe flooding in urbanizing cities, have become a great environmental and financial concern globally. Urban forests are capable of reducing the amount of stormwater runoff, in part, by regulating throughfall via canopy rainfall interception; however, the lack of stand-scale studies of urban throughfall hinders realistic estimates of the benefits of urban vegetation for stormwater regulation. Furthermore, urban forest characteristics that may be influencing rainfall interception are difficult to establish as these environments are extremely heterogeneous and managed, to a large extent, by private residents with varying landscape preferences. To quantify the amount of rainfall interception by vegetation in a residential urban forest we measured throughfall in Raleigh, NC, USA between July and November 2010. We analyzed 16 residential yards with varying vegetation structure to evaluate the relative importance of different descriptive measures of vegetation in influencing throughfall in an urban watershed. Throughfall comprised 78.1–88.9% of gross precipitation, indicating 9.1–21.4% rainfall interception. Canopy cover ($p < 0.0001$) and coniferous trees ($p = 0.017$) were the most influential vegetation variables explaining throughfall whereas variables such as leaf area index were not found significant in our models. Throughfall and vegetation characteristics varied significantly among yards ($p < 0.0001$), between front and back yards ($p < 0.0001$), and between rented and privately-owned yards ($p = 0.001$), suggesting a potentially significant role in stormwater regulation for urban residents.

1. Introduction

Stormwater runoff associated with an increased amount of impervious surfaces is the main cause of poor water quality, flooding, and deteriorating stream health in cities (Cappiella, Wright, & Schuler, 2005; Cunningham et al., 2009; Weijters et al., 2009). Urban forests, defined by Miller (1997) as all woody and associated vegetation in and around dense human settlements, have a great potential for reducing stormwater damage, by enhancing infiltration and evapotranspiration, as well as regulating the amount of throughfall reaching the ground via rainfall interception (Asadian & Weiler, 2009; Cappiella et al., 2005; McPherson, 1998; Xiao, McPherson, Simpson, & Ustin 1998; Xiao, McPherson, Ustin, Grismer, & Simpson, 2000b) (Table 1, Fig. 1). Rainfall interception is the proportion of rainfall that is intercepted by plant surfaces and evaporated directly back into the atmosphere (David, Valente,

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Table 1
Definitions and acronyms.

Acronym in text	Definition
P	Gross precipitation
P_{NET}	Net precipitation = throughfall and stemflow
TH	Throughfall = the proportion of rainfall that penetrates or drips through a plant canopy (Hewlett, 1982)
TH, C	% Cumulative throughfall of gross precipitation (calculated by summing all throughfall values for the study period and dividing by cumulative gross precipitation)
TH, S	% Storm-based throughfall of gross precipitation (averaged from the means of each storm)
I	Interception = the proportion of rainfall that is intercepted by plant surfaces and evaporated directly back into the atmosphere (David et al., 2005)
ST	Stemflow = the proportion of rainfall that flows down to the ground via stems
CC	Canopy cover
LAI	Leaf area index
VSC	Vertical structural complexity
CON	Coniferous tree cover
F	Storm frequency index = variable indicating whether the storm was preceded by one or more rainless days
N	Neighborhood

& Gash, 2005). Most studies have reported interception losses of 10 to 40% of gross precipitation, depending on meteorological factors and the type of vegetation (Crockford & Richardson, 1990; Llorens, Poch, Latron, & Gallart, 1997; Llorens & Domingo, 2007; Link, Unsworth, & Marks, 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 for reducing the adverse impacts of stormwater runoff where it is most needed, study of rainfall interception has been largely overlooked for urban areas. 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 & 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 those in rural forests. Wider crowns and higher evaporation rates caused by wind and elevated temperatures have been found to produce lower throughfall magnitudes, producing

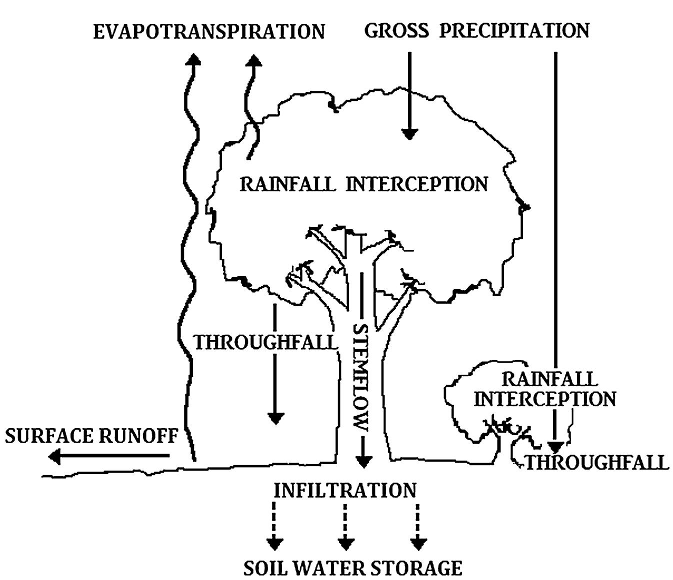

Fig. 1. Partitioning of gross precipitation into throughfall, stemflow, and rainfall interception (modified from Levia and Frost, 2006).

up to 60% less throughfall under individual tree crowns growing in urban areas (Asadian & Weiler, 2009; Xiao & 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 rainfall interception (David et al., 2005, 2006; Gash, 1979; Xiao, McPherson, Ustin, & Grismer, 2000a; Zeng, Shuttleworth, & Gash, 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, Kershaw, Robins, & Morton, 1971). Storms below canopy storage capacity produce less throughfall than storms exceeding canopy storage capacity. Less throughfall is produced when the canopy has sufficient 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, Burk, & Pitts, 1980). Interception losses of 20–40% have been reported in coniferous forests while 10–20% have been found in broadleaved forests (Crockford & Richardson, 1990; Link et al., 2004; Llorens et al., 1997; Llorens & Domingo, 2007). Seasonal changes in canopies also affect the amount of throughfall reduced via rainfall interception. Evergreen trees are capable of interception for a larger part of the year than deciduous trees and are thus especially important in regions with winter precipitation (Xiao et al., 1998). While the quantity of foliage is the most important indicator of canopy storage capacity, crown architecture has also been found to have an influence (Xiao et al., 2000b; Xiao & McPherson, 2011).

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, Bhat, & Jacobs, 2005; Gash, 1979; Gash, Lloyd, &, Lachaud, 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 & Bruijnzeel, 2001; Xiao et al., 2000b). *LAI* may be a better indicator of rainfall interception at the crown-level but accurate measurement for heterogeneous canopies is challenging due to potential bias from direct sunlight penetrating the canopy, resulting in underestimations. This may be accentuated in characteristically heterogeneous urban forests.