Urban trees and rainfall:

an investigation into the benefits for stormwater management

A thesis submitted in fulfilment of the requirements for the degree of Doctor of Philosophy

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Declaration

I certify that except where due acknowledgement has been made, the work is that of the author alone; that work has not been submitted previously, in whole or in part, to qualify for any other academic award; the content of the thesis is the result of work which has been carried out since the official commencement date of the approved research program; and any editorial work, paid or unpaid, carried out by a third party is acknowledged.

Mariana Dias Baptista

13/03/2019

Preface

The work presented here is predominantly my own. Publications and contributions from others are detailed below.

The work presented in Chapter 2 is based on the paper:

Baptista, M. D., Livesley, S. J., Parhmer, E. G., Neave M. and Amati. M. 2018. 'Variations in leaf area density drive the rainfall storage capacity of urban tree species'. *Hydrological Processes,* 32, pp. 3729–3740.

Co-authors Stephen J. Livesley assisted in the set-up of rainfall simulation experiments and Ebadat G. Parhmer assisted in the processing of remotely sensed data. All co-authors provided editorial assistance.

The work presented in Chapter 3 is based on the paper:

Baptista, M. D., Livesley, S. J., Parhmer, E. G., Neave M. and Amati. M. 2018. 'Terrestrial laser scanning to predict canopy area metrics, water storage capacity and throughfall redistribution in small trees'. *Remote Sensing,* 10 (1958), pp. 1–22.

Co-authors Stephen J. Livesley assisted in the set-up of rainfall simulation experiments and Ebadat G. Parhmer assisted in the processing of remotely sensed data. All co-authors provided editorial assistance.

Parts of this study were presented at the following international conferences:

Baptista, M. D., Livesley, S. J., Parhmer, E. G., Neave M. and Amati. M. 2017. 'Three-dimensional tree: a new method to evaluate the interception of rainfall'*. In Green Infrastructure: Nature-based Solutions for Sustainable and Resilient Cities*, Orvieto, Italy. Oral presentation.

Baptista, M. D., Livesley, S. J., Neave, M. and Amati. M. 2018. 'Diverse urban forest improves stormwater management'. In *International Urban Forestry Congress*, Vancouver, Canada. Oral presentation.

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However, during this journey, there were some stormy days (not only literally) that have made me realise how important it is to take care of our mental health. I do not have enough words to thank my therapist, Fernanda, who gave me professional support in moments of doubt and pain. Committing to a PhD is a big challenge and I encourage everyone to seek professional help when needed.

In the middle of this journey, I have been lucky enough to find someone to be my safe port. To Ben: thank you for bringing me peace during this turbulent journey.

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TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

LIST OF ABBREVIATIONS

ALS	Airborne laser scanning
BA	Branch area
BD	Basal stem diameter
CA	Projected canopy area
CH	Canopy height
C_{max}	Maximum storage capacity
C_{min}	Minimum storage capacity
CV	Canopy volume
H	Tree height
LA	Leaf area
LAI	Leaf area index
PAD	Plant area density
PAI	Plant area index
PSA	Plant surface area
TLS	Terrestrial laser scanning

Abstract

Expanding urban areas have replaced the natural landscape. With reducing areas of natural space, evapotranspiration losses and infiltration rates have decreased, disturbing the natural hydrological cycle. As a result, the frequency of floods has intensified in those areas. As part of an integrated solution, city planners have promoted an increase in vegetated areas to enhance evapotranspiration and infiltration rates and, consequently, reduce the runoff effect. In particular, trees play an important role, intercepting water on their leaves and branches during rainfall events and reducing the volume of water that generates runoff. The intercepted volume is directly connected to plant area density, which varies from one species to another, but also from one individual tree to another. Variations in plant area may occur for different reasons during tree life duration, such as severe drought, heat waves, diseases and pruning. However, the effect of this variation on runoff reduction has not been tested.

The present study evaluates the interception process for different trees planted in the City of Melbourne, analysing the impact of species-specific traits and variations in plant area on water storage and spatial-temporal redistribution. Measurements are taken by two different methods: first, as an indoor experiment, where rainfall is simulated and environmental conditions are controlled; and second, as an outdoor experiment, where throughfall is measured in an urban park.

In the indoor simulated rainfall experiment, measurements are taken of C_{max}, the maximum volume of water that a tree can carry on its surfaces while it is raining, and C_{min}, the maximum volume of water that the tree carries when rainfall and dripping have ceased. Three different tree species commonly planted in Melbourne streets and parks (*Ulmus procera*, *Platanus x acerifolia* and *Corymbia maculata*) were studied. Leaf area was manually varied through staged leaf removal, creating four different leaf-density treatments for each tree: full canopy (100% of leaves), half (approximately 50%), quarter (approximately 25%) and woody (no leaves). Additionally, throughfall redistribution is analysed for the same trees with their full canopy. Terrestrial laser scanning (TLS) data is used alongside directly quantified leaf and branch area data to assess the capacity of TLS to predict canopy area metrics and associated canopy interception parameters such as C_{max} and C_{min}. TLS data is also correlated against throughfall distribution on a sub-canopy scale to investigate the predictive capacity.

In the outdoor natural rainfall experiment, three tree species commonly planted in Melbourne parks (*Ulmus procera*, *Ficus macrophylla* and *Eucalyptus microcorys*) are analysed for their potential to intercept rainfall and delay throughfall in urban areas. Similarly, tree metrics are assessed by hemispherical photography and TLS. The collected throughfall and tree metrics are used to predict storage capacity using existing models for canopy interception prediction.

Simulation results show that canopy storage capacity is well correlated to plant surface area (m^2), plant area index (m^2/m^2) and plant area density (m^2/m^3) under controlled conditions. All analyses indicate that *U. procera* is the most efficient species for storing rainfall water within a canopy of equal volume or area index. The outdoor experiment confirms the importance of leaf density on storage capacity, but also the influence of different leaf and branches characteristics, as *F. macrophylla* presents the highest interception rates, but not the highest values for leaf area density.

Analysing the pattern of throughfall under canopy reveals that throughfall and plant density are weakly related, but overall areas of reduced throughfall are associated with the areas of denser canopy above. Additionally, patterns of distribution vary from one species to another, which may be attributable to the size of leaves and distribution of branches and leaves in the canopy volume.

This study contributes to the discipline and practice of urban forestry by distinguishing how variations in leaf density are important to consider when selecting tree species to be planted in urban street and greenspace landscapes, as well as the importance of using adequate management techniques to guarantee good health conditions for urban trees. These findings may provide guidance in relation to the use of trees in stormwater management policies, planning to achieve a higher potential for interception and runoff reduction for mitigating flood occurrences.

Chapter 1. Introduction and Review

1.1. Motivation

Since the beginning of human civilisation, human beings have changed the environment to make it a better place for living. During this process, natural resources have been adapted to our necessities in the name of liveability. Water is one of the most important elements to sustain the life cycle. With the growth of populations and urbanisation around the world, combined with changes in climate, the rainfall cycle has been modified and the reliability of this source compromised. As a result of reckless modifications, climate patterns have changed at a fast pace.

The projected climate-change scenarios expect rising sea levels, changed precipitation rates, longer periods of drought, greater incidence of floods, and more frequent and stronger cyclones and storms (IPCC, 2014). For the first time in history, more than half of the world's population has been living in towns and cities since 2008, and by 2050 this proportion is likely to increase to 68% (UN, 2018). In the next few years, the effects of climate change are likely to impact on hundreds of millions of humans living in urban and peri-urban areas (FAO, 2016). For this reason, urban planners' concern over the development of better stormwater management has increased in the last decades (Roy et al. 2008; Fletcher et al. 2013; Berland et al. 2017).

Urbanisation leads to an increase in impervious surfaces area, which prevents and/or reduces water infiltration, increasing the volume and speed of water running off (Fletcher et al. 2013). As a consequence, the occurrence of floods increases and water quality is degraded by street pollutants carried in runoff (Wissmar, Timm and Logsdon, 2004; Wang, Endreny and Nowak, 2008). At the same time, sealed surfaces decrease the volume of groundwater beneath many cities, since a high quantity of water is quickly drained to catchments (Zhang et al. 2012). In addition, the urbanisation process affects the water balance within the catchment, increasing stream and river recharge rates, and reducing evapotranspiration (Locatelli et al. 2017).

In the past, drainage was shaped naturally by creeks, rivers and streams. Nowadays, urbanised areas rely on rainwater drainage systems to rapidly conduct water away (Rossmiller, 2014). The increase in surface runoff due to the lack of permeability of soils compromises the capacity of this system. One solution would be expanding the rainwater drainage system; however, retrofitting the old systems would demand a large part of city budgets and it is often impracticable due to the level of disturbance in established areas.

According to the City of Melbourne (2012), despite the effectiveness of traditional engineering solutions for water capture and discharge, weather events have shown that certain areas throughout the city are still susceptible to heavy inundation during major storm events. Therefore, urban planners need to employ different actions to create better ways to incorporate the water cycle within the design of cities and towns, and create better management practices (Joint Steering Committee for Water Sensitive Cities, 2009).

One of the alternatives is applying water-sensitive urban design (WSUD) to new developments and renewing areas as part of the strategy to increase stormwater infiltration. Most landscape typologies in cities, from parks to streets, have the potential for WSUD since these techniques are generally adjustable to diverse locations (City of Melbourne, 2012). Stormwater, previously treated as waste, is now managed as a resource and an important urban component which impacts on land and biodiversity and has aesthetic and recreational roles (Joint Steering Committee for Water Sensitive Cities 2009).

Many studies have shown that green areas have positive benefits on water infiltration and storage in the soil, runoff reduction, nutrient and pollutant removal, and groundwater quality (Xiao and McPherson 2011; Van Stan, Levia and Jenkins 2014; Ossola, Hahs and Livesley 2015). Infiltrating and purifying stormwater are important services to mitigate overflow and drought impacts in areas predominantly impermeable. Green spaces can store more runoff water than asphalt, concrete and other hard surfaces, lowering the risk of flooding and improving the quality of water in the environment (Armson, Stringer and Ennos 2013; Zhang et al. 2015). Pervious vegetated areas allow water to percolate and to return to its cycle, being absorbed by plant roots and then evapotranspiring, or reaching groundwater level (Xiao et al. 2007).

However, in an urban area the large amount of water infiltrating the soil may cause damage to underground structures. The integrated initiative adopted by many cities (City of London 2011; City of Melbourne 2012; City of Vancouver 2015) aims to increase the canopy cover in order to reduce runoff during rainfall. Within this context, trees are considered key elements in the green areas, playing an important role in the hydrological cycle by intercepting rainfall. Trees may store part of the water on leaf, branch and stem surfaces (Xiao et al. 2000; Xiao et al. 2007), preventing water from reaching the ground and jeopardising underground infrastructure.

Yet, the role of trees in stormwater management is still poorly understood due to the complexity of assessing the interception process. Providing reliable estimation of the actual contribution of trees to runoff reduction is a challenge. The uncertainties concerning recent studies are partially connected to the lack of standards and inaccuracy when measuring interception and plant area metrics in real-world scenarios (Roy et al. 2008; Livesley, Baudinette and Glover 2014). The need to investigate and quantify the amount of water intercepted by different trees more accurately is evident, so this can better inform urban foresters and planners in order to maximise the benefits of trees for stormwater management.

The development of new technologies and models may help to measure interception rates more accurately. Several studies have investigated the use of remotely sensed data to reduce the amount of time spent collecting canopy metrics and provide more accurate estimates (Alonzo et al. 2015; Lin and West, 2016; Parmehr et al. 2016; Jiang et al. 2017). Although a few studies have employed remotely sensed data to estimate interception losses (Cui et al. 2017; Hassan, Ghimire and Lubczynski 2017), the empirical tradition of upscaling this type of study from controlled environments to the field has not been explored in a detailed way.

Within this context, the present study aims to understand the interception process using a detailed analysis of different methods and tools to assess interception. At the same time, the use of TLS data is tested as a tool for assessing plant area metrics.

In the next sections, I present an outline of this thesis, followed by contextualisation of my research, introducing some important concepts and presenting a summary of previous studies in this field. This chapter concludes with a description of some methods that have been used to measure interception and plant area, giving some background to the methods selected to be used in this study.

1.2. Thesis outline

According to the City of Melbourne (2012), more than 50% of the tree population will be at the end of its useful life in the next decade. Given the pace of change in Australian cities and the rate of disappearance of trees, the contribution of this research is to discover whether a rapid response method can be used to evaluate the rain-intercepting benefits of urban forest canopy cover. So far this has eluded researchers because of the challenges in measuring interception in urban areas.

For this purpose, this thesis investigates the benefits of urban trees for stormwater management by studying the rainfall-interception process using different approaches. This study is divided into two phases of experiment: an indoor and an outdoor experiment. Different methods for estimating interception parameters are compared: direct measurement, estimation from field observations and modelling.

For the indoor experiment, the interception was directly measured using simulated rain above trees in pots for three urban tree species commonly planted in Australia. In this thesis, interception parameters are estimated in a controlled scenario in order to understand the relationship between plant area metrics and canopy storage capacity based on previous studies (Aston 1979; Li et al. 2016; Xiao & McPherson 2016). One of the specific objectives of this study is not only correlating plant surface areas of different species to their capacity to store rainfall water, but also understanding how variation in leaf area may affect the storage capacity in the same tree. For the outdoor experiment, interception was estimated from collected throughfall data on natural rain above greenspace urban trees.

These two different approaches allowed me to understand the interception process in a semi-controlled environment and in a realistic urban scenario, and at different scales. For both scenarios, the empirical Gash model was used to compare measured and modelled results, and to test the reliability of the model to be used for predicting interception.

In a sub-canopy analysis, the variation in plant density within the canopy is correlated to the redistribution of throughfall. I also evaluate the use of remotely sensed data as a tool for assessing tree surface metrics more accurately. A terrestrial laser scanner was used for assessing the tree canopy metrics of small trees in pots, and combined aerial and terrestrial data was used to assess the tree canopy metrics of trees in the urban park. The potential use of laser scanner metrics as a predictor of rainfall interception is evaluated.

To understand the interception process and the benefits of trees for stormwater management, this thesis addresses the following questions:

- How much does the variation in plant area affect the storage capacity of individual trees?
- Are laser scanning metrics a good predictor of storage capacity for an individual tree?
- Can we describe the effect of leaf and branch density on the redistribution of throughfall of individual trees?
- What are the differences when estimating interception for different scales and using different methods?
- How can all of the above information be incorporated into stormwater management policies?

The amount of water stored on trees depends on many aspects, but it is mainly controlled by tree surface characteristics. In Chapter 2, the storage capacity of three tree species is investigated. Results show that not all species present the same characteristics. Yet, different trees within the same species present variations in canopy quality. Using direct methods to estimate leaf and branch area, I discuss the variation in tree surface density from one species to another, but also from one tree to another, depending on environmental restrictions (temperature, water availability, herbivory, space, etc.). This chapter concludes with a brief calculation of runoff reduction in a pictured urban scenario.

In Chapter 3, I describe the second part of the indoor experiment, where I analyse the effectiveness of predicting storage capacity and throughfall redistribution using remotely sensed data. Remotely sensed data is acquired using a laser scanner and retrieved canopy metrics are correlated to direct measurements. The aim here is to check the accuracy of scanned data in retrieving canopy metrics. Then I investigate the relationships between spatial distributions of throughfall and interception parameters with TLS-derived metrics.

In Chapter 4, I demonstrate the application of a simplified model to predict rainfall interception for urban trees in a park. Therefore, throughfall was collected under the canopies of three different tree species during the same rainfall events. The relationship between measured and predicted interception data is discussed.

In Chapter 5, I discuss how the outcomes from this study can inform urban foresters and stormwater managers of the potential quantitative impact of tree characteristics on rainfall interception and how to base decisions on urban forest management. I discuss the benefits of urban trees for stormwater management and their influence on runoff volumes.

In Chapter 6, I highlight the benefits of monitoring the dynamics of vegetation in an urban environment and address the importance of good management of urban trees. I discuss possible limitations concerning the use of trees for stormwater management and how we could deal with them to make this data more useful for urban forest planners and managers. In summary, I conclude my study with a discussion connecting the findings from all three research chapters and the contribution of these findings in a broader context.

1.3. Literature review

1.3.1. The urban forest

Urban green areas can be characterised as urban areas of land predominantly covered by vegetation. Following the same logic, urban forests are those green areas containing trees as their primary elements, comprising all types of forests from woodlands to individual trees within and around urban areas (Randrup et al. 2005). According to the UN Food and Agriculture Organization (FAO 2016), “urban forests can be defined as networks or systems comprising all woodlands, groups of trees, and individual trees located in urban and peri-urban areas; they include, therefore, forests, street trees, trees in parks and gardens, and trees in derelict corners.” The FAO (2016) has classified urban forests into four different groups according to their spatial distribution and use: peri-urban forests and woodlands; city parks and urban forests (>0.5 ha); pocket parks and gardens with trees (<0.5 ha); other green spaces with trees. Each of these groups plays an important role in environmental quality, offering a broad range of ecosystem services in different and complementary ways.

The combination of trees with other green infrastructure is an effective solution for decreasing the amount of stormwater runoff (Zhang et al. 2012; Armson, Stringer and Ennos 2013; Ossola, Hahs and Livesley 2015), improving air quality (Salmond et al. 2013), storing carbon (Nowak et al. 2013), reducing urban energy consumption through shading and cooling (Nowak et al. 2017) and mitigating the impacts of extreme weather and floods (Van Stan, Levia and Jenkins 2014; Xiao and McPherson 2016). Thus, the performance of those services will be mainly linked to the characteristics of the selected species and the arrangement of the trees.

Traditionally, the selection of urban trees species is based on climatic distribution and their adaptability to coping with adverse environmental conditions such as air pollution, and dry and compact soils (Sæbø, Benedikz and Randrup 2003). Those aspects are essential for the establishment of trees in this challenging and stressful environment, namely, urban areas. However, after this selection little attention has been paid to the ecological services that trees may provide to the environment.

Incorporating these services into urban forest planning is a powerful tool that may help to achieve sustainability goals by increasing the value of conservation and providing metrics to better connect multiple community purposes (Hilde and Paterson 2014; Livesley, McPherson and Calfapietra 2016). Therefore, monitoring the dynamic urban forest is an essential tool for informing planners and managers about canopy conditions, distribution of species, age distribution and other factors that can affect water storage capacity during rainfall.

1.3.2. The hydrological cycle in the urban forest

Urbanisation changes land use within catchment areas, causing a reduction in vegetation cover and consequently increasing impermeable areas. All this modification, in a relatively short-term period, disturbs the natural hydrological cycle and has led to many of the environmental problems that we are now facing. Hydrological behaviour varies over time, at hourly, daily, seasonal, annual and inter-annual scales. Some of this variability in a catchment will be due to variations in climatic inputs and seasonal cycles of vegetation growth and deterioration. Some will be due to human-induced changes to the surface of the catchment and the way water moves through the catchment (Arnell, 2002).

The potential infiltration of water into the soil is influenced by changes in catchment land cover, the use of water in the catchment and the development of grey infrastructure, increasing the potential of stormwater runoff formation and flash floods (Arnell 2002; Walsh, Fletcher and

Burns 2012), which has become an important concern for urban planners and managers (Arnell 2002; Wissmar, Timm and Logsdon 2004).

Runoff is a natural process that may happen when the amount of water reaching the ground surface is higher than the volume of water that can be stored by the ground surface (Betson 1964). In cities, major concern about runoff generation arises during high-magnitude events when the amount of water reaching the impervious surfaces rapidly accumulates and runs into sewage systems that are often operating at maximum capacity. In other words, the sewage system in many cities has become obsolete in the face of fast advances in urban densification, and retrofitting this system is expensive and impracticable in most situations.

According to Boyd et al. (1993), the surfaces in an urban catchment may be divided into three groups:

1) impervious areas directly connected to the sewage system, such as streets, footpath, in some cases roofs
2) other impervious areas that are not connected to sewage systems and need to flow over pervious or impervious surfaces before reaching the system, such as roofs
3) pervious and semi-pervious areas, such as gardens and parks.

Most of the stormwater runoff in cities originates from impervious areas connected to the sewage system (Boyd, Bufill and Knee 1993). Consequently, the quality of this water is compromised by increasing amount of pollutants and the volume of runoff water tends to increase with densification of urban centres, with climate-change scenarios predicting a further increase in the frequency of extreme rainfall events.

For this reason, mitigation of the negative impacts of stormwater runoff flowing to urban watercourses is increasingly important (Grey et al. 2018). In their study, Armson et al. (2013) found that lawns have eliminated a large proportion of surface runoff, and trees with associated tree pits – the permeable area around a tree’s base – showed a large reduction in runoff in contrast with asphalt-covered areas. Infiltration into tree pits seems to play an important role in reducing surface water runoff, as it has decreased by up to 62% in areas with tree cover (Armson, Stringer and Ennos 2013).

The presence of trees not only increases the permeability of the ground, but also contributes to returning the potential runoff water to the atmosphere through transpiration and evaporation from the canopy and soil (Gotsch, Draguljić and Williams 2018). The transpiration and evaporation processes promote an air-cooling effect, which is a positive aspect for the mitigation of urban heat islands (Livesley, McPherson and Calfapietra 2016).

Additionally, when we reduce stormwater runoff, we affect not only the quantity, but also the quality of water reaching the city water catchments (Xiao and McPherson 2002). Employing green infrastructure, such as vegetation, to restore some of the natural water cycle processes (EPA 2018), improves the quality of the water reaching catchment systems, as vegetation can intercept air pollutants and sediments (FAO 2016). From an economic point of view, it also decreases the cost of water treatment, reducing the need to invest in water-treatment projects (Zhang et al. 2012). In this context, trees should be key elements in stormwater management, as they can intercept part of the rain (Xiao and McPherson 2002), increase permeability (Grey et al. 2018a) and promote water filtration (Roy et al. 2008). Additionally, these practices may benefit tree development, as they increase water and nutrient availability (Grey et al. 2018).

Predicted scenarios for urban areas suggest that the sustainable management of water resources can be improved by well-managed and healthy urban forests (FAO 2016). To be able to improve the recommendations for urban forestry in relation to the role of trees in stormwater management, however, understanding how tree management affects these hydrological processes is crucial. For this reason, assessment of the interception process should provide comprehensible metrics which can be translated into guidelines for planning and management.

1.3.3. The interception processes

Trees interact with precipitation in three different ways (Figure 1.1): throughfall, stemflow and interception (Crockford and Richardson, 2000). During rainfall events, the raindrops that hit the tree canopy have their characteristics modified: some will fragment, creating smaller drops, while others will accumulate on leaves before falling to the ground as large drops, or flow through branches and trunk until they reach the ground (Geißler et al. 2012). All water that reaches the ground by passing directly through gaps in the canopy or dripping from leaves and branches is considered throughfall. The precipitation collected by the canopy that flows down the stems, branches and trunk to the ground is called stemflow (SF). Finally, the remaining portion of rainfall that is intercepted by the canopy and never reaches the ground surface is called interception or interception loss (Xiao and McPherson 2011).

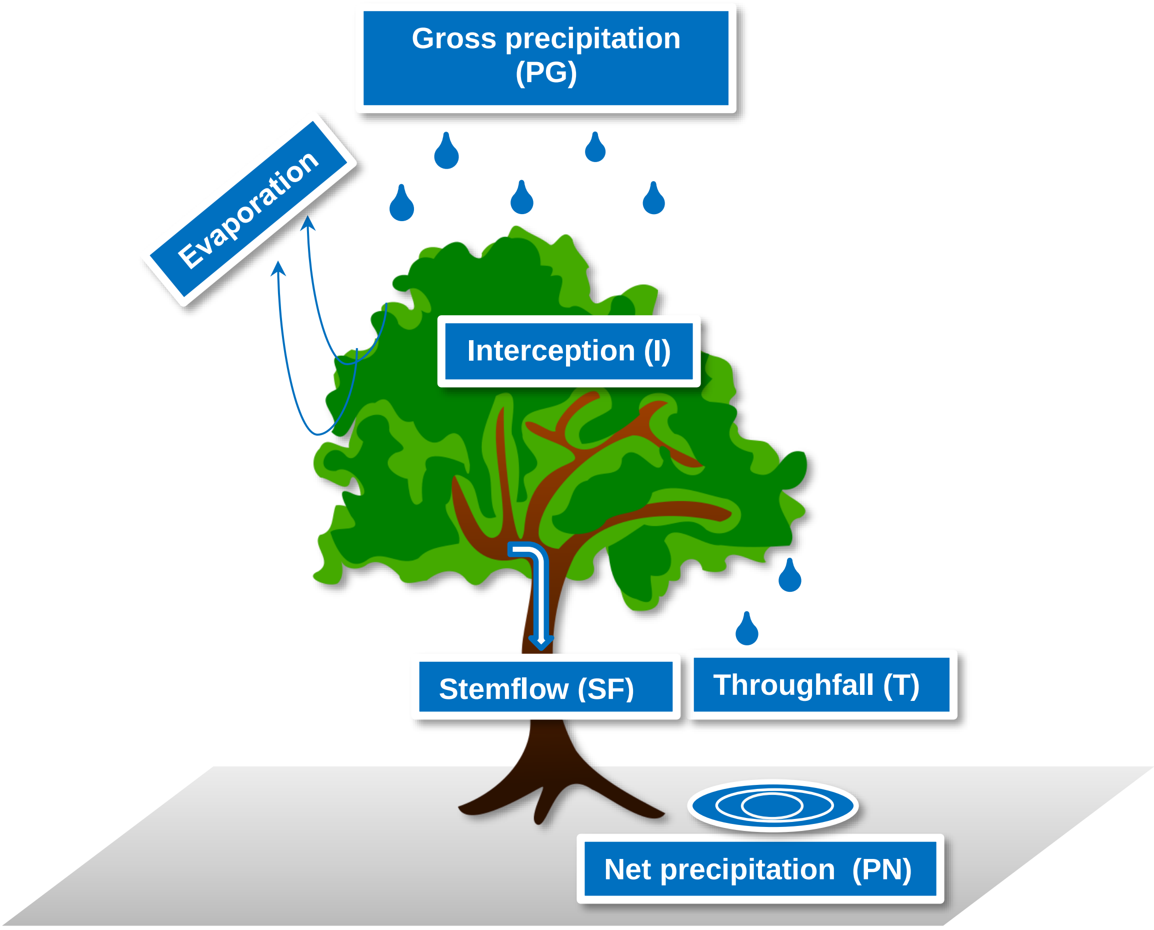


Figure 1.1 Water–tree Interactions during and after a rainfall event

Interception is an important component of the hydrological cycle because it changes not only the amount of precipitation over the soil surface, but also its distribution. Leaves and branches are barriers that reduce the speed and quantity of water reaching the soil surface. Consequently, this attenuates the runoff effect, which is one of the most influential aspects of soil erosion and floods. Intercepted water can also be evaporated or absorbed by leaves, which influences the distributions of water and energy within the urban ecosystem (Xiao and McPherson 2011). Moreover, intercepted water enriches the nutrient status of soil due to the leaching of nutritional components from leaves and branches (Parker 1983; Levia and Frost 2003; Stan et al. 2012).

The water storage capacity of trees canopy is not a constant value, but changes depending on rainfall characteristics, environmental conditions and tree characteristics. Interception effectiveness is directly related to the volume of rainfall received, which will always be influenced by rainfall intensity and duration (Crockford and Richardson 2000; Klamerus-Iwan 2015). Interception values are smaller when precipitation is concentrated into short, intense events. The canopy quickly becomes saturated under these conditions and a large proportion of the precipitation drops off the saturated leaf surfaces (Wilson 2016). Environmental conditions as temperature, relative humidity, net radiation and wind speed set the rate at which water is removed from tree surface storage (Xiao and McPherson 2011). Tree canopy architecture, leaf and stem surface areas, hydrophobicity and seasonal changes in foliation may also influence the amount and timing of flow within the canopy (Crockford and Richardson 2000; Levia et al. 2010; Livesley, Baudinette and Glover 2014).

Barbier et al. (2009) reviewed 28 papers from studies of rainfall interception, throughfall and/or SF in boreal and temperate zone forests. From their analyses of different behaviours among different species, we can consider two basic implications: the amount of water reaching the ground surface, as well as the spatial distribution of water over the soil, are affected by differences in the canopy.

Based on these assumptions, investigations in urban forests have been attempting to better understand the consequences of this effect on the urban environment. In previous studies (Table 1.1), interception values ranged from 14.3% to 82.4%.

Table 1.1. Rainfall partitioning from previous studies in urban areas.

		Rainfall partitioning (%)		
Reference	**Species**	**Interception**	**Throughfall**	**Stemflow**
Xiao et al. (2000)	*Pyrus calleryana*	15.0	77.0	8.0
	Quercus suber	27.0	58.0	15.0
Guevara-Escobar et al. (2007)	*Ficus benjamina*	59.5	38.1	2.4
Asadian and Weiler (2009)	*Pseudotsuga menziesii*	49.1	50.9	–
	Thuja plicata	60.9	39.1	–
Xiao and McPherson (2011)	*Citrus limon*	27.0	71.0	2.0
	Liquidambar styraciflua	14.3	81.6	4.1
	Ginkgo biloba	25.2	73.8	1.0
Livesley et al. (2013)	*Eucalyptus saligna*	27.3	71.0	1.7
	Eucalyptus nichollii	43.9	55.8	0.3
Stan et al. (2014)	*Fagus grandifolia*	21.5	73.2	5.3
	Liriodendron tulipifera	27.8	71.3	0.9
Nytch et al. (2018)	*Albizia procera*	16.4	83.6	–
	Calophyllum antillanum	22.8	77.2	–
Alves et al. (2018)	*Mangifera indica*	48.0	52.0	–
	Pachira aquatica	44.0	56.0	–
	Lichania tomentosa	43.0	57.0	–
	Caesalpinia peltophoroides	28.0	72.0	–

The large range of these results shows the challenge of accurately estimating interception losses, especially because many factors can be affecting the interception process. Xiao and

McPherson (2011) studied how interception effectiveness is correlated to seasonal changes in rainfall and tree traits. They selected three different species: a large gingko, a medium sweet gum and a small lemon tree, gathered throughfall and SF rates under canopies, and associated these with tree characteristics such as Plant Area Index (PAI, see page 18 for definition), bark roughness and branch angle. Although the evergreen lemon tree presented the lowest PAI, it was better at intercepting water than either the deciduous ginkgo or the sweet gum. Because the lemon tree was in leaf during the most of the measured storm events, Xiao and McPherson (2011) concluded that evergreen trees are more effective in their rainfall interception and better at reducing stormwater runoff than deciduous trees over the long term because they keep an area covered for a longer time.

Another study developed in residential areas suggested that canopy cover is more significant in predicting throughfall than PAI (Inkiläinen et al. 2013). Inkiläinen et al. (2013) distributed 26 litre containers in a grid of 10 m x 10 m to ensure having one measurement point per 100 m^2. As they were considering random points in a grid area of 100 m^2, this suggests that the presence of any kind of cover would be more correlated to the throughfall rates than the quality of this cover (expressed by PAI values). Additionally, the complexity in measuring PAI in a heterogeneous area as residential gardens may explain why canopy cover was considered a better predictor for throughfall than PAI.

Although it is a complex metric to measure in heterogeneous urban areas, most models to predict interception use PAI data as the only information about tree characteristics influencing the interception process (Muzylo et al. 2009). Research by Livesley et al. (2014) endorses the importance of using leaf area as a parameter to estimate ecological benefits such as the interception of rainfall. In their research, canopy throughfall was measured beneath two different eucalyptus trees. These species present similar architecture, with some differences in bark roughness and canopy density. They found that trees with denser canopy and greater PAI intercepted more rainfall compared with trees with a less dense canopy, even if their architecture was similar.

In tree canopy–based analyses, individual variations in leaf and branch density, and surface characteristics have been observed to influence water storage capacity. The water storage capacity is the most important parameter that sets the amount of water that can adhere to the tree under determined conditions. The storage capacity of a tree is explained as the water retained by its vegetation at a given time (Llorens and Gallart 2000). In a process-based study, Aston (1979) defined the maximum water retention (C_{max}) as the moment when “the rates of rainfall interception and drainage are equal, neglecting evaporation”. For Aston (1979), C_{max} would increase with an increase in rainfall intensity, which is partially true. However, some studies have shown that storage capacity reaches the maximum amount of water that can be stored independently of the rainfall intensity (Li et al. 2016; Xiao and McPherson 2016) Therefore, the storage capacity is mainly driven by surface area and characteristics.

After a tree reaches its maximum storage capacity and the rain ceases, water continues draining off the canopy, dripping from leaves and branches, or flowing down the stem. After drainage ceases, the remaining water will be only lost by evaporation, defined as the minimum storage capacity (C_{min}), which means that this is the real amount intercepted by the tree and not reaching the ground (Aston 1979; Li et al. 2016).

Leaf and branch inclination and hydrophobicity have been recently studied as factors influencing the interception process (Holder 2013; Carlyle-Moses and Schooling 2015; Goebes, Bruelheide et al. 2015; Goebes, Seitz et al. 2015; Holder and Gibbes 2016). The level of hydrophobicity and other parameters connected to leaf shape appear to be secondarily driving the storage capacity (Goebes, Bruelheide et al. 2015; Holder and Gibbes 2016). Yet, these factors influence the size and kinetic energy of drops, which are important parameters in the redistribution of throughfall under the canopy.

1.3.3.1. Redistribution of throughfall

During a rainfall event, a tree can reduce the amount and speed of water reaching the ground due to its capacity to store water on its leaves and branches. However, not all of the water is stored on those surfaces and it may reach the ground after passing through the canopy. Depending on the intensity of the precipitation event, and adverse environmental conditions such as high wind speed, the water will not remain on the surfaces and can be redirected by branches and stems to the ground. Yet, water can also accumulate in leaves and branches, and drip onto the subjacent layers of the canopy until it finally drops to the ground (Nanko, Hotta and Suzuki 2006; Zabret et al. 2017). This process shows that the spatial redistribution of throughfall is totally dependent on the arrangement of leaves and branches.

Few studies have acknowledged the spatial redistribution of rainfall by individual trees (King and Harrison 1998; Guevara-Escobar et al. 2007; Fathizadeh et al. 2014; Levia et al. 2017). In a forest context, the redistribution of rainfall has the consequence of the redistribution of nutrients and water under the canopy (Stan et al. 2012; Fathizadeh et al. 2014). The pathways along which water runs within the canopy carry important nutrients and influence their availability in the soil near the roots. The redirection of water also influences its availability for the tree and other living organisms dependent on the soil.

From the point of view of urban forestry, the redistribution of water may have different consequences depending on the location of the tree. In a park where trees are surrounded by pervious ground surfaces, the redistribution of water under the canopy affects the availability of water to the plants and the microorganisms that live in the soil, and may affect the absorption of nutrients and the quality of the soil (Ford and Deans 1978; Parker 1983; Geißler et al. 2012). In a streetscape, tree canopies may attenuate the kinetic energy of high-magnitude events (Nanko et al. 2011), affecting the kinetic energy with which the water hits the surrounding impervious surfaces (Geißler et al. 2012) and so reducing the speed of runoff flow. Not only do trees reduce the kinetic energy of raindrops and consequently the speed of throughfall reaching the ground, but the size of drops may also be affected. The size of drops increases after passing through the canopy and the volume of larger drops tend to increase after the canopy is saturated, mainly in low-intensity rainfall events (Nanko, Hotta and Suzuki 2006; Nanko et al. 2011). Larger drops have greater potential to cause erosion if the soil conditions are unfavourable.

The amount of throughfall varies under the canopy and it tends to increase as the radial distance from the trunk increases (King and Harrison 1998; Nanko et al. 2011). This effect seems to be connected to the density of leaves and branches, as the density is higher in the central parts of the canopy and connected to the shape of the canopy, which can favour water to flow mostly on the external layers of the canopy (like an umbrella effect).

1.3.3.2. Stemflow

A proportion of gross precipitation tends to reach the ground surface via SF and it is often not measured at all (Asadian and Weiler 2009). Although the proportions are small, SF concentrates rainfall in a small area, which may increase groundwater (Arnell 2002). Globally, SF has been studied far less than throughfall because it is considered a relatively small proportion of incident rain, typically ranging from 3% to 10% of total precipitation reaching the ground, but it can reach values of 80% in broad-leaved deciduous forests (Schooling 2014).

As interception, SF also varies depending on rainfall characteristics. Levia et al. (2010) found that SF declines considerably when rainfall intensity increases. However, SF will be greater when a rainfall event has intensity peaks, rather than under constant intensity rainfall (Dunkerley 2014). Rainfall inclination angle and wind speed are also associated with higher rates of SF (Carlyle-Moses and Schooling 2015).

The main controls on the amount of SF generated by a tree are the area of the crown, the smoothness of the bark, the position of the tree relative to its neighbours and the configuration of the branches (Arnell 2002; Carlyle-Moses and Schooling 2015). Although high volumes of SF are generally connected with the number of leading stems and bark roughness, Carlyle-Moses and Schooling (2015) found that trees with only one stem and bark with linear furrows (Bark Relief Index, BRI, ranging from 1.15–1.20) may redistribute 1.97–3.61 l mm^{-1} via SF.

Livesley et al. (2014) suggested that bark smoothness is an important characteristic that controls SF, as rougher barks can intercept and store more water. SF is also intensified by broad-leaved trees and it is particularly observed during seasonal defoliation when trees are leafless (Dunkerley 2013), which means an increase in water availability around the trunk. In a street tree context, the availability of water may help in their establishment, as it can improve tree fitness and growth if a permeable surface is provided around the base. Trees in parks benefit from improvement in water availability, as does surrounding understory vegetation. Yet, the increase in water on impervious surfaces may intensify runoff amounts and speeds, and this should be considered in areas prone to soil erosion.

1.3.4. Measuring interception parameters

Mitigation of the negative impacts of stormwater runoff in urban areas is an important issue for urban forest management. As mentioned previously, the growth of urban areas causes a change towards impervious surfaces in place of pervious ones and brings the sewage system closer to its maximum capacity. These changes lead to an evident intensification of flood occurrences. As one of the mitigation actions, cities are investing in expanding their proportion of pervious areas, mainly through increasing green areas and canopy cover.

Many studies have reported the benefit of trees for the reduction of runoff effect by storing water in their canopies (Armson, Stringer and Ennos 2013; Kim and Park 2016; Zölch et al. 2017; Grey et al. 2018a). However, methods to precisely estimate rainfall interception by urban trees are still developing. The estimation of the amount of water intercepted on the canopy can be calculated by different approaches, which can be done directly or indirectly. Additionally, there is no standardised approach and calculation is frequently underestimated by indirect methods (Llorens and Gallart 2000; Muzylo et al. 2009). The advantages and disadvantages of each method will be described in the following paragraphs.

Direct methods for measuring interception were developed for small samples and studies on a small scale, and mostly take place in a controlled environment. The principle of this method is to directly assess the amount of water stored over a given time. Assessments are based on mass change observations that can involve weighing tree components (by submersion or rainfall simulation), calculating branch deflection (mainly used for snow interception), measuring trunk compression or using sway sensors (Aston 1979; Friesen et al. 2015; Li et al. 2016; Xiao and McPherson 2016). This method is more accurate when compared with indirect methods because the total amount of water stored on the plant surfaces is measured immediately. Therefore, the method is effective for measuring the maximum and minimum storage capacity of a plant. However, direct methods may not be employable in every situation because they involve the use of equipment and experiments that may be hard to operate in an outdoor environment. In addition, sometimes the method requires the harvesting of an entire plant or parts of it, and this does not allow us to replicate it over a large scale.

For this reason, an indirect method was created to estimate interception rates without using elaborate equipment and avoiding the harvesting of the plant (or parts of it). The indirect method is based on a canopy water balance estimation and consists of measuring throughfall under the canopy and subtracting it from the net precipitation measured in an open adjacent area (Friesen et al. 2015). This approach is recommended for large-scale research and has been used in many published studies where throughfall was collected under the tree canopy (Guevara-Escobar et al. 2007; Park and Cameron 2008; Asadian and Weiler 2009; Dunkerley 2010; Livesley, Baudinette and Glover 2014). However, some set-ups need a considerable investment in infrastructure to support rainfall collectors

A challenge in large-scale studies may be the heterogeneity of canopy cover (Inkiläinen et al. 2013). Because of this great variation in canopy densities and species, the spatial variation of throughfall is not easily predictable. Therefore, the sampling of points under a covered area may underestimate or overestimate the amount of water intercepted. Increasing the number of samples or using a setting that allows us to move the equipment around may help to solve this problem. However, it is practically impossible to collect the total throughfall amount in large areas and, as such, it must be done for individual trees (Guevara-Escobar et al. 2007).

Interception (I) is calculated by subtracting net precipitation (PN), which is equal to stemflow (SF) plus throughfall (T), from incident precipitation (PI), corresponding to the total amount of rainfall outside the canopy. This value is generally expressed as a percentage.

$I = PI - PN$

where $PN = (SF + T)$

Despite the convenience, indirect methods have limitations when characterising inter-storm dynamics, as they are not particularly accurate (Friesen et al. 2015). For this reason, choosing between those different methods depends on the budget, purpose and level of disturbance you may cause to the trees.

The accuracy of field measurements also depends on several factors, including variations caused by wind, splash effects and water loss through evaporation (Inkiläinen et al. 2013). Additionally, trees are living elements in the urban scenario and very sensitive to modifications of the surrounding environment, and so may need to adjust their shape to these circumstances. Therefore, the value of potential benefits such as avoiding stormwater runoff is highly dependent on the location and context of the urban environment (Alonzo et al. 2016).

1.3.4.1. Rainfall simulation

In the first stage of this project, an experimental study was designed to provide preliminary data to understand how rainfall interception is influenced by different tree species. To achieve this, a rainfall simulator was built to study water storage capacity in a controlled environment. Rainfall simulators provide quick measurements without having to wait for natural rain, while providing results free from the unpredictable variability of natural rain (Hudson 1993).

Although many rainfall simulators have been built for soil studies testing runoff and infiltration effects, the use of simulators is appropriate for studying the interception of rainwater provided by different plant densities (Hudson 1993). In all cases, the key task required from these simulators is to reproduce the physical characteristics of natural rainfall (Assouline, El Idrissi and Persoons 1997). Reproducing natural rainfall is not a simple task. Rainfall simulators may reproduce the natural distributions of drop sizes, with uniform distribution of drops over all testing areas, adopting a realistic intensity to achieve drop impact velocity near natural rainfall terminal velocity (Hudson 1993; Hignett et al. 1995; Sawatsky et al. 1996; Blanquies, Hallock and Scharff 2003). However, the intensity must be controlled over the simulation period, which does not represent natural variability.

Simulated rainfall should be of fairly uniform intensity over the test site. For this reason, the coverage area is suggested to extend for two metres or more to reduce edge effects (Sawatsky et al. 1996). The drop velocity is another important attribute when designing a rainfall simulator. A rainfall simulator must create drops of adequate size and velocity to simulate natural conditions, with drops having the capacity to reach the tree canopy at terminal velocity (Blanquies, Hallock and Scharff 2003). For this purpose, a variety of rainfall simulators can be built, offering different advantages and disadvantages. Basically, rainfall simulators can be separated into two categories: the spraying nozzle type, which produces rain controlled by a high pressure but pulsed to give a lower general intensity; and drop-former simulators designed to produce large drops at near terminal velocity, usually delivered from modules with ranges of internal needles and falling five metres or more (Hudson 1993; Hignett et al. 1995).

In their research, Bowyer-Bower and Burt (1989) compared the two most common types of rainfall simulator and highlighted the advantages and disadvantages of each system. Spraying simulators are more likely to reproduce natural rainfall in terms of drop size distribution and height of fall. It is also possible to achieve a larger range of drop sizes without changing much equipment and these systems can easily achieve rainfall terminal velocity "so that the kinetic energy of simulated rainfall resembles that of natural rainfall" (Bowyer-Bower and Burt 1989). However, spray-type simulators present the common difficulty of producing too high a rainfall rate for the required drop size. Larger rainfall intensities are produced by lower water pressure, which enlarges the size of drops falling over a smaller area. On the other hand, lower rainfall intensity is created by a higher water pressure, which produces smaller drop sizes falling over a larger area (Bowyer-Bower and Burt 1989). Another disadvantage is that this kind of equipment is very wasteful regarding water use, especially at low rainfall intensities (Bowyer-Bower and Burt 1989).

For comparison, drop-forming rainfall simulators were also used in Bowyer-Bower and Burt's (1989) study, having a wire mesh suspended 200 mm below the drop-formers for randomly distributing and fusing water drops into a distribution of drop sizes like natural rainfall. During simulations, the distribution of drop sizes is totally regulated by the dimension of the mesh. A disadvantage of using this type of simulator is that it is easily influenced by temperature changes, because if the air temperature increases, air can enter the tubing of the drop-formers and decrease the rate of dripping and consequently the rainfall intensity. Finally, drop-forming simulators are not recommended for large-scale use since a very large distance (10 metres) is required to reach terminal velocity. Also, this type of simulator does not create a distribution of drops size "unless a variety of drop-forming sized tubes are used". Another negative of the drop-forming simulator is their restricted application to small areas (Blanquies, Hallock and Scharff 2003).

Based on these references, spraying nozzles were chosen for this research, seeing that this experiment requires a large area (16 m^2). To guarantee high uniformity of the spray, the full-cone spray design was used because it produces a wide spraying angle.

1.3.4.2. Rainfall interception models

Rainfall interception models have been developed to estimate the amount of interception loss in vegetated areas based on observed climate data and allometric relationships. From these models, it is possible to quantify the water stored in trees canopies and the effects on the hydrological balance of catchments.

Perhaps the best known interception models are those developed by Rutter et al. (1970) and adapted by Gash, Lloyd and Lachaud (1995). These models are stand-based and mainly applicable to uniformly forested areas (Muzylo et al. 2009). Gash's model (Sadeghi et al. 2015) is a storm-based model that has been successfully used in forestry research and has become widely used in recent decades (Muzylo et al. 2009). In 1995, the original model was adapted to improve a limitation in the description of sparse forest (Gash, Lloyd and Lachaud 1995). However, some studies have successfully adapted this model for use in urban forests (Huang et al. 2017). The success of these analytical models is attributed to the low demand for data and the simple but realistic method to predict interception losses (Gash, Lloyd and Lachaud 1995).

In the revised Gash model, interception, throughfall and storage capacity can be predicted from meteorological data (air temperature, relative humidity, wind speed, gross rainfall, duration of the event) and canopy parameters (PAI) (Huang et al. 2017). In this study, the adapted Gash model (Gash, Lloyd and Lachaud 1995) is used to predict storage capacity with data collected in a rainfall simulation and in an urban park.

1.3.5. Measuring plant surface area

To understand the canopy storage capacity, it is crucial to estimate the surface areas that will potentially store the rainwater. To measure the surface area of a tree, we must consider the characteristics of each basic aerial structure: leaves, stems and branches. Formation and arrangement of each part characterise the tree architecture, which is partially associated with gene expression and does not vary among trees of the same species (Dujesiefken et al. 2005). However, the urban environment presents many constraints for a tree's development which may affect its architecture at the time. Pruning, water availability, vandalism and physical obstacles may impose conditions in which trees are forced to change their external characteristics in order to adapt. Therefore, the tree shape at a mature age represents a manifestation of the balance between internal processes and external environmental limitations (Dujesiefken et al. 2005).

1.3.5.1. Plant Area Index (PAI)

PAI is the most used parameter to predict many ecosystem services, as those benefits are totally dependent on the total surface area of leaves, branches and stems comprising the canopy area. The PAI is a two-dimensional (2D) index which is calculated by dividing the total plant area by the canopy's projected area (Bréda 2003). There are different methods available to estimate PAI, basically divided into direct and indirect. The direct method consists of removing part or all of the leaves and measuring their area using a planimeter or scanner. Although this method is accurate, it is time-consuming (Weiss et al. 2004) and laborious, and does not use data that is readily available on a large scale for decision-makers.

Therefore, indirect methods for measuring PAI have often been employed because they are more convenient, allowing for the sampling of a larger area and not disturbing the vegetation. Indirect methods are essentially estimations of the area based on observations of other variables (Jonckheere et al. 2004). Traditional indirect methods for measuring PAI include photo-based analysis and specially designed devices to measure plant area (e.g. Licor) and all rely on the estimative of light detection through the gaps in canopy images (Jonckheere et al. 2004; Weiss et al. 2004).

In the last few years, the development and improvement of remote-sensing technologies have held the promise of a scalable method for assessing PAI (Zheng, Moskal and Kim 2013;

Alonzo et al. 2015; Y. Lin and West 2016). Because sensors and images may provide the path of a ray of light passing through the canopy, remote-sensing techniques can mimic conventional methods for measuring the leaf area index (LAI) as they are based on the retrieval of gap fractions from vegetated areas (Danson et al. 2007; Antonarakis et al. 2010). Therefore, studies such as those of Alonzo et al. (2015), Seidel, Fleck and Leuschner (2012), Takeda et al. (2008) and Morsdorf et al. (2006) have conducted fieldwork to collect laser scanning (LS) data and correlated this with canopy gap fraction to estimate PAI, and found significant associations between both metrics.

LS data (also known as light detection and ranging – LiDAR) generates three-dimensional (3D) point clouds by using an instrument that emits pulses of light that are reflected by trees, ground surfaces and other terrestrial features (Plowright et al. 2016). There are basically three different approaches to producing LS data: airborne, terrestrial and mobile. Holopainen et al. (2013) describe airborne laser scanning (ALS) as a method based on LiDAR range measurements from an aircraft where the precise orientation of these measurements between sensors is defined "using a differential global positioning system (GPS) technique and an inertial measurement unit (IMU)". From these references, the position (x, y and z) of a reflecting object can be assessed. The georeferenced point cloud provided by ALS data allows us "to calculate digital terrain models (DTMs), digital surface models (DSMs) corresponding to treetops and three-dimensional (3D) models of an object (e.g. canopy height model (CHM))" (Holopainen et al. 2013). One of its particularities is the capacity to infiltrate gaps in the foliage, allowing ALS to "directly measure the vertical aspects of tree crowns and forest canopies (Plowright et al. 2016). Therefore, this technology has been used in forest investigation for two basic proposes: canopy height distribution and single tree detection (Wang, Weinacker and Koch 2008; Plowright et al. 2016). Also, this technology has been employed to measure tree height, biomass and LAI for single-tree studies (Alonzo et al. 2015) and for the classification of trees at leaf type, genus and species level (Alonzo, Bookhagen and Roberts 2014). LS data can be employed to reproduce the vertical canopy structure as it is highly accurate in 3D measurement (Wang, Weinacker and Koch 2008).

Terrestrial laser scanning (TLS) (also known as ground-based laser scanning) consists of a scanning system mounted on a tripod and is used mainly for detailed surveys in small areas, as its high-density scan radius is "less than a few tens of metres" (Holopainen et al. 2013). TLS is not recommended for large areas, because the data processing may be time-consuming due to the high density of point clouds scanned. However, for the same reason TLS can provide accurate and detailed point clouds (Lichti, Gordon and Stewart 2002) and, consequently, the advantage of easier recognition of trees, which is essential for estimating tree characteristics (Holopainen et al. 2013).

Each method presents disadvantages regarding tree detection: ground-based data can be affected by understory shrubs, while airborne data can be affected by canopy occlusion (Holopainen et al. 2013). However, the usage of LS data in urban forestry remains limited due to the complexity of the landscape and, until the present, there are not many studies regarding the use of TLS in urban areas (Moskal and Zheng 2012; Holopainen et al. 2013).

From the point of view of urban forestry, LS data can provide detailed maps of the urban forest structure and function at the individual tree scale, which may improve comprehension of the spatial distribution of ecosystem services in the city, and better guide planning and management decisions (Alonzo et al. 2016). Because the interception of rainfall is a process that occurs in a 3D space, the understanding of 3D LS data to use for estimating plant area seems essential now. Improving the use of this data may motivate better use of these well-known technologies in the processes of prediction and evaluation of tree benefits for stormwater management in cities.

1.3.6. Monitoring ecosystem services

As mentioned previously, assessing the urban forest structure is required in order to estimate the ecosystem services provided by the urban forest, such as stormwater runoff reduction. To comply with the sustainable use of trees in stormwater management, it is essential to keep track of the urban forest conditions and check if the expected results are being achieved. Thus, monitoring is an important phase of management as it provides feedback on the results of practices, allowing planners to adjust priorities and review the management plan (FAO 2016). In the first stages of urban forest planning, monitoring must be integrated into the management plan to guarantee the sustainability of the system. According to the Guide on Urban and Peri-Urban Forest (FAO, 2016), the management of urban trees can be divided into five steps (Figure 1.2):

1. Assessing resources
2. Identifying scope and needs, and setting priorities
3. Developing the management plan
4. Implementing the management plan
5. Monitoring and evaluation

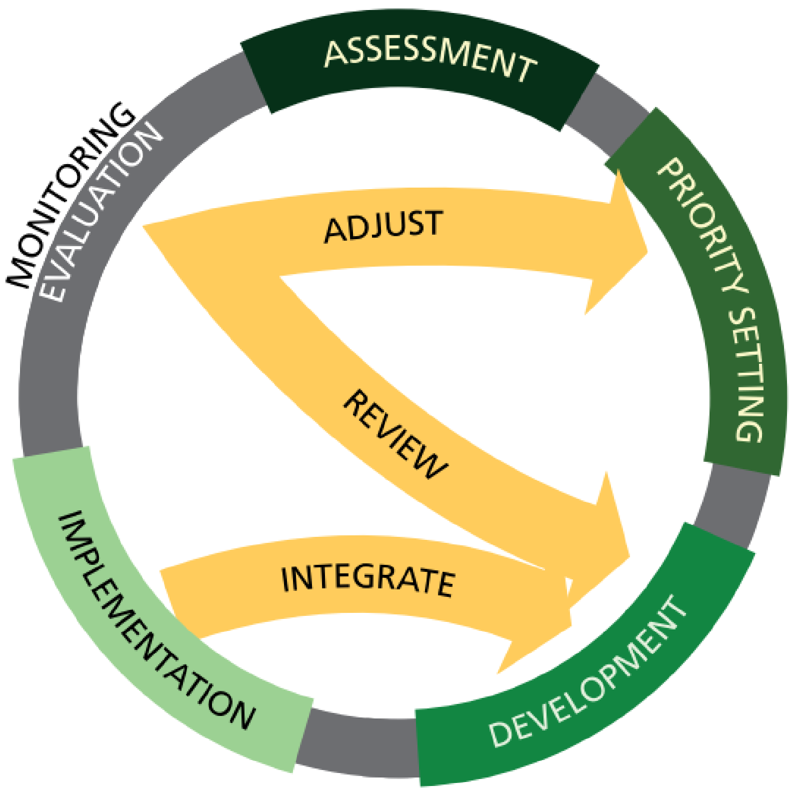


Figure 1.2 The urban forest management cycle (FAO 2016).

The concept of managing natural resources in urban environments was developed in North America only in the 1960s (Konijnendijk et al. 2006). At that time, tree inventory was the most employed tool to assess tree health (Baker 1993). Although assessing trees' health is essential to the sustainability of an urban forest, monitoring an urban forest goes far beyond the management of trees. Urban trees should be managed to fulfil three different purposes: political, social and biological (Baker 1993). Thus, the concept of monitoring should "include information not only about trees but also about the benefits they provide to people" (Baker 1993).

Over the past few decades, significant effort was made to assess the ecological services provided by urban trees. In the mid-90s, the USDA Forest Service started combining different methods to use urban forest cover as a metric to evaluate structural data and use this to model urban forest ecological services (Nowak et al. 1996). In the late 2000s, the Urban Forest Effects (UFORE) model was adapted to create the i-Tree model, which was cooperatively developed by a private–public partnership. Since then, the software have expanded to 131 countries as a tool to "assess and value forest resources, understanding forest risk, and developing sustainable forest management plans to improve environmental quality and human health" (Nowak, Maco and Binkley 2018).

Although the use of i-Tree has spread among important cities in the world, canopy cover has been the most adopted parameter for monitoring the urban forest (City of Melbourne 2012; City of Vancouver 2015; City of London 2011). This metric is used in conjunction with aerial photography and satellite images. Assessment from an aerial view benefits urban foresters by providing a general view across the whole area (Baker 1993). So, when the use of remotely sensed data was popularised into different areas of urban planning, the use of this metric simplified the collection of data.

Yet, assessing and monitoring the urban forest is a challenging task given the complexity of interactions between trees and the surrounding environment. Additionally, the heterogeneity of the urban forest makes it hard to trust in generalised models. As we advance and simplify the use of new technologies and techniques such as LS data, we must develop a more accurate way to monitor the ecosystem services provided by the urban forest.

Chapter 2. Variations in leaf area density drive the rainfall storage capacity of urban tree species

2.1. Introduction

In Chapter 1, the concept of interception was introduced and a summary of documented methods for estimating it was presented. Several studies have demonstrated the important role of urban trees in reducing runoff in cities (Armson et al. 2013; Zölch et al. 2017; Grey et al. 2018b). By intercepting rainfall and storing part of it on their leaves and branches, trees may reduce the amount and speed of water running onto impervious surfaces. Storage capacity will depend on the rainfall event, the climate conditions, and tree characteristics and canopy density. These canopy characteristics vary greatly among different species and their phenology. Furthermore, these canopy characteristics can vary greatly among individual trees of the same age, size and species.

In this chapter, a method is developed to test how canopy density and leaf characteristics of three different tree species affect storage capacity under simulated rainfall conditions. Three species are selected (*Ulmus procera*, *Platanus* x *acerifolia* and *Corymbia maculata*), each being of the same height and similar canopy dimensions. Storage capacity is measured using a mass balance approach during a 15-minute indoor simulated rainfall event (2.54 mm/h). Canopy metrics are estimated using a terrestrial laser scanner. Canopy surface area is measured through destructive harvesting and leaf/twig/branch scanning. To investigate variations in the canopy leaf density, leaves are systematically removed to create four treatments: full, half, quarter and woody.

Canopy storage capacity is well correlated to plant surface area (m^2), PAI (m^2/m^2) and plant area density (m^2/m^3). All analyses indicate that *U. procera* is the most efficient species for storing rainfall water within a canopy of equal volume or area index.

Overall, this chapter contributes to understanding how variation in the leaf density affects the storage capacity. Results reveal the complexity of evaluating the interception of rainfall by tree canopies, as there are multiple factors affecting storage capacity.

2.1.1. Background

By mid-2009, the number of inhabitants in cities globally surpassed the number of people in rural areas for the first time (FAO 2016) and this trend of increasing urban settlement is expected to continue into the foreseeable future. From a hydrological point of view, urbanisation changes the physical characteristics of watersheds and directly affects the timing, quality and quantity of surface flows within them (Armson, Stringer and Ennos 2013). In particular, urbanisation results in an increase in impervious surface areas, which reduces the movement of water below ground and increases storm runoff volumes (Arnell 2002). Depending on the magnitude of the precipitation event, urban storm runoff can cause floods (Wheater and Evans 2009) and erosion (Berland et al. 2017), and actively transports urban contaminants into receiving waterbodies (Yang and Zhang 2011).

To avoid the problems associated with stormwater runoff, urban centres are often supported by complex engineered drainage networks consisting of a connected system of surface inlets and underground pipes that are designed to transport stormwater out of the urban environment as quickly as possible. Unfortunately, many of these urban stormwater drainage networks were constructed when cities were less dense and had fewer impervious surfaces, and before climate change was widely known to increase future storm intensities (Wilson 2016). As such, many urban stormwater drainage systems are currently functioning close to or at capacity, placing their associated urban centres at higher risk of repeated flooding (Moore et al. 2016). Upgrading and re-engineering the drainage network of a city is both costly and technically challenging, and this encourages the consideration of alternatives to help reduce runoff, such as increasing urban green spaces and vegetation cover (Ossola, Hahs and Livesley 2015; Zhang et al. 2015; Armson, Stringer and Ennos 2013; Zhang et al. 2012) and implementing WSUD technologies (Lloyd 2001; Roy et al. 2008).

Trees have the potential to play an important role in modifying urban hydrological cycles, as their leaves, branches and stems directly intercept and temporarily store water during precipitation events (Livesley, McPherson and Calfapietra 2016). Some of this water is lost as evaporation, reducing its contribution to stormwater runoff, and some is delayed, reducing peak discharges (Xiao and McPherson 2002; Levia et al. 2011). Armson et al. (2013), for example, identified that surfaces beneath trees in the urban region of Manchester, UK had 60% less runoff than comparable surfaces without trees. As such, trees have the potential to play an important role in reducing stormwater impacts in urban environments.

The process whereby trees capture precipitation is referred to as interception and is known to vary depending upon the tree species under consideration. Research has shown that characteristics such as bark roughness, branch inclination, and leaf roughness and angle directly affect tree canopy interception rates and determine the maximum and minimum canopy storage capacity (C_{max} and C_{min}) (Li et al. 2016; Van Stan, Levia and Jenkins 2014). Smoother bark and leaves, as well as branch and leaf angles of orientation, are known to influence SF and throughfall rates (Xiao and McPherson 2011; Livesley, Baudinette and Glover 2014; Li et al. 2016; Holder and Gibbes 2016).

An important characteristic of trees that greatly determines their capacity to intercept and store water is the overall surface area of the canopy made up of individual leaves (Aston 1979; Li et al. 2016; Xiao and McPherson 2016). As such, LAI, or the surface area of leaves included in one square meter of ground area (m^2/m^2), is commonly used to represent the ability of a tree to intercept and store water (Yang, Endreny and Nowak 2011; Xiao and McPherson 2016; Li et al. 2016; Goebes et al. 2015; Barbier, Balandier, and Gosselin 2009; Aston 1979). Although the areal extent of leaves is clearly important for interception, less well understood is the influence of plant area density (PAD), or the total leaf and stem area per unit volume of the canopy (m^2/m^3). Many urban trees grow in confined street canyons that limit lateral canopy growth and they are frequently pruned to avoid wires and poles or facilitate traffic movement. This may change the ratio of leaf to stem matter and make PAD an important parameter to consider in interception analyses. Little, however, is known about how changes in leaf density affect the amount of water stored in trees over time.

The aim of this chapter is to analyse how changes in leaf area affect surface water storage capacity and to identify the associated proportional contribution that is made by woody surfaces (stems and branches). This involves evaluating and comparing the interception of rainfall by three tree species that are commonly used in urban landscapes in Melbourne, Australia. Specific objectives are to: (1) measure and compare canopy area metrics (including plant surface area, PAI and plant area density) for each species; (2) measure maximum and minimum water storage capacities (C_{max} and C_{min}, respectively) for each species; (3) estimate the effect of varying leaf area density on tree water storage capacity; and (4) compare leaf and woody surface area contributions to canopy storage for each species. Understanding how architectural differences between species and trees influence water storage will help inform urban forest managers about which species to plant if reducing urban stormwater runoff is a strategic priority (Xiao and McPherson 2011). Similarly, the information will demonstrate how tree pruning, different levels of leaf loss (e.g. through storms, herbivory or drought) and canopy senescence with age will influence the interception and storage of precipitation.

2.2. Materials and methods

2.2.1. Trees

Three tree species were investigated in this study, with four replicate trees examined for each species, resulting in a total of 12 trees being measured. The included species were London plane (*Platanus* x *acerifolia*), English elm (*Ulmus procera*) and spotted gum (*Corymbia maculata*), which were selected based on their common use in urban parks and street plantings in Melbourne, Australia (Table 2.1). For the remainder of this chapter, the individual

Corymbia trees are referred to as CM1 to CM4, the *Ulmus* trees are referred to as UP1 to UP4 and the *Platanus* trees are referred to as PA1 to PA4.

Platanus x acerifolia, or London plane, is the most planted species in the City of Melbourne landscape. Plane trees are hybrid deciduous species presenting broad leaves with 3 to 5 lightly, unevenly triangular lobes and large pointed teeth. The smooth bark is pale grey, green and cream, and presents an exfoliating appearance. This species is largely employed in urban areas throughout the world because of its tolerance of air pollution, root compaction and wide differences of climate (Hull 2009).

Ulmus procera, or English elm, is the second most commonly planted species in Melbourne. English elms are deciduous species that present round to oval leaves, toothed with a rough and hairy surface texture, which may grow up to 9 cm in length.

Corymbia maculata, or spotted gum, appears in the third position of Melbourne's common tree ranking. The spotted gum has alternate, lance-shape leaves with a short stalk. The leaves are dark green, often paler below, with a length that ranges from 10 to 30 cm and width from 1 to 6 cm.

Table 2.1. Species characteristics

Common name / *Species*	**Leaf habit**	**Leaf profile**	**Bark**	**Street tree profile**
Spotted gum *Corymbia maculata*	Evergreen			
London plane *Platanus x acerifolia*	Deciduous			
English elm *Ulmus procera*	Deciduous			

In this study, the 12 trees were grown in 100 L pots. All trees had their basal stem diameter (BD), tree height (H), canopy height (CH), projected canopy area (CA), canopy volume (CV), leaf area (LA – method explained below) and branch area (BA – method explained below) measured. These were then used to calculate the following parameters: LAI, or the surface area of leaves included in 1 m^2 of ground area – calculated as LA/CA; branch area index (BAI), or the surface area of branches included in 1 m^2 of ground area – calculated as BA/CA; plant surface area (PSA), or the total surface area covered by a plant – calculated as BA + LA; PAI, or the surface area covered by a plant in 1 m^2 of ground area – calculated as PSA/CA; and plant area density (PAD), or the total leaf and stem area per unit volume of canopy – calculated as PSA/CV. Trees presented comparable BDs ranging from 6.2 to 9.7 cm and initial CVs that ranged from 5.61 m^3 to 7.99 m^3.

2.2.2. Rainfall simulation

To measure the volume of water stored by the canopy, each tree was subjected to multiple rainfall simulation experiments. To avoid the effects of wind and direct solar irradiance, these experiments were undertaken indoors, which kept precipitation rates constant and uniform, and ensured an appropriate raindrop size distribution as defined by Knasiak, Schick and Kalata (2007). The rainfall simulator consisted of seven full-cone, wide-angle nozzles (Model TG-SS4.3W, Spraying System Co., Wheaton, IL, USA) placed 2 m apart in a hexagonal arrangement and controlled by a single pressure valve (Fig. 2.1). The nozzles were positioned on a frame with a pulley system that allowed the height above the tree canopies to be adjusted.

Prior to the simulation runs, nozzle calibration tests were performed to investigate the spatial and temporal variability of the simulated rainfall at different precipitation rates (2.5, 5.1, 7.6 and 10.2 mm/h). Each nozzle was tested over a 10 s period following the work of Kibet et al. (2014) and Knasiak, Schick and Kalata (2007). To test spatial uniformity of the rainfall 172 containers (diameter of 80 mm) were placed at ground level (4.7 m below the nozzles) in a grid with an equal spacing distance of 0.25 m. Coefficients of variation (COV) were then calculated for the water received in the containers for each test event to assess uniformity. The best uniformity was found for the 2.54 mm/h precipitation rate, which required the rainfall simulator to operate at mains pressure of 67 kPa, producing a flow rate of 1.6 L/min. A rainfall rate of 2.54 mm/h for 15 minutes is classified as Very Frequent in Melbourne, with more than 12 occurrences per year (Bureau of Meteorology, 2017).

Rainfall uniformity was also checked at different heights above the ground (0.5, 1, 1.5 and 2 m). The best uniformity (COV < 25%) was achieved at 2 m. As the rainfall simulator frame could be raised to a maximum height of 4.7 m, the trees in this study were limited to a height of 2.7 m so that the rainfall was uniform once it intercepted the top of a canopy. To accommodate this, all trees were top-trimmed to ensure they did not exceed a height of 2.7 m. Many street trees in Melbourne and other cities that retain overhead powerlines are commonly lopped to maintain a clearance zone between the top of the tree and the powerlines. The experimental set-up, therefore, replicated real-world conditions.

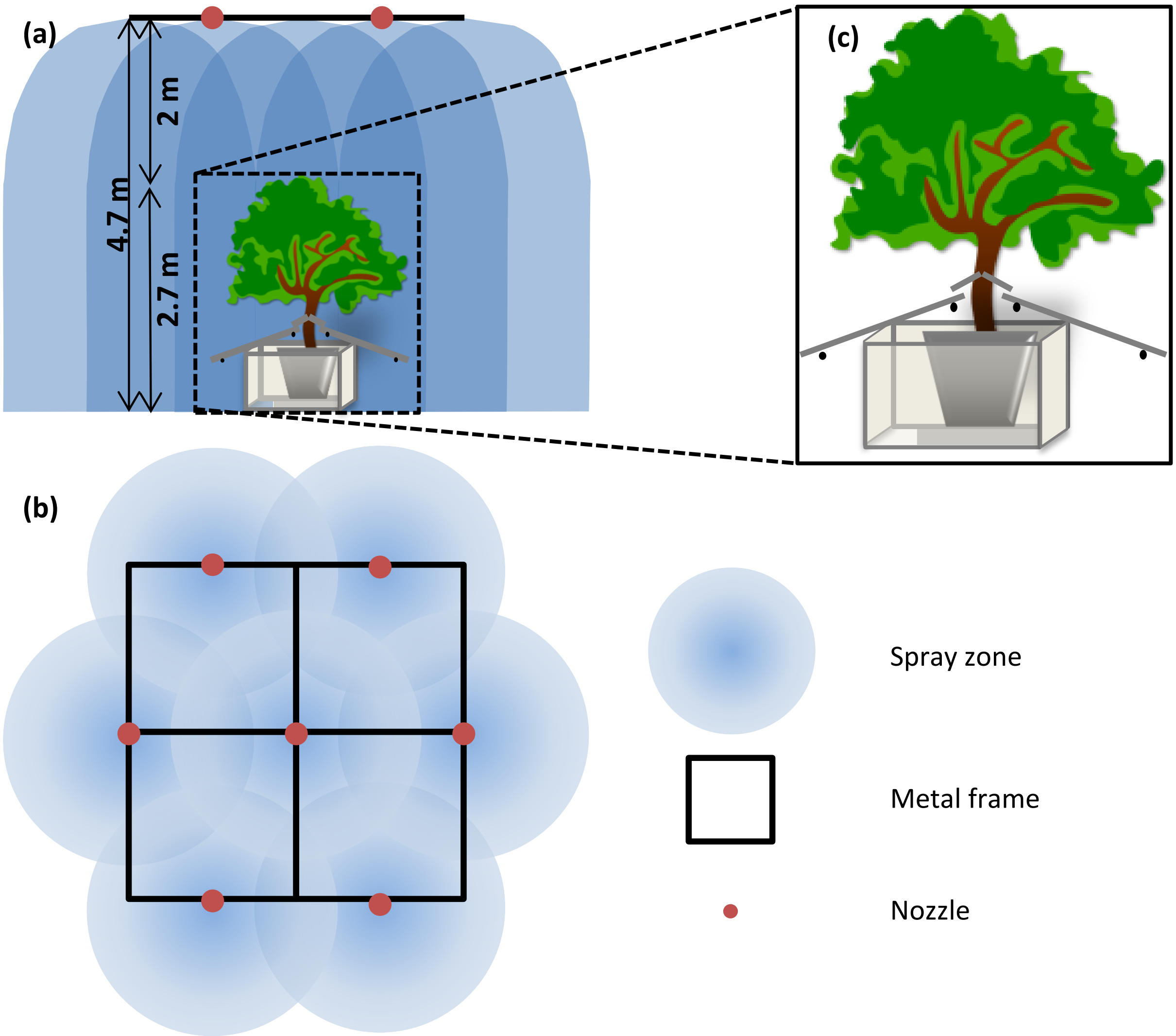


Figure 2.1. Rainfall simulator cross-section view(a); top view of simulator spray zone (b); small plastic roof attached to the tree to prevent water dripping into the pot (c).

2.2.3. Calibration

A calibration process was performed according to a protocol for conducting rainfall simulations elaborated by Kibet et al. (2014). Firstly, nozzles were tested for water flow regularity. A plastic bucket was placed under a nozzle and water was collected during a 10 s period. This process was repeated for each nozzle. The discharge was measured by graduated cylinders and the values had to correspond with the recommended water flow for each kind of nozzle (Knasiak et al. 2007).

After stabilising the regularity of water flow, the second part of the calibration process was to test the spatial uniformity. In this test, the coefficient of variation (COV) for precipitation in the whole area was calculated. The COV was calculated based on the standard deviation (SD) and mean (M) of the collected water volume measured at different time points.

COV = SD/M

This test was performed for different heights of the nozzle assembly. One 172 containers (diameter of 80 mm) were placed at 0.25 m apart on a hexagonal grid at ground level. In the first test, the simulator frame was positioned at its maximum height (4.7 m). Simulated rain was collected in plastic cups (250 ml) during continuous flow, and water volumes were measured using a graduated cylinder. Values in millilitres (mL) were converted into millimetres per minute (mm/min).

The process was performed for three different intensities of rainfall. Better uniformity was found for the nozzle that delivered lower rates of rainfall (2.5 mm/min). Therefore, this nozzle was selected for this experiment.

After achieving a good coefficient of variation at 4.7 m, the next step was to run the test at different heights in order to check uniformity on the tree top level (heights of 1.5 to 2.5 m). An acceptable result for uniformity was achieved at 2 m of height. For this reason, every tree had its top cut at 2.7 m.

2.2.4. Water storage capacity measurements

Before the start of each rainfall simulation experiment, the tree being investigated was placed on a balance (150 kg capacity, 20 g resolution) to continuously measure mass. Water storage (i.e. interception) was calculated as the change in mass balance of the tree during exposure to rainfall. To prevent SF or throughfall entering the pot and therefore contributing to an increase in measured tree mass, each pot was carefully covered with plastic sheets that directed throughfall outside the measurement system (Fig. 2.1c). A small plastic roof was bonded to the tree stem above these plastic sheets with silicone adhesive. These roofs were made of smooth plastic and steeply pitched to avoid ponding and to direct SF away from the pot to the outside of the measurement system. Therefore, the number of drops held on the small roof at any one time was not considered to have a significant impact on storage variability.

Once a tree was placed on the balance, the rainfall simulator was run for a period of 15 min and tree weight was recorded every 5 s. Maximum interception storage (C_{max}) was measured as the increase in weight observed at the end of the 15 min rainfall simulation (Fig. 2.2). Measurements continued to be taken for another 15 min following the end of the simulated rainfall, ensuring that throughfall and SF had ceased. The water remaining in the canopy at this point was identified as representing the minimum interception storage (C_{min}) (Fig. 2.2).

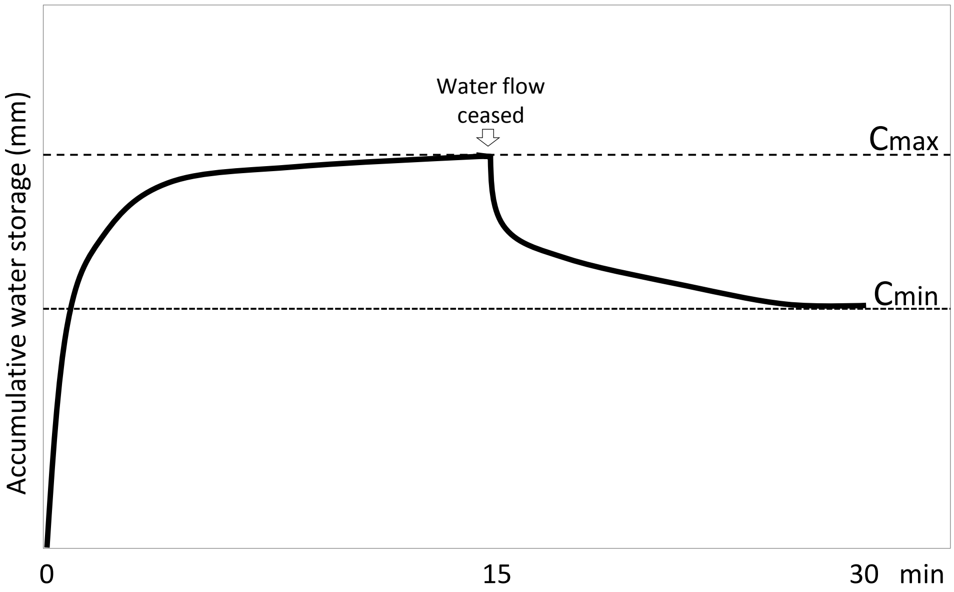


Figure 2.2. Dynamic of the water storage capacity of tree canopies for 30 min after a simulated rainfall of 15 min. Maximum storage capacity (C_{max}) is the maximum amount of water intercepted after a 15 min rainfall. Minimum storage capacity (C_{min}) is the amount of water effectively stored in the canopy (and later evaporated) after 15 min dripping.

Released throughfall is considered the rainfall that hits the tree surface but drops from the canopy. This process is important in the interception dynamics because the kinetic energy of raindrops may decrease after hitting the tree surface and reduce the speed of runoff. The percentage of attenuation is calculated by the difference between C_{max} and C_{min} and then dividing the result by C_{max}.

2.2.5. Sequential leaf removal to reduce canopy leaf density

Canopy water storage was initially measured using rainfall simulation for each of the 12 trees (x4 *C. maculata*, x4 *P. acerifolia*, x4 *U. procera*) with their canopies intact (Full canopy). The trees were then given at least 24 hours to dry, and then every second leaf was removed from all branches, reducing the canopy leaf density from 100% to approximately 50% (Half canopy). Canopy water storage was then re-measured using rainfall simulation on all 12 trees again but at Half canopy. After a period of drying, every second leaf of the half canopy was removed to reduce canopy leaf density from 50% to 25% (Quarter canopy). Canopy water storage was then re-measured using rainfall simulation for all 12 trees but this time at Quarter canopy. Finally, all the remaining leaves were removed and canopy water storage of the bare tree architecture (Woody) of all 12 trees was measured. In total, this resulted in 48 rainfall simulations, 12 for each level of canopy leaf density (100%, 50%, 25% and 0%).

The first half of the removed leaves had their areas directly measured using a leaf area meter (LI-3100 Area Meter, Li-cor, Lincoln, USA). The leaves were initially oven-dried at 60 °C for 48 h, after which their dry leaf mass was determined and a ratio of leaf area by leaf mass was calculated for each tree. All remaining leaves were also oven-dried and had their leaf area calculated by this ratio. This produced a calculation for the total leaf area (LA) for each tree.

After the final simulations, the woody material for each tree was collected and divided into two groups depending on their diameter class: ≥ 1 cm or < 1 cm. Branches in the larger diameter class had their lengths and diameters measured manually. Branches with a diameter of less than 1 cm were measured using a photo-scanning method. First, branches were placed in a light box with a camera (ELMO HV-5100XG Visual Presenter and ELMO TT-12 Document Camera, Plainview, NY, USA) and photographed against the light to capture their exact shadow. A metal rod of known diameter and length was placed in every photo to provide a quality check on the size of the branches. The pictures were then printed and scanned to obtain monochromatic images that could be accurately analysed using the π/2 analysis of the Delta-T SCAN© software (Delta-T Devices Ltd, Burnwell, England), which returned estimates of branch length, area and volume. This resulted in the calculation of the total branch area (BA) for each tree.

2.2.6. Terrestrial Laser Scanning (TLS)

The canopies for every full canopy tree were assessed using a hand-held laser scanner ZEB1 (GeoSLAM Ltd., Nottingham, UK), which consists of a swinging head that shoots multiple laser beams to scan horizontally and vertically with a 270° field of view (GeoSLAM 2015). These scans produced a point cloud for every tree at each canopy condition (full, half, quarter and woody). A concave hull method was then used to calculate tree canopy metrics such as projected CA and CV from the point cloud (Fig. 2.3). To undertake the scans, the target tree was placed in a space with an unobstructed radius of 2 m. The trees were then scanned by walking around them three times at 1–2 m with the scanning device positioned a few centimetres from the body to deliver optimum point cloud accuracy and density. Studies using TLS data to retrieve tree metrics have recommended the use of multiple scans to reduce the occlusion of objects (Seidel, Fleck and Leuschner 2012; Moskal and Zheng 2012).

To standardise the point clouds, duplicated points should be removed from the dataset. Therefore, the random downsampling method was applied, and the two or more points that were within 2 mm of another one were retained and the others removed. This process detected 1% of points as being duplicated points. Then, a statistical de-noising algorithm was applied to remove outlier points, also called dongle points, from the laser point cloud. Based on a 3-sigma test, points with a confidence level of 99.7% were considered inliers. To apply this method, the M and SD of 10 neighbour points were calculated, and points which did not pass the 3-sigma test were considered noise points. In other words, points with a weak connection to sample points were detected as noise points and removed from the point cloud. In this research work, less than 2% of points were detected as outliers. The point cloud data manipulations were performed using CloudCompare 2.6.2 software.

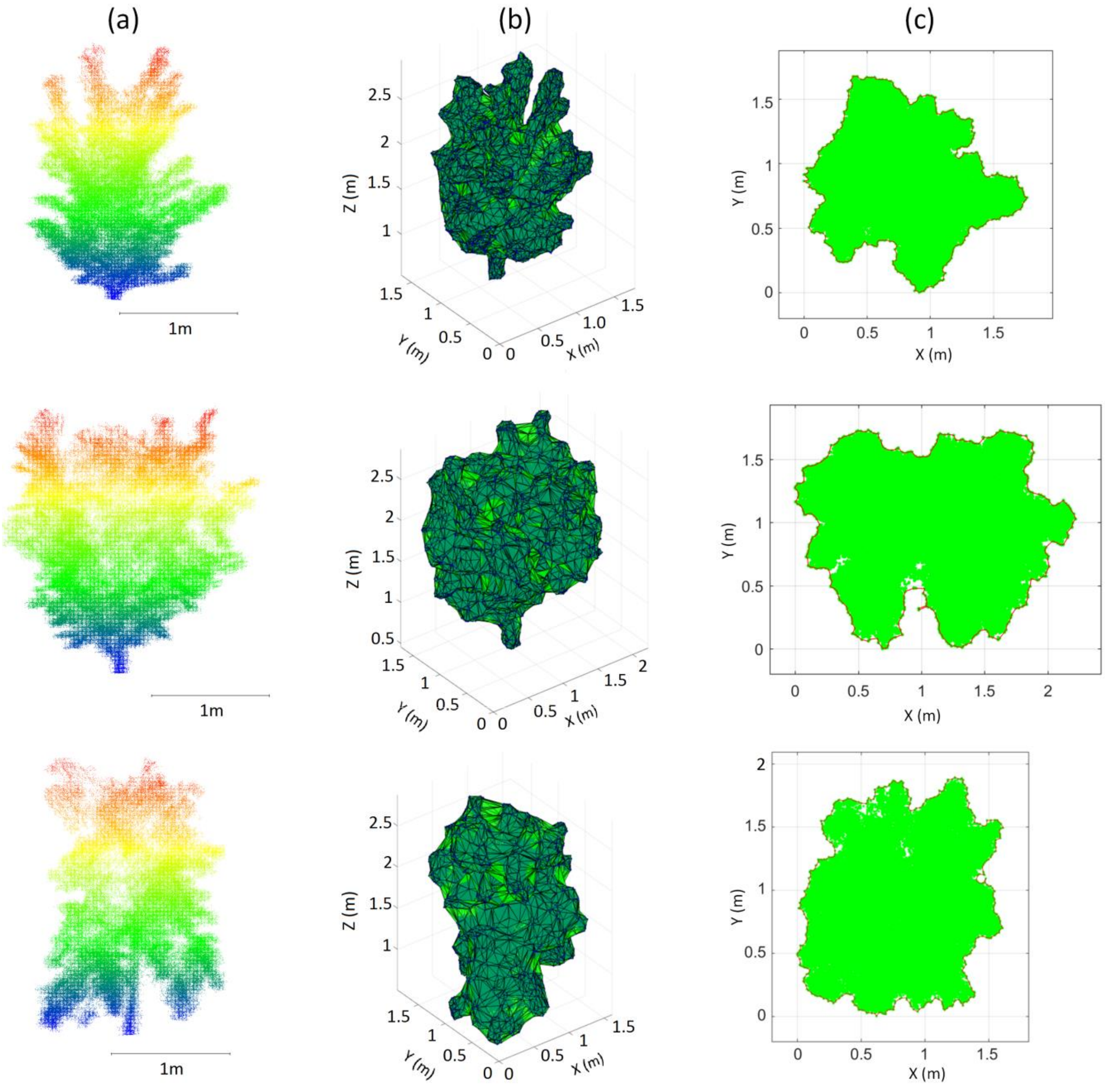


Figure 2.3. (a) Tree canopy point cloud of *C. maculata* (CM1), *P. acerifolia* (PA1) and *U. procera* (UP1), from top to bottom respectively; (b) calculated canopy volume by concave hull method; (c) projected canopy area calculated by concave hull method.

2.2.7. GASH model

The adapted model for sparse forests by Gash (1995) is an empirical, storm-based model that has been employed in many studies to predict interception (Muzylo et al. 2009). This model uses meteorological data and tree parameters to predict storage capacity, interception and throughfall. To apply the Gash model (1995) it is necessary to assume that: (a) events are series of discrete storms separated by periods of time long enough to allow the canopy to dry; (b) meteorological conditions are constant during the event; and (c) there is no dripping from the canopy.

Canopy cover (*c*) was estimated based on a tree's PAI and the coefficient of extinction (*k*) (Deguchi, Hattori and Park 2006), which was considered to be 0.5 for all three species (Bréda, 2003).

$$c = 1 - exp(-k * PAI) \qquad \text{(I)}$$

SF (Equation II) and retention (Equation III) were estimated using a derived equation (Deguchi, Hattori and Park 2006) using diameter at breast height (DBH) as the controlling tree metric. From this data, the SF volume (Ps) can be generally approximated from gross rainfall (P_G) using Equation IV.

$$a_s = 0.0081\ (DBH)^{1.4906} \ \text{(II)}$$

$$b_s = 0.0154\ (\mathrm{DBH})^{1.8639} \ \text{(III)}$$

$$P_s = a_s P_G - b_s \ \text{(IV)}$$

where, a_s represents the quantity of water intercepted by the canopy that is diverted to SF and b_s is the amount of water retained on the trunk. This equation was derived by Deguchi, Hattori and Park (2006) who studied various trees in Japan.

The mean amount of rainfall to saturate the canopy (P_g) (equivalent to the maximum storage capacity [C_{max}]), was predicted using the following equation (Eq. V), assuming no evaporation from the trunk, where S is the mean storage capacity, E_c is the mean evaporative rate, P is the gross rainfall and c is the canopy cover. Rainfall intensity (R) was calculated by dividing the gross precipitation by the duration of each event. Evaporative rate was calculated based on the Penman–Monteith equation (Pereira, Gash, David and Valente 2009).

$$P_g = -\frac{\bar{R}}{\bar{E}_c}\frac{S}{c}\ln[1 - \bar{E}_c\bar{R}] \qquad \text{(V)}$$

The interception was then calculated using the Gash's (1995) modified model (Eq. VI).

$$\begin{cases} I = c.P_G & for\ (P_G < P_g) \\ I = c\ .P_g + \left(c.\frac{\overline{E_c}}{\overline{R}}\right)(P_G - P_g) & for\ (P_G > P_g) \end{cases}$$

2.2.7.1. Testing model efficiency

The canopy storage capacity was directly measured for the studied trees. The results were then contrasted with predicted storage capacity. The storage capacity was predicted using the same environmental conditions of the experiment: gross rainfall of 0.63 mm, rainfall intensity of 2.5 mm/h, average air temperature of 26.4 °C (calculated from the Bureau of Meteorology database) and wind speed of 0 m/s. The predicted results were compared with the maximum and minimum storage capacities (C_{max} and C_{min}).

The root mean square error (RMSE) was calculated for testing the efficiency of the Gash model to predict storage capacity (P_i) in relation to the observed data (O_i) (Eq. VII).

$$RMSE = \sqrt{\frac{\sum_{i=1}^{n}(P_i - O_i)^2}{n}} \qquad \text{(VII)}$$

2.2.8. Statistical analyses

Statistical analyses were undertaken to determine the best predictor of water storage capacity and to validate the relationships between tree metrics and interception parameters. Analyses of covariance (ANCOVA) were performed to identify differences between species, with C_{max} or C_{min} values held as the dependent variable and the tree characteristics of PSA, PAI and PAD as the covariates. These analyses indicated some errors in the calculations of C_{min} for CM1 and CM2, which recorded negative differences between the Full and Half canopy data for C_{min}, and for UP2, which returned a negative difference between the Half and Quarter canopy data for C_{min}. Consequently, these samples were removed from the dataset. A post-hoc Tukey test was used to validate statistical differences between species and all statistical analyses were performed in RStudio 1.0.153.

2.3. Results

2.3.1. Range and variation in canopy surface area metrics

Of the three species considered in this study, *P. acerifolia* recorded the largest LA, BA, PSA and PAD. In contrast, *C. maculata* recorded the lowest metrics for all canopy characteristics considered in this study (Table 2.2). *U. procera* generally sat between the other two species, although it recorded the largest LAI and the largest PAI. These differences are all statistically significant at $p \leq 0.05$.

Table 2.2. Measured metrics of studied trees

Tree ID	Species	BD(cm)	H (m)	CH (m)	CA (m^2)	CV (m^3)	LA (m^2)	LAI	BA(m^2)	BAI	PSA (m^2)	PAI	PAD (m^2/m^3)
CM1		8.28	2.70	1.35	2.32	4.93	4.27	1.84	0.23	0.10	4.50	1.94	0.91
CM2	Spotted gum	7.80	2.70	1.12	2.50	5.06	3.28	1.31	0.29	0.12	3.57	1.43	0.71
CM3	*Corymbia maculata*	9.71	2.70	1.50	2.81	6.97	4.73	1.68	0.41	0.15	5.14	1.83	0.74
CM4		8.12	2.70	1.15	2.84	5.49	4.81	1.69	0.23	0.08	5.04	1.77	0.92
Mean		8.47	2.70	1.28	2.62	5.61	4.27	1.63	0.29	0.11	4.56	1.74	0.82
PA1		7.80	2.70	1.98	2.58	7.53	8.38	3.25	0.90	0.35	9.28	3.60	1.23
PA2	London Plane	8.91	2.70	2.15	3.00	8.96	7.85	2.62	1.03	0.34	8.88	2.96	0.99
PA3	*Platanus x acerofolia*	9.39	2.70	2.07	2.82	7.05	9.78	3.47	1.28	0.45	11.06	3.92	1.57
PA4		7.80	2.70	2.00	3.17	8.42	8.76	2.76	0.98	0.31	9.74	3.07	1.16
Mean		8.47	2.70	2.05	2.89	7.99	8.69	3.02	1.04	0.36	9.74	3.39	1.24
UP1		7.64	2.70	2.09	1.60	7.55	7.44	4.65	0.49	0.30	7.93	4.96	1.05
UP2	English Elm	7.48	2.70	2.05	1.49	6.57	7.89	5.30	0.49	0.33	8.38	5.62	1.28
UP3	*Ulmus procera*	7.64	2.70	1.82	1.50	6.52	7.12	4.75	0.57	0.38	7.70	5.13	1.18
UP4		6.21	2.70	1.93	1.50	6.35	6.20	4.13	0.39	0.26	6.59	4.40	1.04
Mean		7.24	2.70	1.97	1.52	6.75	7.17	4.71	0.49	0.32	7.65	5.03	1.14

*Note: BD=Basal diameter; H=Tree height; CH=Canopy height; CA=Canopy projected area; CV=Canopy volume; LA=Total leaf area; LAI=Leaf Area Index; BA=branch area; BAI=branch area index; PSA=Plant surface area; PAI=Plant area index; PAD=Plant area density.

2.3.2. Impact of tree species and leaf reduction on canopy storage

Average estimates for both C_{max} and C_{min} were highest for *U. procera*, followed by *P. acerifolia*, and *C. maculata* for all density classes (Fig. 2.4, Table 2.3). The one exception to this was the Woody class for *P. acerifolia*, and *C. maculata* which had the same values for C_{max} (0.06 mm) and C_{min} (0.01 mm). Unsurprisingly, the average values for C_{max} and C_{min} both decreased as canopy leaf density was reduced. After the first leaf removal phase (Half canopy), canopy storage rates had declined by 12%, 55% and 50% for *C. maculata*, *P. acerifolia*, and *U. procera*, respectively. By the end of the second leaf removal phase (Quarter canopy), canopy storage rates had declined by 38%, 76%, and 53%, for *C. maculata*, *P. acerifolia*, and *U. procera*, respectively. Finally, when all leaves were off (Woody), canopy storage rates had decreased by 62%, 90%, and 87%for *C. maculata*, *P. acerifolia*, and *U. procera*, respectively.

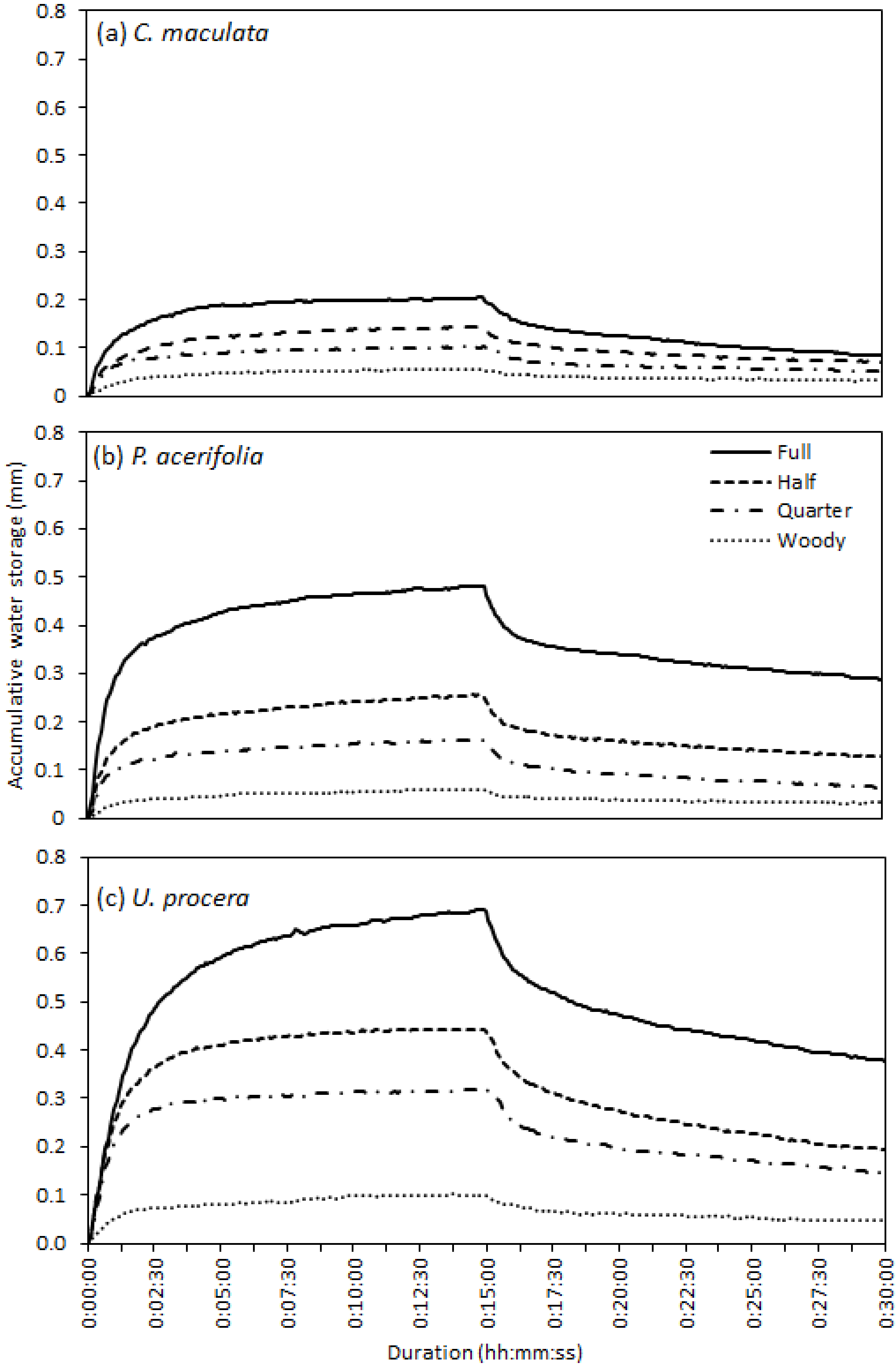


Figure 2.4. Cumulative tree canopy water storage for *C. maculata*, *P. acerifolia* and *U. procera* during 15 min simulated rainfall (rate mm/h) and 15 min after the rainfall ceased. Canopy water storage was measured for full (100%) foliage canopy (solid line), then half (50%) foliage canopy (dashed line), quarter (25%) foliage canopy (dot-dash line) and finally with all leaves removed (0%) and the woody stem and branch architecture only (dotted line). Each line is the mean of four replicated tree measures (N=4).

Table 2.3. C_{max} and C_{min} results (mm) for different species (CM: *C. maculata*; PA: *P. acerifolia*; UP: *U. procera*) in different leaf density; M and SD.

	Canopy density classes							
	Full		Half		Quarter		Woody	
Tree ID	C_{max} (mm)	C_{min} (mm)	C_{max} (mm)	C_{min} (mm)	C_{max} (mm)	C_{min} (mm)	C_{max} (mm)	C_{min} (mm)
CM1	0.25	0.09	0.22		0.10	0.03	0.06	0.03
CM2	0.18		0.13	0.06	0.10	0.06	0.05	0.02
CM3	0.19	0.08	0.17	0.05	0.11	0.05	0.06	0.04
CM4	0.18	0.08	0.11	0.08	0.10	0.06	0.06	0.03
Mean ± SD	0.20 ±0.03	0.08 ± 0.01	0.16 ±0.04	0.07 ± 0.01	0.10 ±0.01	0.05 ± 0.01	0.06 ±0.01	0.03 ± 0.00
PA1	0.52	0.31	0.32	0.17	0.20	0.11	0.08	0.05
PA2	0.40	0.23	0.20	0.09	0.16	0.08	0.06	0.03
PA3	0.57	0.32	0.31	0.17	0.16	0.04	0.06	0.03
PA4	0.44	0.29	0.22	0.10	0.14	0.04	0.05	0.03
Mean ± SD	0.49 ±0.07	0.29 ± 0.03	0.26 ±0.05	0.13 ± 0.04	0.16 ±0.02	0.07 ± 0.03	0.06 ±0.01	0.03 ± 0.01
UP1	0.51	0.31	0.40	0.19	0.31	0.12	0.11	0.06
UP2	0.83	0.39	0.49	0.14	0.42		0.11	0.03
UP3	0.77	0.41	0.50	0.24	0.33	0.14	0.11	0.07
UP4	0.67	0.39	0.39	0.21	0.32	0.18	0.07	0.03
Mean ± SD	0.69 ±0.12	0.38 ± 0.04	0.44 ±0.05	0.19 ± 0.02	0.34 ±0.04	0.15 ± 0.03	0.10 ±0.01	0.05 ± 0.01

The percentage of water that is considered released throughfall was calculated by the difference between C_{max} and C_{min}. On average *C. maculata*, *P. acerifolia*, and *U. procera* attenuated 57.9%, 40.9% and 45.3% of rainfall, respectively.

2.3.3. Relations between canopy water storage and surface area metrics

The ANCOVA analyses returned several significant differences between the tree species for both C_{max} and C_{min} (Table 2.4). The relationship between C_{max} and PSA was significantly different ($p \leq 0.05$) for all three species. Notably, at the same PSA *U. procera* was intercepting and storing almost twice as much water as the other two tree species, as indicated by the *b* correlation coefficient (Fig. 2.5a, Table 2.4). For C_{max} against both PAI and PAD, there were no significant differences between the trends observed for *P. acerifolia* and *C. maculata*, but *U. procera* was significantly different to the other two species (Figs 2.5c and 2.5e, Table 2.4).

Table 2.4. Summary for linear regressions parameters (x: independent variable; y: dependent variable; a: intercept; b: slope; R2: coefficient of determination; sign: Tukey's result at 95% of significance).

Species	x	y	a	b	R^2	Sign.(95%)*	Figure
C. maculata	PSA	C_{max}	0.060	0.031	0.718	a	
P. acerifolia	PSA	C_{max}	0.000	0.044	0.855	b	5a
U. procera	PSA	C_{max}	0.075	0.088	0.974	c	
C. maculata	PSA	C_{min}	0.033	0.011	0.769	a	
P. acerifolia	PSA	C_{min}	-0.015	0.03	0.773	a	5b
U. procera	PSA	C_{min}	0.038	0.043	0.817	b	
C. maculata	PAI	C_{max}	0.055	0.088	0.808	a	
P. acerifolia	PAI	C_{max}	0.002	0.127	0.892	a	5c
U. procera	PAI	C_{max}	0.074	0.134	0.982	b	
C. maculata	PAI	C_{min}	0.032	0.029	0.797	a	
P. acerifolia	PAI	C_{min}	-0.017	0.076	0.805	a	5d
U. procera	PAI	C_{min}	0.037	0.066	0.835	a	
C. maculata	PAD	C_{max}	0.057	0.182	0.768	a	
P. acerifolia	PAD	C_{max}	0.006	0.336	0.875	a	5e
U. procera	PAD	C_{max}	0.073	0.595	0.985	b	
C. maculata	PAD	C_{min}	0.032	0.064	0.806	a	
P. acerifolia	PAD	C_{min}	-0.010	0.199	0.780	a	5f
U. procera	PAD	C_{min}	0.035	0.294	0.853	b	

*Significant differences between species are marked with different letters.

A similar pattern of no difference between *P. acerifolia* and *C. maculata* was observed for C_{min} against both PSA and PAD (Figs 2.5b and 2.5f, Table 2.4). However, for C_{min} against PAI, there was no significant difference between the results returned for the three species (Fig. 2.5d, Table 2.4). Collectively, these results indicate that *U. procera* has a significantly greater water storage capacity (C_{max} and C_{min}) than *P. acerifolia* and *C. maculata* for most canopy surface metrics.

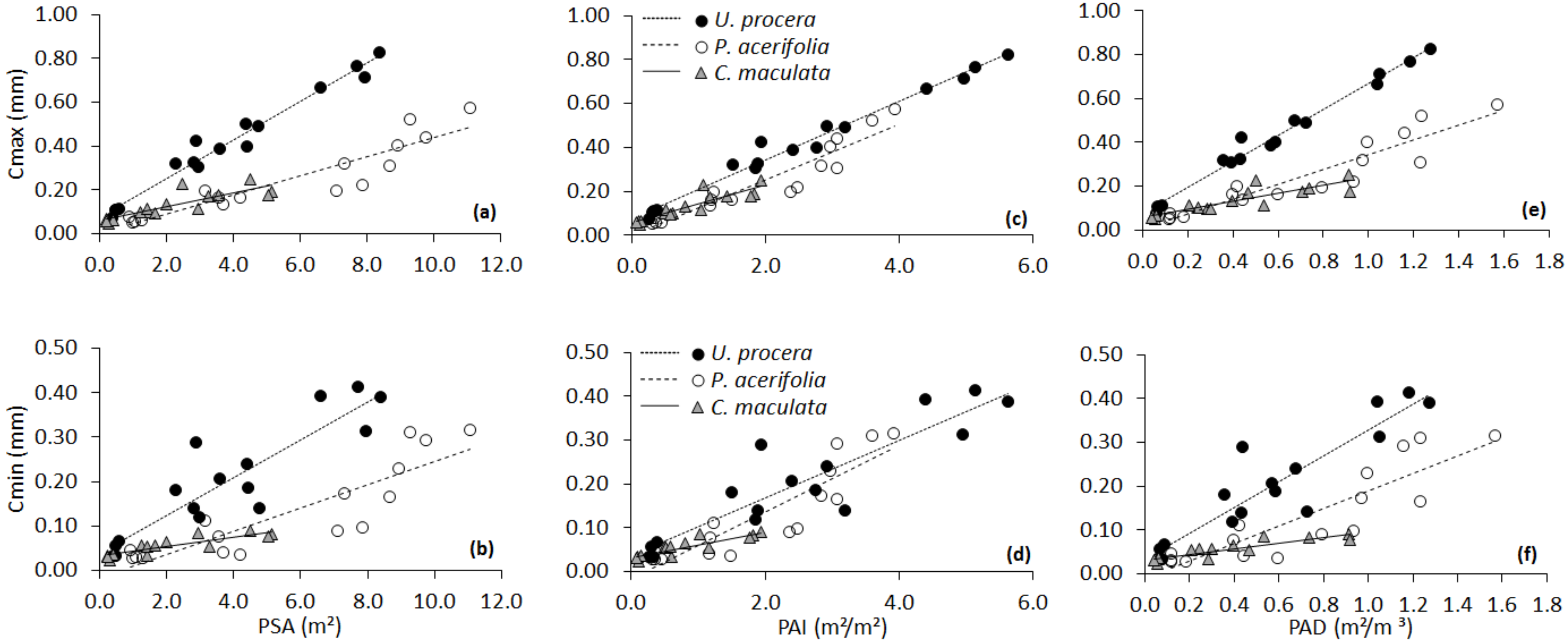


Figure 2.5. Linear regression analyses between canopy surface metrics (plant surface area [PSA]; plant area index [PAI]; and plant area density [PAD]) and interception parameters (maximum [C_{max}] and minimum [C_{min}] storage capacity) for three tree species (*Ulmus procera, Platanus* x *acerifolia* and *Corymbia maculata*): a) PSA x C_{max}; b) PSA x C_{min}; c) PAI x C_{max}; d) PAI x C_{min}; e) PAD x C_{max}; and f) PAD x C_{min}

2.3.4. Importance of leaf area and woody surface areas for canopy storage

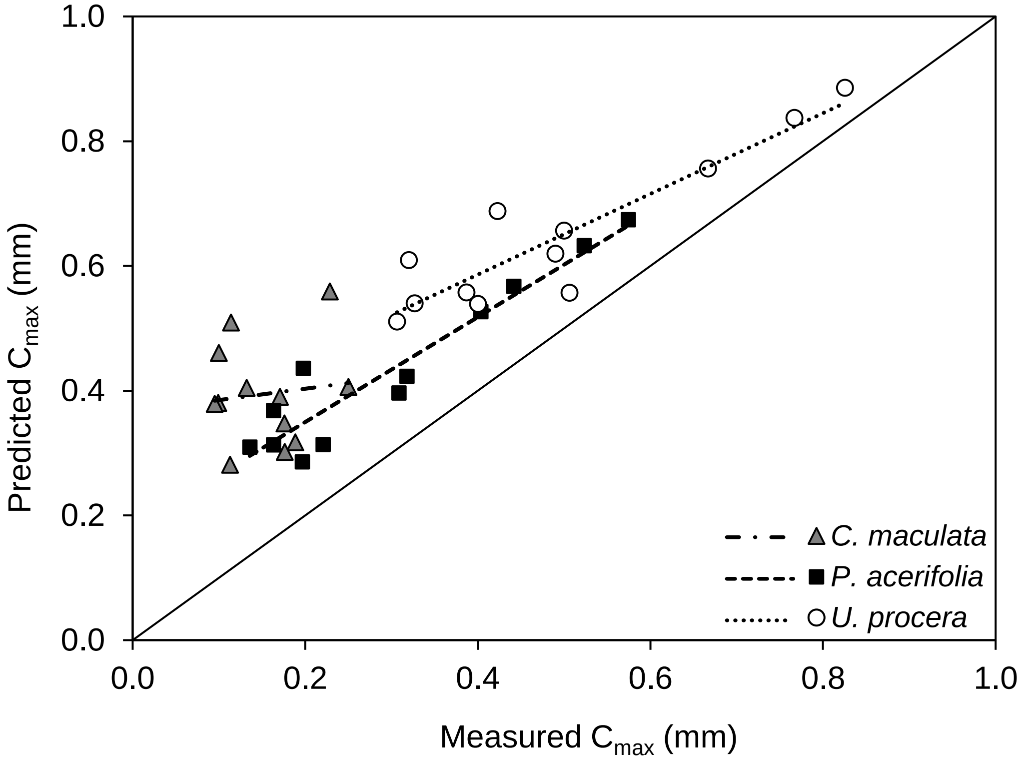
When comparing the C_{min} values for the Full canopy data to the Woody (no leaf) data, the results indicate that the majority of the water was stored by the leaf surfaces of these species rather than the woody fabric (Table 2.5). However, the importance of water interception and storage by woody components of the canopy varied with tree species. For *U. procera* and *P. acerifolia* water storage on woody components represented approximately 10% of the total canopy stored volume, whereas for *C. maculata* approximately 40% of the water volume was stored on the surface area of the woody components.

Table 2.5. C_{min} values per plant compartment (mm) and corresponding comparative importance for water storage (%).

	Mean C_{min} ± STD (mm)				
Tree species	Leaf	%	Woody	%	Total
C. maculata	0.05 ±0.00	59.20	0.03 ±0.00	40.80	0.08 ±0.01
P. acerifolia	0.26 ±0.03	89.70	0.03 ±0.01	10.30	0.29 ±0.03
U. procera	0.33 ±0.04	87.20	0.05 ±0.01	12.80	0.38 ±0.04

2.3.5. Contrasting predicted and directly measured storage capacity

The Gash model was used to predict storage capacity and interception, which were later correlated respectively with the observed C_{max} and C_{min} (considered the true interception) (Fig. 2.6). Results for the predicted interception are overestimated for all species and again present a strong correlation for *P. acerifolia* (y = 0.85x + 0.14; R^2 = 0.93) and *U. procera* (y = 0.71x + 0.25; R^2 = 0.91) trees. The predicted C_{min} presents weak correlation with the directly measured values for *C. maculata* (y = 0.18x + 0.37; R^2=0.01). The calculated RMSE was 0.14 mm, 0.17 mm and 0.26 mm for *P. acerifolia*, *U. procera, and C. maculata* results, respectively.



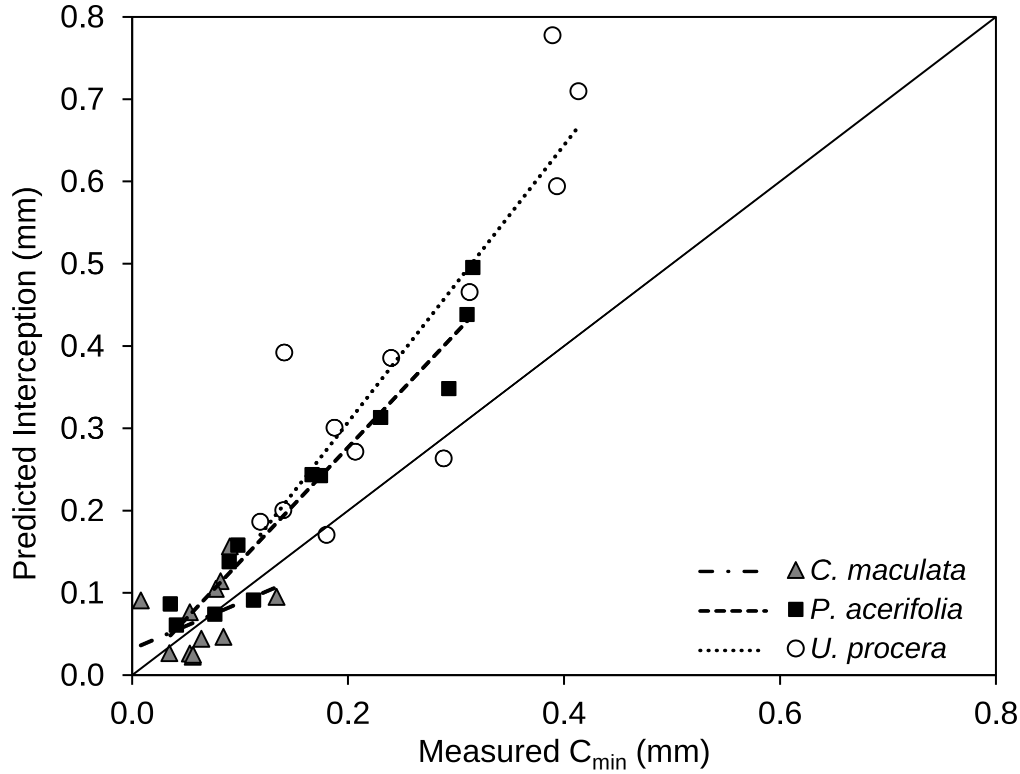


Figure 2.6. Efficiency test of Gash model prediction based on results of the indoor experiment: (a) correlation between measured and predicted C_{max} (mm); (b) correlation between measured and predicted C_{min} (mm).

2.4. Discussion

2.4.1. Range and variation in canopy surface area metrics

The canopy surface area metrics of PSA, PAI and PAD vary between the three species (Table 2.2) investigated in this study. In this research, the PSA was directly influenced by the size and quantity of the leaves and branches on a tree, regardless of their spatial distribution. For example, the size of *P. acerifolia* leaves is likely to have contributed to this species having a greater overall PSA (9.74 m^2) than either *U. procera* (7.65 m^2) or *C. maculata* (4.56 m^2) (Table 2.1). Interestingly, *U. procera* also returned a relatively large PSA, despite having smaller leaves. However, the total recorded LA for this species indicates that it had a high number of leaves per tree and this resulted in its relatively high PSA. *Corymbia maculata* recorded both the lowest total LA and lowest BA in this study, but also had a comparatively large CA and therefore it recorded the lowest PSA.

In contrast to PSA, the results for PAI indicate the importance of the arrangement of foliar elements within the canopy to this variable (Bréda 2003). *Ulmus procera* had the smallest average CA of the three species considered in this study but a relatively large total LA leading to a denser, closer canopy. As such, and despite not having the highest PSA, *U. procera* recorded the highest PAI, which in this sense can be interpreted as a measure of the density of the leaves (and branches) in a compressed 2D plane. Once again, *C. maculata* with its relatively sparse canopy recorded the lowest PAI.

Finally, PAD, which describes the vertical distribution of leaf density, has been used in forest studies because it is considered to provide a better indication of actual plant–atmosphere interactions than measures such as LAI (Lalic and Mihailovic 2004). Although calculating PAD in isolated canopies is easier than in interconnected forested canopies, this approach has not been used much for describing urban trees (Meir, Grace and Miranda 2000; Lalic and Mihailovic 2004) and therefore there is scope to consider the use of this parameter in the current research. In this study, values for PAD were greatest for *P. acerifolia* (1.24), followed by *U. procera* (1.14) and *C. maculata* (0.82).

For urban foresters, these results reveal that an increase (or decrease) in canopy plant area density can vary between species, which has implications for ecological and hydrological functioning, particularly through canopy water storage and the generation of impervious runoff. In urban street canyons where tree canopy growth is likely to be restricted in height by restrictions or obstructions (awnings, telegraph/power cables) and in lateral spread (between buildings and vehicle roadways), trees with denser canopies are likely to perform the ecological functions of rainfall interception and water storage better than species with more open canopies.

In summary, in this study *P. acerifolia* had the highest PSA and PAD but not the highest PAI. In contrast, *C. maculata* recorded the lowest values for all three of the canopy surface area metrics considered in this research. These findings indicate that these three metrics have slightly different relational trends with species, suggesting that the outcomes of predictive models that incorporate them will be dependent on species choice and the metric that is used to describe them.

2.4.2. Canopy water storage in relation to plant surface area metrics

Prior work demonstrates the importance of the intercepting surface area to storage capacity (e.g. Aston 1979; Li et al. 2016; Xiao and McPherson 2016) and the present research supports these findings. In this study, *U. procera* with a Full canopy recorded an average C_{min} of 0.38 mm, which means that this species stored 0.38 L of rainfall per square metre of canopy cover under a rainfall intensity of 2.54 mm hr^{-1}. For the same conditions, *P. acerifolia* stored 0.29 L and *C. maculata* stored 0.06 L. Li et al. (2016) observed similar C_{min} values ranging between 0.13 mm (±0.02) to 0.41 mm (±0.08) for four different tree species under simulated rainfall intensity of 10 mm hr^{-1}. Variation in the canopy storage capacity of urban trees, or any tree, is generally attributed to differences in leaf area and morphology (Xiao and McPherson 2016), although little work has been done to investigate the relationship between this and the canopy volume metrics considered in this study.

The results of the rainfall simulation experiments are slightly unexpected given that *P. acerifolia* had a larger CA, a larger total leaf area (PSA) and large leaves with serrated edges that might be likely to facilitate greater water adherence to a leaf (Goebes, Bruelheide et al. 2015; Holder and Gibbes 2016). Not surprisingly, this species retained more canopy water than *C. maculata* which has waxy, pendulous leaves and smoother bark surfaces that promote the rapid drainage of water from the canopy, which may partially explain the small water storage capacity of this tree species (Crockford and Richardson 2000; Park and Cameron 2008; Livesley et al. 2014; Carlyle-Moses and Schooling 2015). Despite its leaf morphology, however, *P. acerifolia* stored less canopy water than *U. procera* which also had rough leaves but a lower CA and total leaf area. This suggests that leaf and/or branch characteristics have an important role to play in explaining the water retention capacity of the study trees.

Further, *C. maculata* drained more water than would be normally accounted for by PAI. For pendulous trees such as *C. maculata*, where the foliage and branches are not parallel to the ground surface, the angles of the leaves and branches need to be factored in to better calculate the tree benefit. These findings, therefore, suggest that although PAI is commonly used in ecological benefits modelling, the actual benefit a particular species provides may be overestimated when this parameter is used because it does not account for leaf and branch inclination (Stadt and Lieffers 2000).

Canopy surface areas are constantly changing according to the stage of tree maturity (natural canopy senescence, deciduous phenology), environmental stress conditions (drought, heat, storm) and management practices (pruning, lopping, pollarding) (Bréda 2003; Jonckheere et al. 2004). While many of these changes are hard to predict, deciduous phenology is not and, when *U. procera* and *P. acerifolia* drop their leaves in winter, there will be a large reduction in storage capacity rates of up to 90% (Table 2.3). Extending this over the course of one year, deciduous trees are estimated to intercept approximately 14% less water than evergreen species (Barbier, Balandier and Gosselin 2009). However, our results suggest that this is not borne out for the selected species. Based on monthly aerial photographs in Melbourne, *U. procera* and *P. acerifolia* are bare for a period of five months each year. Considering monthly rainfall is relatively consistent between seasons in Melbourne (Bureau of Meteorology 2017) and based on calculations comparing C_{max} and C_{min} for the Full and Woody canopy conditions, both the deciduous species, *P. acerifolia* and *U. procera*, would store 57% and 87% more water, respectively, in one year than the evergreen species, *C. maculata*, which has a far smaller plant area density and highly hydrophobic leaves and branches.

Although C_{max} and C_{min} both represent measures of canopy interception, relationships between them and canopy metrics are somewhat complex. C_{max} is a dynamic metric, measured under rainfall conditions where drops of water are hitting the leaves and bouncing or falling off them (Li et al. 2016; Xiao, McPherson et al. 2000). On the other hand, C_{min} is the static interception storage and is measured after excess rainfall has drained off the leaf (Li et al. 2016). The relationships between the species considered in this study and C_{max} and C_{min} suggest they vary slightly depending on the choice of canopy surface metric and the species under consideration. For example, *U. procera* recorded statistically higher C_{max} and C_{min} values for all canopy surface metrics except PAI for C_{min}. The rougher leaves of *U. procera* may be effective at slowing down the water and ensuring larger maximum storage for a given leaf area. As such, the storage capacity of this species is a function not only of leaf area but also of leaf roughness. In contrast, *P. acerifolia* and *C. maculata* returned statistically similar trends between the canopy surface metrics and C_{max} and C_{min}, except for PSA and C_{max}. Once again, these findings indicate the need to individually consider species' responses to canopy surface metrics. It is worth noting that, although previous research also points to the importance of varying rainfall characteristics on canopy storage capacity (Klamerus-Iwan 2015; Li et al. 2016), the use of constant rainfall intensity in this study indicates that variations observed in C_{max} and C_{min} reflect variations in canopy area metrics only.

2.4.3. Comparing leaf and woody surface areas to canopy water storage: contrasts with previous work

This study indicates that leaves (arrangement and morphology) are important with regards to intercepting rainfall on trees. However, these findings are slightly in contrast to those of Li et al. (2016), who tested C_{max} and C_{min} for four tree species under different rainfall intensities over 60 min. They found the average C_{max} was 2.6 times larger for branches than for leafy surfaces. In the present study, the C_{max} and C_{min} values indicate that leaves collected considerably more water than woody tree parts for all three species. The only exception to this was C_{min} for *C. maculata* for which the Woody storage was higher than the leaf storage. These results may reflect the nature of the particular species that were considered in our study. *Ulmus procera* and *P. acerifolia* both have branch inclinations of greater than 45° and all three species have smooth bark, influencing a rapid draining off of water. In addition, *C. maculata*, as well other species of the same genus, is well-known for high investment in producing woody biomass and has leaves that are pendulous and covered in wax to reduce water loss via transpiration, which helps it survive in drier regions (Hallam 1970). This combination of conditions also reduces the volume of water that is stored on both the leaves and the branches of these trees.

Finally, it is possible that the decision to use juvenile trees may have underestimated the contribution of the woody parts to water storage. As trees mature, their bark tends to roughen and they grow larger branches, both of which are likely to capture more water than occurs on juvenile trees (Barbier, Balandier and Gosselin 2009). Further research into the study species using mature trees is required to determine whether this is the case.

2.4.4. Contrasting predicted and directly measured storage capacity

In this study, the predictions for *C. maculata* have shown a weak correlation between predicted and observed storage capacity. Differences between species were also observed on Sadeghi et al.'s (2015) study. In their study, the model showed a poorer performance for the species with higher LAI, more horizontal leaves/branches, larger crown width and rougher bark, which are the opposite characteristics of *C. maculata*. Those characteristics are not accounted for by the model, but they influence directly the storage capacity and indirectly the evaporative loss (Sadeghi et al. 2015). This result may support the argument that the Gash model is species-specific, as the predictions based on the indoor model translated better the interception rates for *P. acerifolia*, while not as reliably for *C. maculata*.

2.4.5. Potential contribution of canopy water storage to reducing stormwater runoff

To illustrate the potential implications of this research, a simple but practical application has been undertaken to calculate the impact of urban tree species selection on runoff reduction in a theoretical streetscape. The hypothetical scenario was a 50 m long street (5.5 m wide) covered in asphalt with two footpaths each 2.5 m wide, generating a total impervious area of 525 m^2 (50 m long x 10.5 m wide). The objective for this street was to reduce stormwater runoff volumes by planting four trees using the three studied species of *U. procera*, *P. acerifolia* and *C. maculate* (Fig. 2.6).

A 5 mm hr^{-1} 1-hour duration designed rainfall event received across the 525 m^2 surface area will generate 2625 L of water. Assuming that the first 1 mm of incident rainfall is stored on the surface and does not become runoff (Boyd, Bufill and Knee 1993), the total runoff generated from this surface will be 2100 L. This represents the approximate amount of water running off to the stormwater drainage system and associated waterways, but any tree placed on this impervious surface will act to catch some of that rainfall. For the purpose of this exercise, four trees each with a 10 m wide canopy are placed on the footpaths, producing a combined tree canopy area of 192 m^2. Excluding the fraction of the canopy that is not shelter for the impervious public area (38.8%), the canopy area will receive a total of 961.3 L of rainfall (with the remaining rainfall volume falling on the impervious surface outside the tree canopies). Based on the C_{min} values observed in this study, the water storage of *Corymbia maculata*, *Platanus x acerifolia* and *Ulmus procera* would be approximately 114, 415 and 545 L, respectively. Therefore, for a 5 mm rainfall event, this would be a 5%, 20% and 26% reduction in runoff, respectively.

Despite being an important part of rainfall partitioning for mature isolated trees (Carlyle-Moses and Schooling 2015), water loss via SF has not been counted in these calculations because the example assumes that the SF water is running directly onto an impervious surface and is counted as runoff water. However, in a realistic setting further research could integrate information on the presence or absence of permeable surfaces at or near tree bases, so as to acknowledge another significant ecosystem service that trees provide in streetscapes (Carlyle-Moses and Schooling 2015).

Although the runoff reductions would vary depending upon rainfall characteristics (duration, intensity, antecedent conditions, etc.), this small activity highlights the potential role that tree canopies can provide through interception and canopy storage, and points to their capacity to help mitigate flood risk and reduce the occurrence of the ‘urban stream syndrome’ in cities.

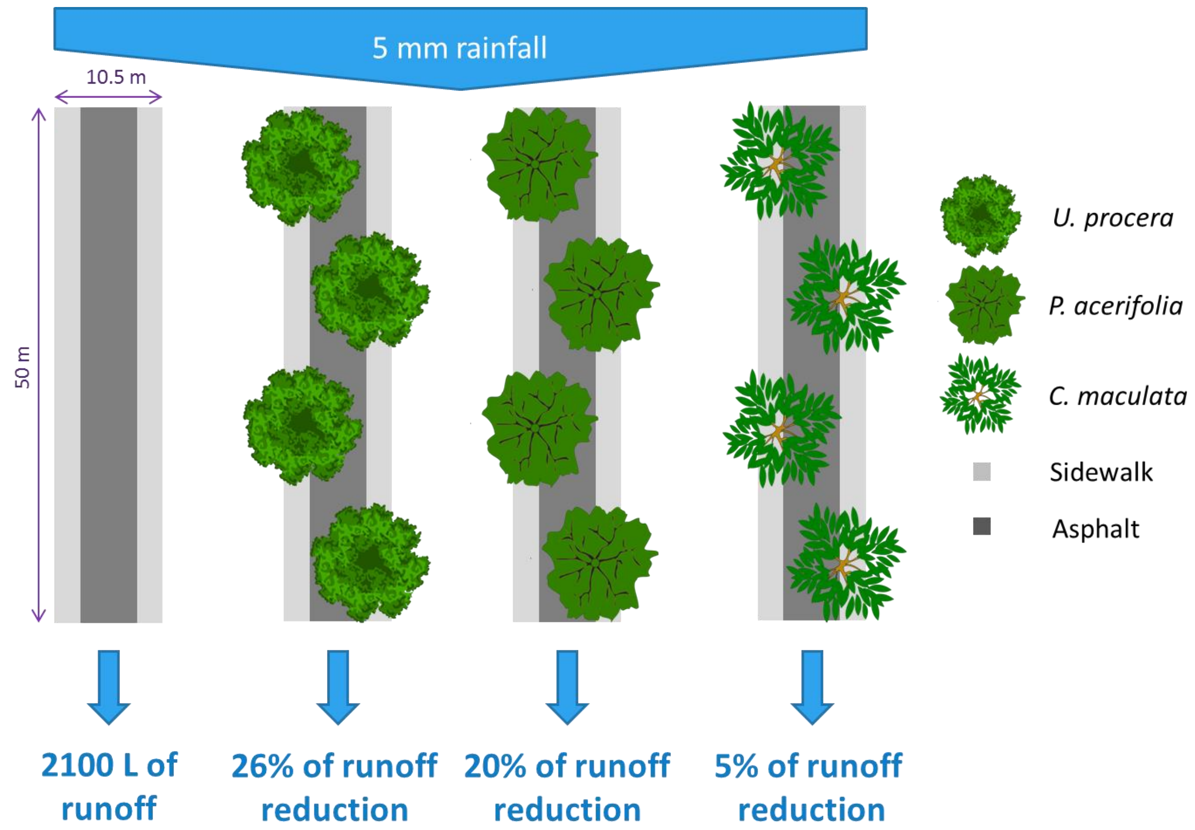


Figure 2.7. Runoff production and reduction in four different scenarios.

2.5. Summary

To understand the canopy interception process, rainfall simulation experiments were used to estimate the maximum and minimum canopy storage capacity (C_{max} and C_{min}, respectively) for three tree species commonly used as street trees in the City of Melbourne, Australia. The selected study species were *Ulmus procera*, *Platanus* x *acerifolia* and *Corymbia maculata*. For each species, four individual trees were subjected to four rainfall simulation events, with the trees being sequentially defoliated between events. This allowed for comparisons of C_{max} and C_{min} between species and under various degrees of foliation (from having a full canopy to being completely devoid of leaves).

The results of this study indicate that common tree canopy area metrics such as PSA (plant surface area), PAI (plant area index) and PAD (plant area density) show varying responses to rainfall storage depending on species and extent of defoliation. *Ulmus procera* routinely stored more water than either *P. acerifolia* or *C. maculata*, even though *P. acerifolia* had higher average PSA and PAD metrics. This finding indicates the importance of understanding how these surface area metrics vary between species and of identifying how each individual metric impacts on rainfall storage by trees. As such, when planning urban forests for flood mitigation, managers need to take into account important differences between species, including leaf and branch area, roughness and angle.

This study also reveals that the contribution of woody material to storage capacity varies between species, however, is not quite as significant, as in most cases the trees in this study stored most of their water on their leaves. This finding is very important when considering the balance of evergreen and deciduous trees because deciduous trees remain without leaf for a long period. This suggests that evergreen trees will always have a greater storage capacity (over time) than their deciduous counterparts, but in this study the evergreen species (*C. maculata*) stored less water over the course of a year than the other two species, both of which are deciduous.

Chapter 3. Terrestrial laser scanning to predict canopy area metrics, water storage capacity and throughfall redistribution in urban trees

3.1. Introduction

From the findings in Chapter 2, the interception process was understood from the water storage perspective. The previous discussion focused on the interaction between the water coming from the rainfall simulator and plant surfaces, which varies from tree to tree but also when the density of leaves varies within the same tree.

To validate the use of new technologies to remotely sense the trees, the second part of the experiment focuses on testing the use of terrestrial laser scanning (TLS) data to predict plant area metrics and, consequently, canopy storage capacity. The correlations between directly measured and remotely sensed data are presented and its applicability to predicting canopy storage capacity is discussed.

Additionally, this chapter aims to understand the influence of plant area on the spatial distribution of throughfall. For this, throughfall data was collected simultaneously to storage capacity using vials distributed under the canopies. The spatial redistribution of rainfall under tree canopies is affected by tree configuration, which is significantly connected to the arrangement of leaves and branches. Rainfall redistribution is important when considering the occurrence of soil erosion and flood linked to high-intensity rainfall (Geißler et al. 2013). However, few studies debate how plant surface area (PSA) influences water distribution under tree canopies (Goebes, Bruelheide et al. 2015).

3.1.1. Background

Trees are an important component of the urban environment, as they can cool air temperatures to moderate (Lin and Lin 2010; Shashua-Bar, Tsiros and Hoffman 2010; Qin et al. 2014), decrease air pollution (Nowak et al. 2013; Salmond et al. 2013), reduce noise (Klingberg et al. 2017), stimulate social connection (Holtan, Dieterlen and Sullivan 2015) and reduce storm runoff effects (Armson, Stringer and Ennos 2013; Gotsch, Draguljić and Williams 2018), as well as many other benefits. Understanding, quantifying and communicating the benefits of trees are particularly important from an urban planning perspective, as a raised awareness of the scientific evidence base may help set policies and future management planning for urban forests.

Quantifying the role of urban trees in the mitigation of runoff water is important, as the frequency of floods has increased in densely urbanised areas in the last few years. The increase in impervious areas during urbanisation disrupts the natural cycling of water, reducing the number of naturally vegetated areas and, consequently, the permeability of the system. Additionally, stormwater infrastructure in many cities was designed for a less intensely urbanised landscape and is at or exceeding designed runoff capacity and, as a result, large rainfall events can frequently lead to flooding. Many cities in the world have set targets to increase tree canopy cover as one of the nature-based solutions to help mitigate the occurrence of floods (City of London 2011; City of Melbourne 2012; City of Vancouver 2015).

However, predicting the impact of the urban forest on stormwater management is complex and so is its planning, primarily because predicting the impact of urban trees is not easy given the complexity of tree structural elements and the surrounding environment. Therefore, recent research has attempted to integrate knowledge from different discipline areas to better predict tree metrics and their hydrological impact (Moskal and Zheng 2012; Alonzo et al. 2015; Jiang et al. 2017). Part of this integration of knowledge involves reaching a precise understanding of the relationships between remotely sensed data and the effects of different canopies upon rainfall interception, storage and throughfall.

Recently, TLS techniques have gained increased attention as a method to directly measure the 3D shape of tree canopies and consequently estimate different tree characteristics (Holopainen et al. 2013). Although TLS data has been tested for retrieving tree metrics (Clawges et al. 2007; Antonarakis et al. 2010; Zheng and Moskal 2012; Zheng, Moskal and Kim 2013; Lin and West 2016; Abegg et al. 2017), the use of TLS-derived data for predicting ecosystem service processes, such as shading, pollution interception and rainfall interception parameters, is still yet to be developed and tested.

Understanding how tree canopy characteristics at the whole-tree and leaf levels influence canopy interception, storage and throughfall redistribution dynamics is fundamental for advancing the use of trees for stormwater management. Both canopy storage capacity and throughfall dynamics are driven by a combination of different tree attributes, as well as rainfall characteristics and environmental conditions (Klamerus-Iwan 2015; Xiao and McPherson 2016; Van Stan, Levia and Jenkins 2014). In the case of canopy storage, PSA, roughness and angle of inclination influence the volume of water that can be stored during and after rainfall ceases. Fundamentally, trees with greater PSA, rougher surfaces and lower inclination possess greater canopy water storage (Holder 2013; Livesley, Baudinette and Glover 2014; Li et al. 2016; Holder and Gibbes 2016).

Similarly, the volume of water passing through the canopy (throughfall) is affected by tree configuration, which is a function of the arrangement of leaves and branches (King and Harrison 1998; Levia and Frost 2006; André et al. 2011; Goebes, Bruelheide et al. 2015). In addition, the spatial redistribution of throughfall under a tree canopy is modified and shaped by a variety of canopy characteristics. These changes have been studied and importance has been given to modification of rain characteristics such as the kinetic energy of drops, drop size and velocity (Nanko et al. 2011; Geißler et al. 2013). Raindrop characteristics are linked to the occurrence of soil erosion and flood mainly during high-intensity rainfall events (Geißler et al. 2013). Moreover, the availability of water and nutrients deposited with the throughfall flux positively influences soil biodiversity and root development (Levia and Frost 2003). However, few studies discuss how specific leaf and tree architectural traits, such as the arrangement of leaves and branches, influence water distribution under tree canopies (Nanko et al. 2011; Fathizadeh et al. 2014; Goebes, Bruelheide et al. 2015).

This study proposes a new way to make use of TLS and thereby add value to the work of urban forestry professionals. It investigates the potential of deriving plant area metrics from TLS data clouds, to avoid expensive and laborious manual methods of leaf area data collection that require destructive sampling. It combines the use of remote-sensing techniques with knowledge of water–tree interaction dynamics, aiming to validate the use of TLS-derived data to predict both interception metrics and throughfall distribution.

In the first part of this study, the relationships between plant surface metrics and TLS-derived data are investigated. Based on previous work (Clawges et al. 2007; Antonarakis et al. 2010; Zheng, Moskal and Kim 2013), the first hypothesis is that TLS-derived metrics are good predictors of PSA metrics. Most of the previous approaches have used an algorithm to extract gap fractions from TLS point clouds and, from this, an approximation of leaf area index (LAI) (Hosoi and Omasa 2006; Danson et al. 2007; Antonarakis et al. 2010; Zheng, Moskal and Kim 2013). Two approaches commonly applied are the 3D voxel-based canopy profiling (VCP) method (Hosoi and Omasa 2006) and a 2D approach which converts “the point cloud data set from Cartesian coordinates to spherical coordinates in order to be similar to hemispherical photography” (Antonarakis et al. 2010). The present study differs from the cited works by investigating whether the number of scanned points correlates with manually calculated plant area metrics. TLS-derived metrics are then tested to predict one of the water storage capacity parameters, minimum storage capacity (C_{min}). The second hypothesis is that TLS-derived metrics are effective in predicting both C_{min} and throughfall redistribution.

In the second part of this chapter, the process of spatial redistribution of throughfall is studied in more detail, aiming to understand how tree structure can affect the total throughfall redistribution. Therefore, the TLS data will be used in a subcanopy analysis, providing a novel approach (King and Harrison 1998; Fathizadeh et al. 2014).

The specific objective of this chapter is to investigate: (a) the efficacy of TLS data to predict urban tree morphological characteristics by correlating directly measured plant area metrics with TLS-derived metrics; (b) the use of TLS-derived metrics to predict water storage capacity; and (c) whether the use of TLS-derived metrics can provide information at the subcanopy scale to understand canopy throughfall distribution. Results may add to previous knowledge on the use of TLS data for canopy metric estimation and can possibly be used in such a way as to predict interception parameters and throughfall distribution. Also, the results will improve understanding of the throughfall process, providing a theory-based discussion for future research.

3.2. Methodology

Rainfall was simulated above trees (at 2.7 m height) in pots of three different species in a controlled indoor environment. Trees were scanned by a TLS to generate the point clouds to measure canopy projected area and volume and derive the following metrics: number of points (NP); number of points per projected canopy area (NPA); and number of points per canopy volume (NPV). Trees were then destructively sampled and PSA (leaf area plus branch area) was measured. Then, TLS-derived data was correlated to the minimum storage capacity (C_{min}) and throughfall collected under individual tree canopies during simulated rainfall.

3.2.1. Trees

Canopy water storage and throughfall were measured for the same 12 trees described in Chapter 2. *Ulmus procera*, *Platanus × acerifolia* and *Corymbia maculata* were selected for their distinct canopy characteristics and because they are commonly used in the streetscapes of the City of Melbourne. The studied trees were grown in 100 L pots and had comparable basal stem diameters ranging from 6.2 to 9.7 cm, and initial canopy volumes that ranged from 5.61 m^3 to 7.99 m^3 (Table 2.1).

3.2.2. Canopy surface area manipulation and measurement

The leaf density was manipulated with the purpose of simulating differences in water storage capacity from a canopy in good to poor health. Leaf surface area was manipulated in stages: after canopy water storage measurements and TLS scanning was completed on trees with 100% of their canopy (labelled Full canopy) and when every other leaf on a branch was removed and leaf areas were directly measured using a leaf area meter (LI-3100 Area Meter, Li-cor, Lincoln, USA). The process was repeated another two times until all leaves were removed, as described in Chapter 2.

After water storage capacity measurements and TLS scanning, the woody material for each tree was collected and divided into two groups depending on their diameter class: ≥1 cm or <1 cm. Each branch group had its length, area and volume estimated as described in Chapter 2.

3.2.3. Rainfall simulation

Rainfall was simulated under the same conditions described on Chapter 2: intensity of 2.5 mm/h for 15 min. Full details for this method and for keeping constant precipitation rates, uniformity and raindrop size are available in the previous chapter (Knasiak, Schick and Kalata 2007). Full details on how the rainfall simulator was constructed, trialled and operated with the trees beneath are also presented in the previous chapter.

3.2.4. TLS data collection and processing

A 3D image of each tree canopy was captured using a hand-held laser scanner (ZEB1, GeoSLAM Ltd, Nottingham, UK). The methods for collecting TLS are fully described in Chapter 2. Point clouds data were processed using CloudCompare 2.6.2 software. The denoising process is also described in Chapter 2.

A concave hull method was then used to calculate tree canopy metrics, such as canopy project area and canopy volume, from the point cloud. A 2D graph of point density distribution was created in Cloud Compare from the processed point cloud. Firstly, the 3D point cloud was converted to 2D data by ignoring z-axis information. Then, the density of points was calculated based on the number of neighbours in a 10 cm pixel. A point density map was created and converted to a matrix, where the values for point density were scaled up to a grid composed of 11 × 11 cm pixels. For throughfall analyses, the 3D point cloud was converted into a grid-based 2D graph according to the density of points from the top view of the whole tree and then scaled to the same resolution as the throughfall grid data collection. Point cloud density was classified into five different percentiles: low, low to medium, medium, medium to high, and high density. These classes of density were correlated with throughfall categories for each pixel.

3.2.5. Canopy water storage measurements

Each tree was placed on a balance (150 kg capacity, 20 g resolution, EM-150KAL, A&D Weighing, Thebarton, Australia) to continuously measure the change in mass before, during, and after a 15 min simulated rainfall event (0.6 mm). From this, the maximum and minimum canopy water storages were calculated from the changes in mass balance: (i) during the 15 min rainfall (C_{max}); and (ii) from the end point of the rainfall event followed by 15 min of excess water dripping from the canopy (C_{min}). All trees had their canopy water storage measured for the different canopy density treatments: Full canopy, Half, Quarter and Woody. Full details on these calculations and the experimental approach used to collect the data are presented in Chapter 2.

3.2.6. Throughfall distribution

During measurements of water storage capacity for trees in their full (100%) canopy, total throughfall was measured using small graduated plastic vials (50 mL, opening diameter 2.8 cm, model PP, Sarstedt Inc., Germany). Vials were evenly distributed under the canopy in an 11 cm spaced grid of 18 × 17, with 9 vials being excluded to fit the tree stem (n = 297). These vials were held in place by plastic trays attached to tables to ensure they were truly vertical in orientation and in the same position under each rainfall simulation (Fig. 3.1). Vials were labelled according to their position in the grid and remained in position during the 15 min rainfall simulation followed by 15 min post-rainfall dripping. After these 30 mins, vials were weighed on a 2-decimal-place balance (3100 g capacity, 0.01 g resolution, GF3000, A&D Weighing, Thebarton, Australia). Any water on the outside surface of a vial was wiped away before weighing. The average mass of a plastic vial was subtracted from the total mass and the remaining mass converted to water volume (mL), assuming the density of water as 1.0 g/mL. Each water volume was then converted to water throughfall (mm) by dividing the mass by the area of the opening of the vial (6.16 cm^2). The vials covered about 5% of the total area under each tree canopy.

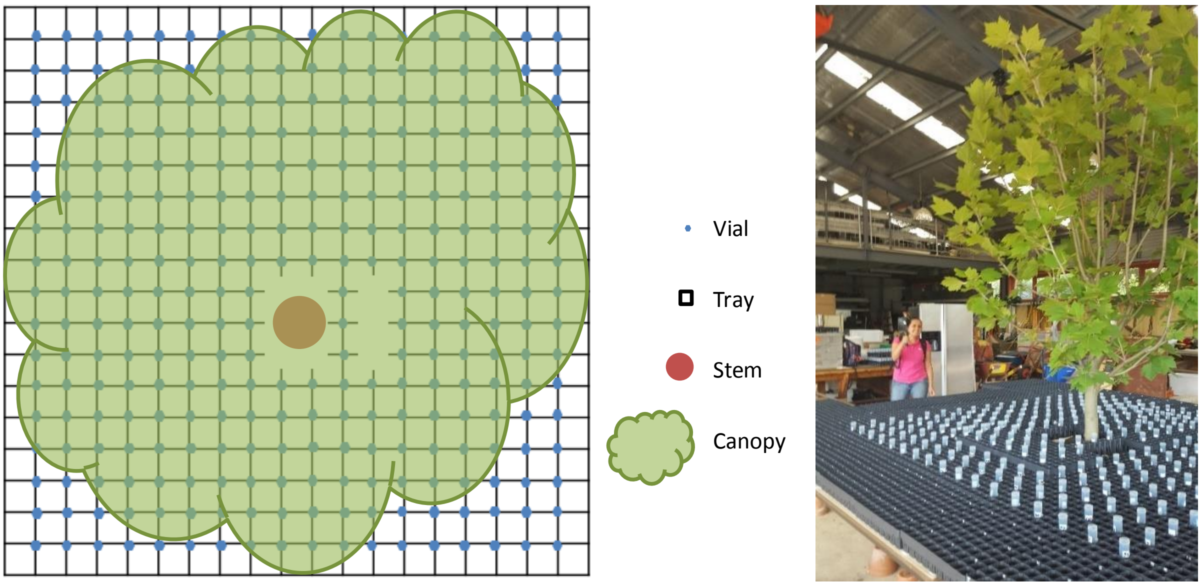


Figure 3.1. The arrangement of vials under the canopy: plan view and photo.

3.2.7. Data presentation and statistical analysis

Metrics derived from TLS data are presented as NP, NPA, which represents NP divided by the calculated canopy projected area, and NPV, which represents NP divided by the estimated concave canopy volume. TLS-derived metrics were correlated with the directly measured plant area: linear regressions analyses were performed between PSA and NP; plant area index (PAI) and NPA; and plant area volume (PAV) and NPV. Analyses of covariance (ANCOVA) were performed to identify differences between species, with plant surface metrics (PSA, PAI and PAD) held as the dependent variables and TLS-derived metrics (NP, NPA and NPV) as the covariates. These analyses are intended to test the hypothesis that TLS-derived metrics are good predictors of plant surface metrics.

In the second part of analysis, TLS-derived metrics were correlated to the interception parameter, C_{min}. ANCOVA were performed to identify differences between species, with C_{min} held as the dependent variable and TLS metrics (NP, NPA and NPV) as the covariates. These analyses intended to answer whether TLS-derived metrics are effective in predicting C_{min}.

For the throughfall redistribution analyses, the average throughfall (mm), the COV and the SD were calculated for every simulation. The average throughfall for each tree was calculated based on the volume of water collected in vials that were covered by the canopy. For this reason, the point density matrix and data of throughfall volume collected in the vials which overlapped and were outside (beyond) the canopy cover area were excluded for this calculation. During this experiment, two trees needed to be replaced, UP2 and UP3. In this process, UP3 was not scanned for the full (100%) canopy condition; therefore, throughfall calculations for this tree were based on the total incident area. A Kendall correlation test was performed to analyse the correlation between the throughfall volume and density of points.

To analyse throughfall distribution, each point of collection was categorised according to the interception rate calculated. To do so, the interception for each point was calculated by subtracting the collected throughfall values from the average incident rainfall, obtained from four control treatments without trees. Then, each point was categorised: negative results for throughfall were considered ‘concentration’ zones and positive results were considered ‘reduction’ zones. This information was correlated with the five different classes of density derived from the TLS point clouds. Maps of throughfall distribution, throughfall categories and class of canopy density were created on ArcGIS and statistical analyses were performed on RStudio.

3.3. Results

3.3.1. Correlations between TLS data and tree metrics

Firstly, the number of points for each tree was assessed and derived tree metrics were calculated from the scanned data (Table 3.1). TLS metrics were correlated to directly measured metrics to validate the effectiveness of TLS data in predicting plant surface metrics (Figure 3.2).

Table 3.1. Values of plant surface metrics, TLS metrics and interception parameters collected for each studied tree.

Tree ID	PSA (m^2)	PAI (m^2/m^2)	PAD (m^2/m^3)	NP (points)	NPA (points/m^2)	NPV (points/m^3)	C_{max} (mm)	C_{min} (mm)	TF (mm)
CM 1	4.9	2.1	1.0	68365	29468	13856	0.25	0.09	4.53
CM 2	3.9	1.6	0.8	60732	24293	12014	0.18	**	4.67
CM 3	5.6	2.0	0.8	91938	32718	13182	0.19	0.08	5.19
CM 4	5.4	1.9	1.0	75053	26427	13667	0.18	0.08	4.18
PA 1	9.5	3.7	1.3	91518	35472	12159	0.52	0.31	3.49
PA 2	9.2	3.1	1.0	80686	26895	9004	0.40	0.23	4.08
PA 3	11.4	4.0	1.6	81179	28787	11523	0.57	0.32	3.85
PA 4	10.0	3.2	1.2	96613	30477	11475	0.44	0.29	3.95
UP 1	8.2	5.1	1.1	55945	34966	7409	0.71	0.31	4.48
UP 2	8.6	5.8	1.3	51684	34687	7868	0.83	0.39	4.53
UP 3	7.9	5.3	1.2	41920	27947	6431	0.77	0.41	4.50*
UP 4	6.8	4.5	1.1	37216	24811	5864	0.67	0.39	4.27

* Including total incident area

** Value excluded due to measurements error

Notes: PSA: Plant surface area; PAI: Plant area index; PAD: Plant area density; NP: Number of points; NPA: Number of points per canopy area; NPV: Number of points per canopy volume; C_{max}: maximum storage capacity; C_{min}: minimum storage capacity; TF: throughfall.

Linear regressions between TLS and manually measured metrics show a significant relationship for all species (R^2 > 0.7). The variances between the variables related to scanned points and those related to tree measurements were not significantly different for any of the regressions performed, as validated by the F-test (Table 3.2). All regressions for *U. procera* presented higher values for coefficient *b*, showing a steeper slope compared to the other two species (Figure 3.2).

ANCOVA tests for NP and PSA, and NPV and PAD, show a significant difference between the studied species (*p*-value <0.05). On the other hand, the relationship between NPA and PAI shows no significant difference between species (*p*-value >0.05).

Table 3.2. Summary of linear regression parameters and significance tests for correlations between scanning-derived and plant surface metrics.

Species	X	y	a	B	R^2	F-test
U. procera	NP	PSA	−5.677	3×10^{-4}	0.826	8.3×10^{-50}
P. acerifolia	NP	PSA	−0.182	1×10^{-4}	0.792	1.0×10^{-54}
C. maculata	NP	PSA	−1.006	1×10^{-4}	0.942	4.0×10^{-58}
U. procera	NPA	PAI	−3.944	3×10^{-4}	0.823	9.9×10^{-50}
P. acerifolia	NPA	PAI	−0.156	1×10^{-4}	0.802	8.9×10^{-55}
C. maculata	NPA	PAI	−0.540	8×10^{-5}	0.927	4.4×10^{-58}
U. procera	NPV	PAD	−0.900	3×10^{-4}	0.811	1.2×10^{-49}
P. acerifolia	NPV	PAD	−0.077	1×10^{-4}	0.813	1.2×10^{-54}
C. maculata	NPV	PAD	−0.267	8×10^{-5}	0.927	5.9×10^{-58}

Notes: x: independent variable; y: dependent variable; a: intercept; b: slope; R2: coefficient of determination; F-test at 99% of significance

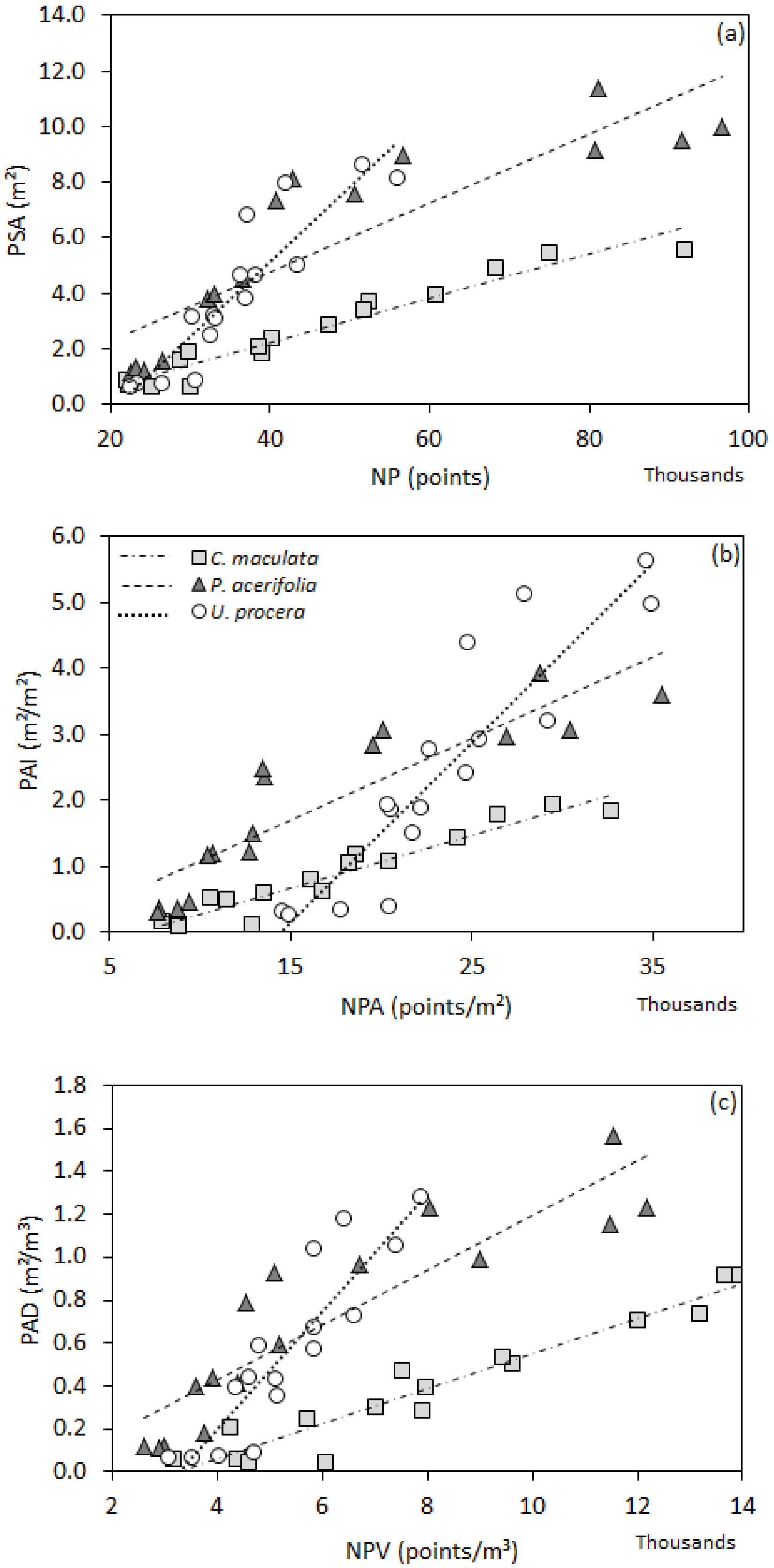


Figure 3.2. Linear regressions between TLS-derived metrics and plant surface metrics: (a) number of points (NP) × plant surface area (PSA); (b) number of points per canopy area (NPA) × plant area index (PAI); (c) number of points per canopy volume (NPV) × plant area density (PAD).

3.3.2. Correlation between TLS data and rainfall interception parameters

Regression tests were then performed to assess the effectiveness of using TLS-derived metrics in prediction of the water storage capacity of the studied tree species. Correlations between measured and TLS metrics were significant for all correlations, except for NPA × C_{min}.

ANCOVA analyses returned several significant correlations between the scanned metrics and C_{min}. ANCOVA tests demonstrate that all interactions are significantly different between species and the number of points (p <0.05). Therefore, linear models were separately performed for each species (Table 3.3, Fig. 3.3).

For all linear regressions, *U. procera* is the species showing greatest water storage capacity when compared to *P. acerifolia* and *C. maculata*, even if the number of points scanned was lower than for the other two species. However, *U. procera* presents the lowest coefficient of determination (R^2 <0.6) compared to the other two species, highlighting that this relationship is more subject to random effects than with the other trees.

Table 3.3. Summary of linear regression parameters for correlations between scanning-derived metrics and C_{min}.

Species	X	y	a	b	R^2
U. procera	NP	C_{min}	1×10^{-5}	-0.161	0.512
P. acerifolia	NP	C_{min}	4×10^{-6}	-0.063	0.929
C. maculata	NP	C_{min}	8×10^{-7}	0.019	0.667
U. procera	NPA	C_{min}	2×10^{-5}	-0.018	0.544
P. acerifolia	NPA	C_{min}	1×10^{-5}	-0.062	0.951
C. maculata	NPA	C_{min}	2×10^{-5}	-0.130	0.634
U. procera	NPV	C_{min}	7×10^{-5}	-0.194	0.580
P. acerifolia	NPV	C_{min}	3×10^{-5}	-0.060	0.943
C. maculata	NPV	C_{min}	5×10^{-6}	0.016	0.700

Notes: x: independent variable; y: dependent variable; a: intercept; b: slope; R^2: coefficient of determination

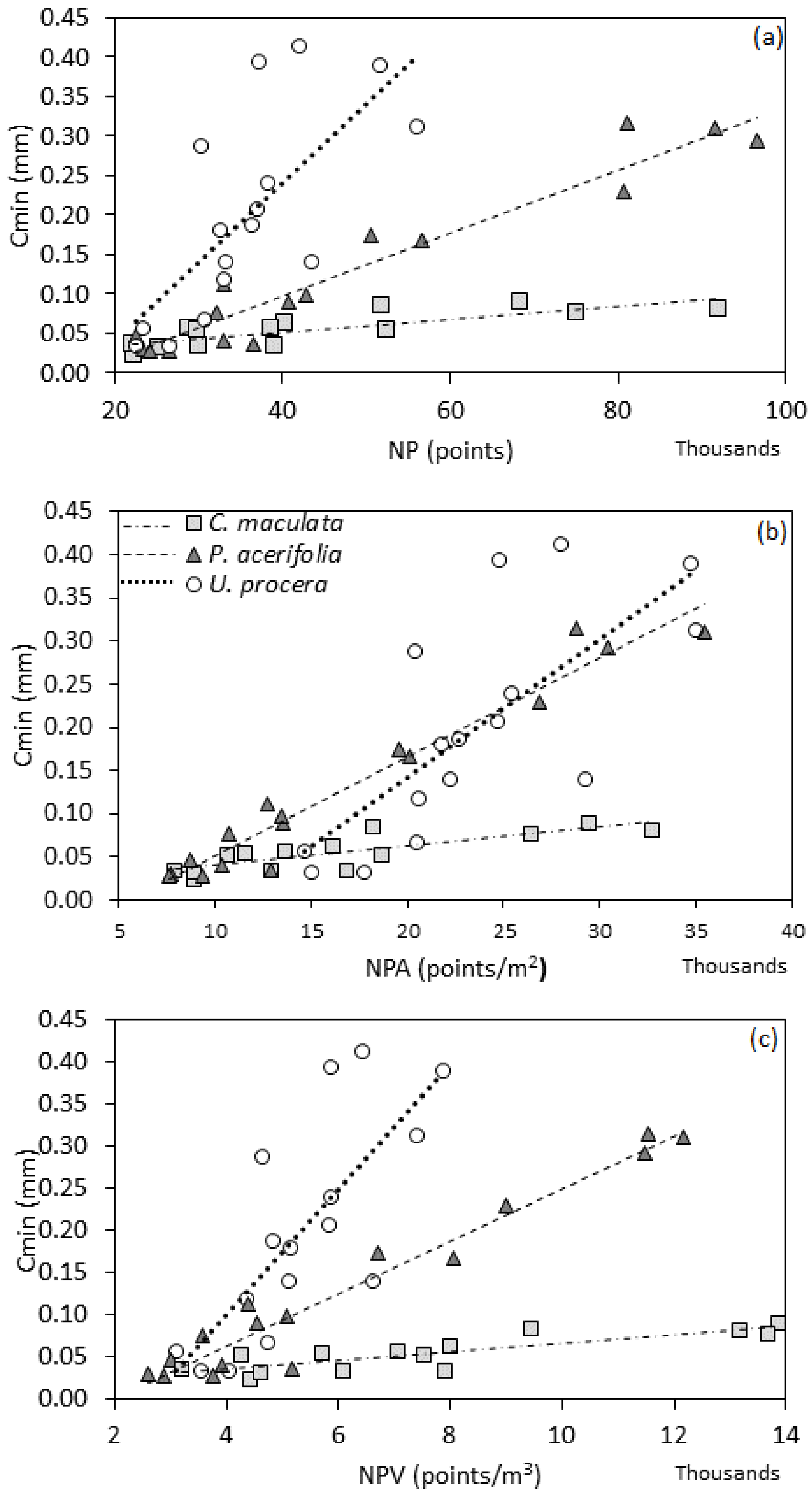


Figure 3.3. Linear regression between TLS-derived metrics: (a) number of points: NP; (b) number of points per canopy projected area: NPA; (c) number of points per volume: NPV; and water storage capacity parameter (C_{min}).

3.3.3. Throughfall and spatial redistribution

An average rainfall of 0.9 mm was calculated from four controlled treatments (no trees), with an SD of 0.3 and a coefficient of variation of 28% (Table 3.4). The average values of throughfall per species were 1 mm, 0.8 mm and 0.9 mm for *C. maculata*, *P. acerifolia* and *U. procera*, respectively (Table 3.4).

Table 3.4. Average rainfall (control treatment) and throughfall in mm (Avg), standard deviation (SD) and coefficient of variation (COV) for studied trees.

	Control			***C. maculata***			***P. acerifolia***			***U. procera***		
ID	Avg	SD	COV	Avg	SD	COV	Avg	SD	COV	Avg	SD	COV
1	1.0	0.3	30%	0.9	0.3	38%	0.8	0.8	107%	0.9	0.5	54%
2	0.9	0.2	28%	1.0	0.5	49%	0.8	0.9	112%	0.9	0.5	48%
3	0.8	0.3	27%	1.0	0.7	68%	0.8	0.8	100%	0.9	0.4	42%
4	0.8	0.3	28%	0.9	0.4	49%	0.8	0.7	84%	0.9	0.5	55%

In the subcanopy analysis, a slight similarity of the canopy contour can be seen in the throughfall distribution map when overlain by the canopy density map, showing the greater value of throughfall in areas around the canopy's dripping edge (Figs 3.4–3.6). During this experiment, two trees needed to be replaced (UP2 and UP3) and unfortunately UP3 was not scanned and so not counted in this throughfall analysis.

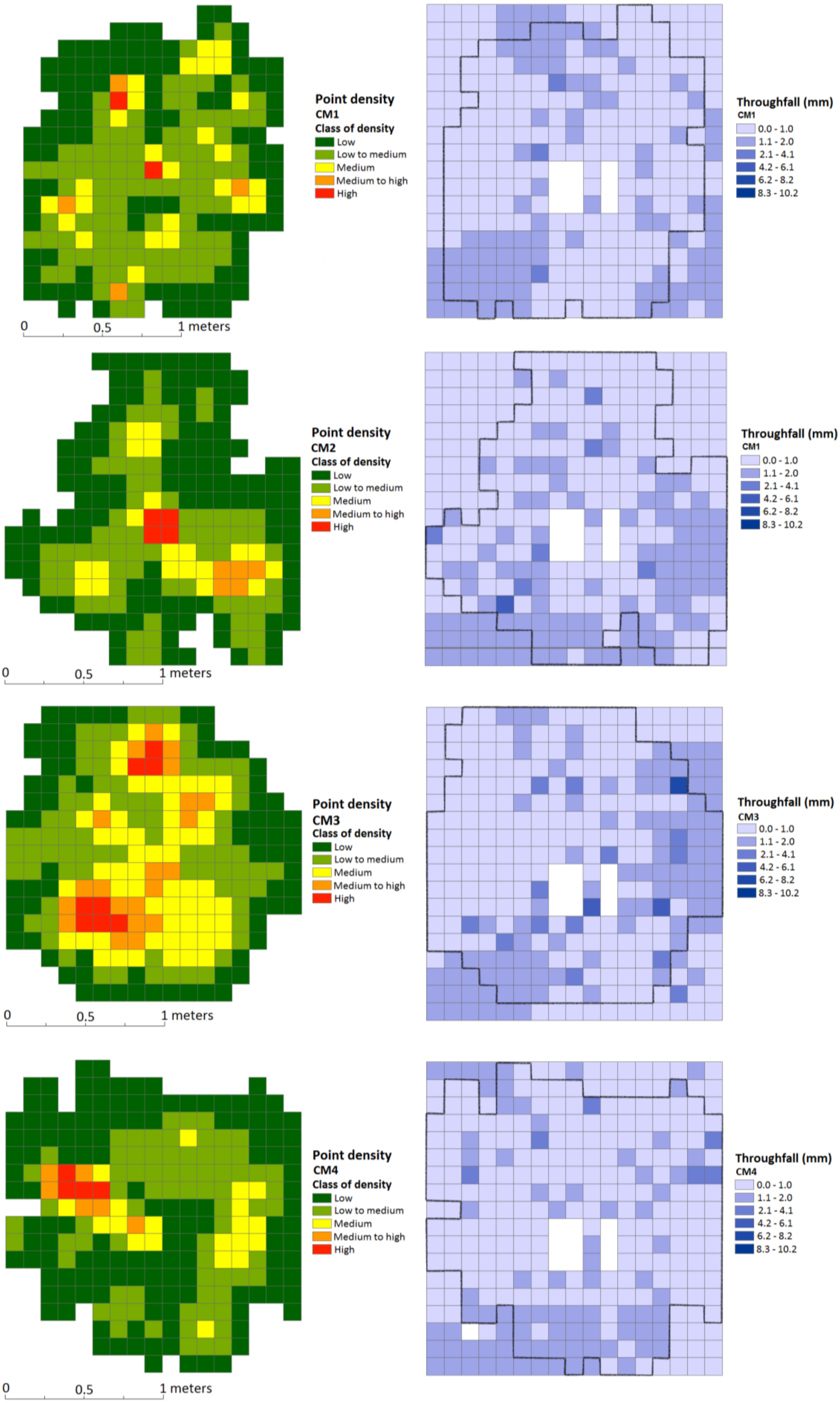


Figure 3.4. Canopy density and throughfall redistribution maps for all studied *C. maculata* trees.

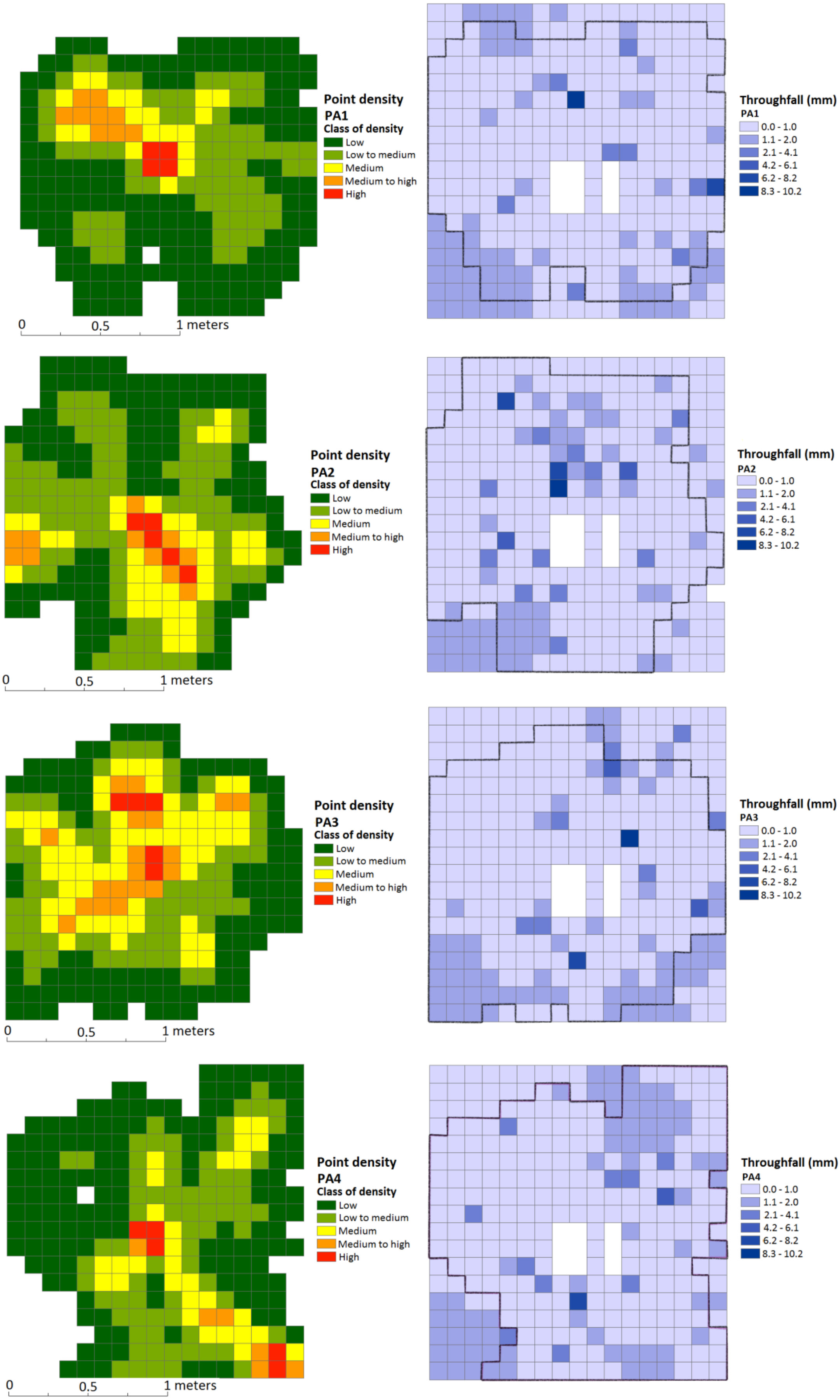


Figure 3.5. Canopy density and throughfall redistribution maps for all studied *P. acerifolia* trees.

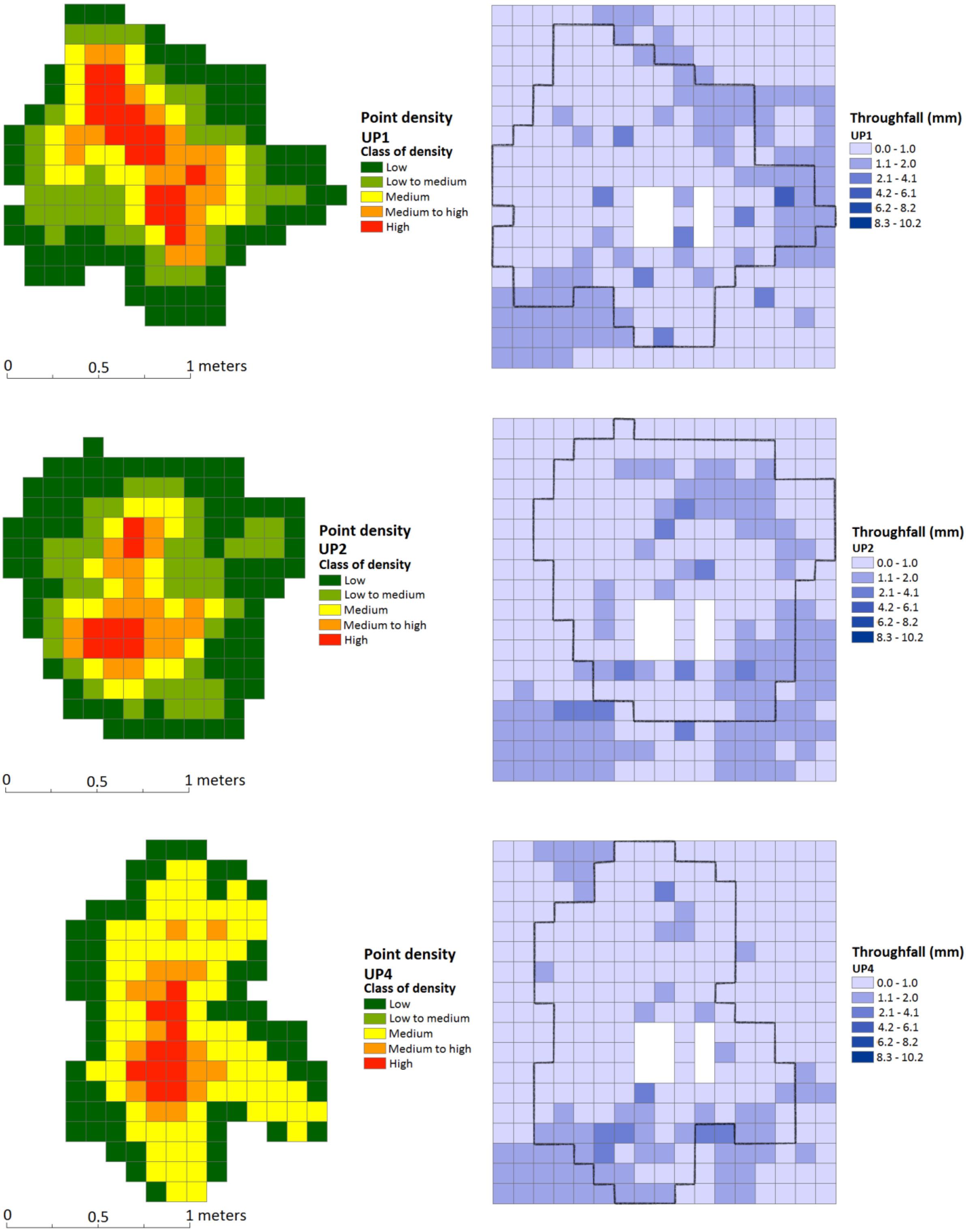


Figure 3.6. Canopy density and throughfall redistribution maps for three studied *U. procera* trees.

Kendall's correlation presents a *p*-value = 3.793 × 10^{-8} and coefficient tau = −0.0769, indicating a significant negative correlation between canopy density – represented by the density of points – and throughfall, but a weak coefficient of correlation. For this reason, density was grouped into five different classes and throughfall data was categorised according to the interception calculation for each point where throughfall was collected (Figure 3.7). Points categorised as concentration indicate a throughfall volume higher than the incident precipitation (negative interception), whereas reduction points indicate a throughfall volume lower than the incident precipitation (positive interception).

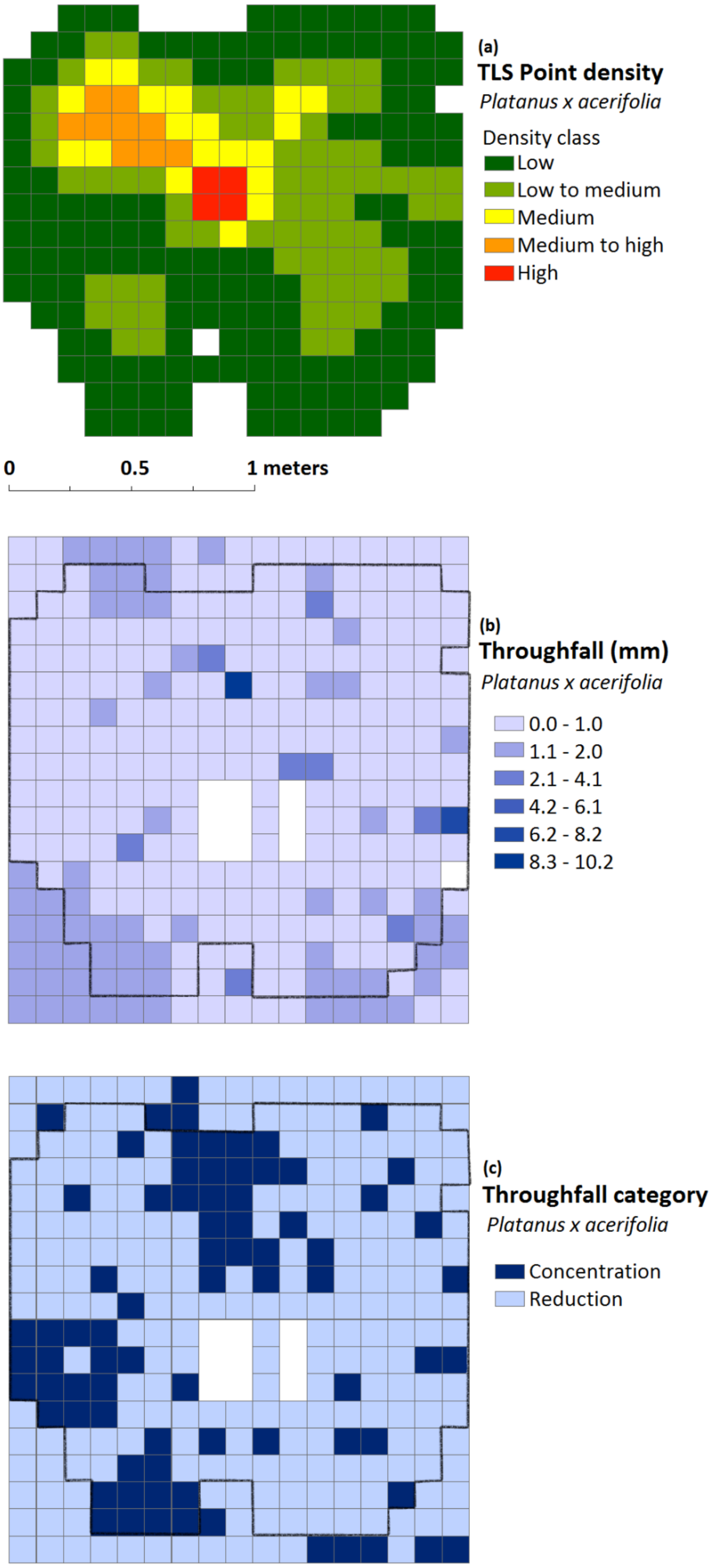


Figure 3.7. (a) Point density map; (b) throughfall distribution; and (c) throughfall category map showing zones of reduction and concentration for tree PA1.

For all species, most canopies were classified as low-density zones. High-density zones were visually identified in the scanned data as predominantly woody (Table 3.5). According to the categorical classification for the throughfall collection points, *C. maculata* and *P. acerifolia* present more reduction zones than concentration ones; on the other hand, *U. procera* presents a slightly higher number of concentration zones than reduction ones.

Table 3.5. Distribution of reduction and concentration of throughfall zones according to class of point density.

		U. procera (n=3)		*P. acerifolia* (n=4)		*C. maculata* (n=4)	
Density classes	Percentile	C*	R**	C	R	C	R
Low	< 20%	162	98	214	403	276	340
Low to medium	21 - 40%	41	57	69	170	81	100
Medium	41 - 60%	22	34	17	38	29	36
Medium to high	61 - 80%	9	26	1	15	6	11
High	> 80%	3	6	2	3	1	1
Subtotal		237	221	303	629	393	488
Total		458		932		881	

*Concentration; **Reduction

Despite the weak correlation between throughfall volume and point density, Mann–Whitney U-test analysis shows a significant association between density and throughfall categories for *P. acerifolia* (p = 0.009, p <0.05) and *U. procera* (p = 0.000, p <0.05), while the difference is not significant for *C. maculata* (p = 0.302, p >0.05) (Fig. 3.8). As can be expected, the denser the canopy as measured by TLS, the more the canopy acts as a shelter.

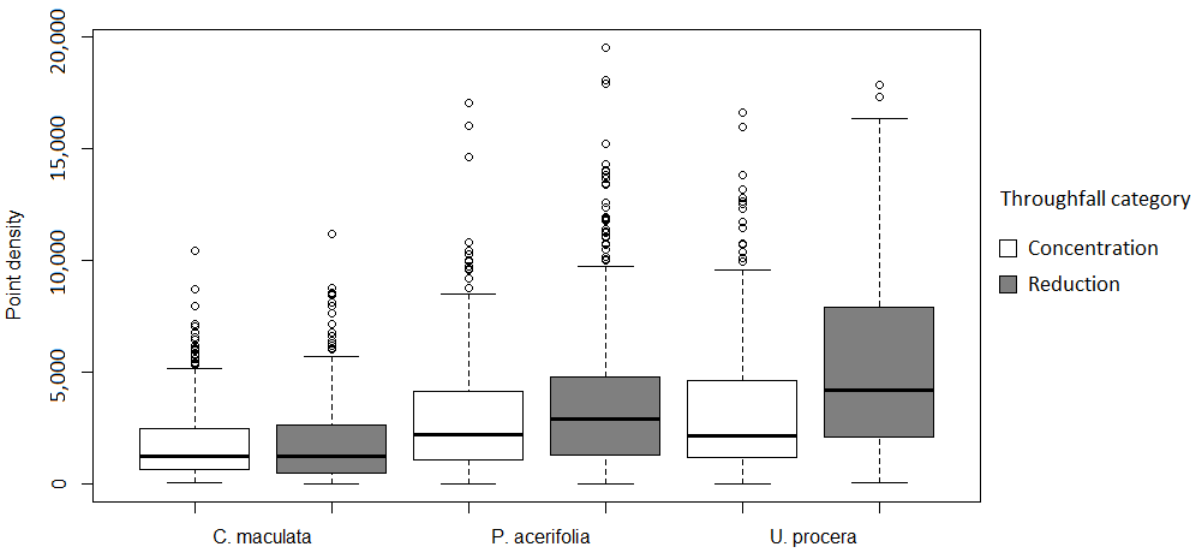


Figure 3.8. Box plots of the distribution of point density in the two different throughfall categories for each species.

3.4. Discussion

3.4.1. Correlation TLS data and tree metrics

For all combinations tested, linear regressions show a strong correlation between the measured and scanned metrics (Table 3.2, R^2 >0.70; *p*-value <0.01). Likewise, studies retrieving LAI from TLS data have shown a significant correlation between plant surface metrics and remotely sensed data (Antonarakis et al. 2010; Seidel, Fleck and Leuschner 2012; Zheng, Moskal and Kim 2013; Lin and West 2016). This study confirms the strong correlation between surface area metrics and the number of scanned points, and therefore provides encouragement for the use of TLS data for tree metrics estimation, although the results show that there is variation in this between species.

Significant differences between the species in ANCOVA analysis indicate that differences in plant structure, such as leaf size and angle, have an influence on a different number of points per canopy. Because each point in the TLS data corresponds to the laser beam that reached any canopy surface (branch or leaf), I expected that the number of scanned points would correlate with actual values and not suffer any species influence if the plant structures were at the same level of scanning. For example, *U. procera* presented a greater slope in all regression analyses when compared to the other two species. In this case, the greater slope is an indicator that the results for plant surface metrics are greater in comparison with the scanned metrics. However, *U. procera* presents the lowest coefficient of determination, indicating a weaker correlation between plant surface metrics and scanned metrics. On the other hand, *C. maculata* presents smaller results for plant surface metrics in relation to scanned metrics and a higher coefficient of determination compared to *U. procera*. Therefore, this suggests that the number of points may be underrepresented for *U. procera*. Because the accuracy of the laser scanner is about 0.02 m, smaller leaves are harder to capture with the device (Clawges et al. 2007). In this case, *U. procera* leaf size may be affecting the results, as smaller leaves tend to return a less accurate representation of leaf surface area. On the other hand, the size of leaves may favour the retrieving of the leaf surface area for *C. maculata* and *P. acerifolia*.

The angle of leaves also has an influence on the accuracy of data acquired (Zheng and Moskal 2012; Woodgate et al. 2015). Smaller leaf angles tend to lead to underestimation in leaf area estimates, while greater leaf angles tend to do the contrary and lead to overestimation (Woodgate et al. 2015). In our study, this may have occurred, particularly for our *C. maculata* results. Although *C. maculata* does not present the highest value for plant area metrics, the number of TLS points is greater than for the other two tree species, which may be explained due to *C. maculata* having pendulous leaves with greater angles of repose.

Additionally, the occlusion effect may play a role in misrepresentation of the 3D canopy. The high density of plant surfaces may have hindered the retrieval of information from deeper layers of the canopy. Issues with occlusion are described in studies using TLS data (Seidel, Fleck and Leuschner 2012; Zheng and Moskal 2012; Abegg et al. 2017) and the possibility of occlusion occurrence may be reduced with the capturing of multiple scans, which is possible using a mobile terrestrial laser scanner. Even so, occlusion can still happen when collecting data with mobile devices, because internal features cannot be captured from an inside view unless the scanner device is introduced into the canopy, which is still not a parameterised method.

Moreover, ground-based surveys tend not to capture the top part of a tree well, depending on their height. In previous studies, the attenuation of the laser beam and its reflectance has posed a limitation to the use of TLS data (Danson et al. 2007; Antonarakis et al. 2010). In our study, trees were not higher than 2.7 m, which did not limit the representation of the highest region of the canopy. However, the occlusion and attenuation effects can affect the assessment of larger trees, particularly in an outdoor urban environment.

As a limitation, this study did not measure secondary factors that may be causing the difference among species' signatures (e.g. leaf angle). Additionally, using juvenile trees may have underestimated the role of woody parts in laser detection, as larger branches (when older) may be captured more easily by the process. This fact should be considered when scanning mature trees in an urban context because mature trees tend to present denser canopies, which may intensify the occlusion effect by hindering the laser scanner from penetrating deeper into the canopy (Clawges et al. 2007). However, as a matter of comparison, PAI for mature trees in an urban streetscape in Melbourne ranges from 0.6 to 5.2 for *Platanus* × *acerifolia*, 2.1 to 7.6 for *Ulmus procera*, and 1.3 to 3.1 for *Eucalyptus scoparia* (Sanusi et al. 2017), which is comparable with the measured PAI for the trees in our study (Table 3.1).

3.4.2. Correlation TLS data and rainfall interception parameters

U. procera presents a greater slope in all regression tests, showing greater water storage capacity when compared to *P. acerifolia* and *C. maculata*, even if the number of scanned points was lower than for the others. This fact indicates that parameters other than plant area must be affecting C_{min}, as the number of scanned points is dependent on the presence of a surface to reflect the laser beam. Higher values of C_{min} are explained by characteristics that promote canopy water storage capacity, such as greater PSA (Li et al. 2016), but also leaf and bark hydrophobicity (Holder 2013; Holder and Gibbes 2016) and branch and leaf inclination (Levia et al. 2011), which were not measured during this study.

The significant interaction between species and parameters studied indicates that specific canopy arrangements may explain differences in water storage capacity. In this study, for example, *C. maculata* leaves presented an angle close to 90° in relation to the ground, which may be more easily captured by TLS, thus explaining why *C. maculata* presents the highest values of points per area and volume. The higher inclination angles of leaves and branches create gaps inside the canopy, which allow penetration of the laser beam from a ground-level scanner. On the other hand, this characteristic also prevents water from sticking to the tree (Livesley, Baudinette and Glover 2014) and reduces the water storage in this species.

Additionally, TLS-derived metrics do not take into account other important microscale characteristics of the leaves or bark, such as hairs, waxy cuticles, serrated laminar, and coarse and papery bark layers. Those aspects are important because C_{min} is affected by them, and they were not measured in this study (Rosado and Holder 2013; Holder and Gibbes 2016) and cannot be measured by TLS data of this type.

Branches play an important role in water storage capacity (Li et al. 2016). From the scanned data, the calculated proportion of the number of points shows that 34% of the scanned surface is associated with woody parts for *C. maculata* trees, 28% for *P. acerifolia*, and 55% for *U. procera*. Branch surfaces may store part of the incident rainfall, being responsible for storing up to 40.8% of the intercepted rainfall for *C. maculata*, 11.7% for *P. acerifolia*, and 12.8% for *U. procera.* Branches can also be responsible for draining water out of the plant system via SF, which is not counted as intercepted water. Studies have shown that SF is an important component of the interception process for some species (Carlyle-Moses and Schooling 2015), redirecting up to 10% of incident rainfall to the ground, depending on the rainfall characteristics (Levia et al. 2011). However, SF was not measured, as this study focuses on water storage capacity and throughfall analyses.

3.4.3. Spatial redistribution of throughfall

Under natural rainfall conditions, canopy throughfall redistribution will be influenced by changes in rainfall volume, such that spatial heterogeneity or coefficients of variation decrease as rain volume increases (Park and Cameron 2008; Fathizadeh et al. 2014). Other abiotic factors that may increase throughfall volume under a tree canopy are extended rainfall duration and higher rainfall intensity (Crockford and Richardson 2000; Staelens et al. 2008; Zabret et al. 2017). However, in the rainfall simulations of this study, these factors were kept constant; therefore, the differences in the spatial distribution of throughfall may be more confidently attributed to specific differences in the canopy characteristics among the tree species.

At a forest scale, a previous study (Schumacher and Christiansen 2015) found a significant correlation between throughfall and LiDAR-derived metrics in broad-leaved, coniferous and mixed forests in Denmark. However, the variance in throughfall was best explained by the LiDAR density matrix for annual precipitation rates. The explanatory power of LiDAR-derived data increases as the temporal resolution decreases from monthly to seasonal and annual rainfall. This indicates that, for a single rainfall event, the link between point cloud data such as TLS-derived metrics and rainfall will be obfuscated by noise. However, over many events in a season or a year, TLS-derived metrics could provide a prediction of throughfall.

Previous studies have demonstrated a level of uncertainty in regards to throughfall spatial distribution results and correlation with forest attributes because of the high variation in collected data (Keim, Skaugset and Weiler 2005; Loescher, Powers and Oberbauer 2002). However, as suggested by Voss, Zimmermann and Zimmermann (2016), an increase in the number of sampling points may improve the quality of collected data, as it may overcome high variation over a small area. In this study, the plot size is 1.87 × 1.98 m and the distance between cups equals 11 cm. Therefore, the total area covered by the vials (6.2 cm^2) represents about 5% of the total area, which is greater than in previous works (Zimmermann and Zimmermann 2014).

Statistical analyses have shown a significant correlation between throughfall reduction zones and denser canopy for *U. procera* and *P. acerifolia*. A higher density coincides with areas of lower throughfall because it corresponds to a larger plant surface to store water (Aston 1979). However, some trees present hotspots with high values of throughfall under an area of high point density in the middle of the canopy projection area. As can be seen by overlapping the throughfall redistribution with the point density map, the canopy structure may be influencing the redistribution process, as the arrangement of leaves and branches in this region conducts the water that has dropped from other layers to the bottom.

Patterns of distribution are different from one species to another. Visually, maps of throughfall distribution show a varied pattern. Statistically, throughfall maps for *P. acerifolia* trees present higher values for the coefficient of variation compared to the other two species. The significant difference may be influenced by the size of leaves and distribution of branches and leaves in the space. More open canopies, such as is the case with *C. maculata* trees, present more concentration spots when compared to *P. acerifolia*. However, the volume of water collected on concentration spots under the *P. acerifolia* canopy is much higher than the values measured under the *C. maculata* canopy. Water seems to be concentrating in the layers over the bottom line and rainwater has been redirected to these spots. This effect may be explained by taking the approach suggested by Xiao, McPherson et al. (2000): a tree canopy can be divided into different horizontal layers. Rainfall that has reached a given layer could have either passed through the gap in the canopy or been intercepted by plant surfaces in the next layer. In the case of *P. acerifolia*, with the largest and flattest leaves among the three species, the leaves are favouring the interception and formation of a large drop, because all water that drips onto the leaf surface takes longer to accumulate before dripping onto the next layer. At the same time, these characteristics increase the shelter effect in other areas of the redistribution map.

Previous studies have correlated the spatial redistribution of throughfall underneath tree canopies to the erosive potential of drips reaching the ground surface (Nanko et al. 2011; Geißler et al. 2012). In natural forests, most of the splash-induced erosion caused by throughfall is hindered by understory vegetation and litter cover (Calder 2001). However, in the urban forest, surface litter may not be present and understory vegetation limited to turfgrass only. So, for urban trees planted above either bare soil or sparse understory vegetation, especially if the land is sloping, trees that greatly redistribute throughfall may lead to greater erosion and greenspace damage. Furthermore, increasing the complexity of understory vegetation beneath green space trees has been demonstrated to increase the infiltration of throughfall and thereby decrease the occurrence of surface water runoff (Ossola, Hahs and Livesley 2015).

3.5. Summary

On this chapter, the number of scanned points has been tested in relation to directly measured plant surface metrics and the potential to capture the variations in leaf area assessed. Using the same set-up of the Chapter 2 experiment, I have explored the use of the terrestrial scanner as a tool to translate the plant surface area. Data was collected for 3 different species and 4 different trees of each species, making a total of 12 trees. Trees had their canopy volume and area estimated, and the number of scanned points per canopy was considered a parameter to estimate the plant area.

This data was correlated to manually measured metrics, showing a significant relationship between metrics. For this reason, I have tested the scanned metrics as a predictor of storage capacity based on the measurements provided in Chapter 2. Yet correlations between directly measured and remotely sensed data were significant, and so the use of scanned metrics needs to be developed to be considered in calculations of storage capacity. The regressions in this chapter have presented significant differences in the slope and level of association between the metrics of different tree species.

These findings aim to simplify the gathering of plant area data and apply this data to facilitate prediction of the storage capacity of urban trees. However, practitioners should consider the differences between species to be managed before making assumptions based on TLS data. Differences in leaf morphology seems to underestimate plant surface metrics, as can be observed in the *U. procera* results.

The second part of this chapter has presented results on the redistribution of rainfall after it passes through the canopy on a small scale. Maps of canopy density and throughfall rates are correlated, but throughfall rates and plant density show a weak correlation for regressions. However, a reduction in throughfall is associated with the presence of a denser canopy zone for two species, *P. acerifolia* and *U. procera*. These findings complement previous studies on the complexity of rainfall redistribution after reaching the tree canopy, which may guide practitioners in selecting tree species and types of ground cover used under urban trees.

The findings in this chapter encourage more research into the integrated use of new technologies such as TLS in the assessment of trees, thereby allowing us to predict tree canopy metrics with more confidence.

Chapter 4. Predicting canopy water storage capacity of different tree species in an urban park

4.1. Introduction

In Chapter 3, I have evaluated the use of remotely sensed data as a tool for estimating tree biophysical variables and the possibility of employing this data for predicting interception parameters and throughfall redistribution. The measurements took place in a controlled environment using a simulator to reproduce rainfall, which allowed us to deeply analyse data on a sub-canopy scale. However, the dynamics of rainfall are completely different in a natural set-up (Dunkerley 2008) and the interception process is also influenced by the size of trees that are fully grown outdoors in a park, garden or on the street.

This chapter compares two different methods to estimate interception on trees in an urban park: indirect calculation based on throughfall observations and prediction of interception using the Gash model. For this reason, throughfall data was collected under three different species in a park in Melbourne. The observed data was used to calculate interception rates. The rainfall data and tree metrics were applied to the existing Gash model aiming to estimate the interception parameters. The results are contrasted with the observed data. This assessment aims to test whether the Gash model is a good predictor of runoff reduction in urban trees.

The results presented in this chapter may add to previous knowledge about the rainfall partitioning of urban trees. The upscaling of results and the prediction of canopy storage capacity may give guidance in relation to the potential of different tree species to reduce runoff effects, encouraging the use of trees as part of integrated solutions for stormwater management.

4.1.1. Background

The need to evaluate ecosystem services provided by trees in the urban environment has become more urgent in recent decades as the number of people living in urban areas has surpassed the numbers in rural areas (UN 2018), inevitably leading to growth in impermeable surface areas. With the development of new residential areas, the existing natural areas that surround cities and remain within cities are under pressure and often urbanised, which modifies natural water-cycle dynamics. The hydrological cycle is one of the most affected in this process of urbanisation, as about 80% of rainfall becomes runoff on impervious surfaces (Walsh, Fletcher and Burns 2012). Consequently, the incidence of flood during rainfall events of high magnitude has increased in many cities.

Floods may occur when the amount of runoff water directed to the pipes of a sewage or stormwater system is greater than the system's capacity. In many cities, these systems are becoming obsolete, as they were constructed for lower capacity many years ago. Catchments offer limited capacity for water storage and, combined with the low permeability of the ground surfaces, explains the higher occurrence of floods observed over past years (Stovin, Jorgensen and Clayden 2008). Yet, initiatives for renovating these systems are expensive, as they involve extensive underground work (Stovin, Jorgensen and Clayden 2008; Berland et al. 2017).

The runoff effect can occur naturally when the amount of water reaching the ground is higher than the infiltration potential of the soil. In an urban area, though, less than 1 mm of rain is stored in impervious surfaces like asphalt and concrete (Boyd, Bufill and Knee 1993). The exceeded volume runs through the surface until it reaches a basin or permeable area where water can infiltrate. To decrease runoff volume running into overloaded systems, reduction solutions should be incorporated into stormwater management.

Planting more trees and increasing urban forest canopy cover is one of the alternatives for reducing the runoff effect in urban areas. Areas with trees reduced runoff flow by 60% when compared with asphalted areas (Armson, Stringer and Ennos 2013), not only by storing water in their canopies but also by reducing the rate at which water reached the ground surface and became runoff. Yet, measuring interception parameters such as the canopy water storage capacity in urban trees is a difficult task (Livesley, Baudinette and Glover 2014). The complexity of interactions hinders the collection of such detailed data and much more sophisticated methods need to be developed to be able to capture this data with more accuracy.

Studies have been able to directly measure throughfall and stem flow (Asadian and Weiler 2009; Carlyle-Moses and Schooling 2015; Guevara-Escobar et al. 2007; Livesley, Baudinette, and Glover 2014), but storage capacity has always been estimated in outdoor conditions. For this reason, models have been created and refined to predict storage capacity more precisely. Some studies have addressed how to predict the amount of rainfall intercepted by trees and most of these account for canopy cover, or another biophysical parameter, by using diameter at breast height (DBH) and leaf area index (LAI) in their predictions (Deguchi, Hattori, and Park 2006; Gash, Lloyd, and Lachaud 1995; Rutter et al. 1970; Xiao et al. 2000). The revised Gash model (Gash, Lloyd and Lachaud 1995) was modified to estimate interception loss in sparse canopy forests. Recently, this model has been applied to understanding interception losses using a single-tree based approach (Huang et al. 2017; Pereira et al. 2009).

4.2. Materials and methods

4.2.1. Study area

The experiment was conducted at Yarra Park, Melbourne, Australia. Melbourne historical climate data shows annual mean maximum and minimum temperatures ranging from 19.8 °C and 9.6 °C, while the average annual precipitation (1970–2016) is 534.5 mm (Bureau of Meteorology 2016). Melbourne is sited in a region of temperate climate (Cfb) according to the Köppen–Geiger classification (Peel, Finlayson and McMahon 2007), which means that all four seasons are distinct, with winter mostly humid and cold, and summer hot and dry. The pattern of rainfall shows seasonal influence and most precipitation occurs during winter and spring (Agriculture Victoria 2019).

The data was collected in an event-based interval. Because trees need to be in leaf to understand the interception process, and deciduous trees lose their leaves in the middle of autumn (Mid-April) and do not come back into leaf until the beginning of spring (September–October), interception measurements were not undertaken during this period. Rainfall events occur more frequently between September and November, but rainfall events of greater magnitude tend to occur more often during the summer months (Stern 2005). For this reason, this study includes rainfall events between December 2016 and April 2017, when deciduous trees were in full leaf and the incidence of high-magnitude storms was greater.

Figure 4.1. (a) Total area of Yarra Park; (b) location of studied trees in the park: red circle is *Ulmus procera*, yellow circle is *Ficus macrophylla* and blue circle is *Eucalyptus microcorys*.

Yarra Park is a private urban park that is open to the public (Figure 4.1). It is located to the south-east of the Melbourne central business district (CBD), about two kilometres from the main post office, traditionally the distance marker used to mark the centre of cities in Australia.

Historically, the area had important recreational use, as it was used by Aborigines from the local Wurundjeri people for hunting and fishing (East Melbourne Historical Society n. d.). In 1873, the area was officially reserved and an urban park with an extent of 240 acres was created. The area has suffered many interventions since then. Nowadays, Yarra Park comprises an area of approximately 28 hectares and is managed by the Melbourne Cricket Club as it houses the Melbourne Cricket Ground (MCG). The park is open to the public and users utilise the space for recreation, sports activities and pathways, and it is also used for carparking during events held at the MCG and surrounding event spaces.

The park is located inside the Port Phillip and Westernport catchment area, being an important permeable zone in the city, and has a significant value for the community, as it is surrounded by residential areas but also contains important areas designated for sports and recreation. Trees cover approximately 45% of the total park area (12.6 hectares), including 1212 trees of 58 different species and cultivars (*Tree Logic Pty. Ltd* 2013). Elms are the dominant tree species planted in the avenues, while eucalypts are the dominant specimens planted in the lawn (*Tree Logic Pty. Ltd* 2013). The park plays an important role in the conservation of remnant eucalypt trees, with special significance of a heritage river red gum (*Eucalyptus camaldulensis*), the “Scarred tree”, which is evidence of the use of the land by the traditional custodians, the Wurundjeri people (*Tree Logic Pty. Ltd* 2013).

4.2.2. Species description

Yarra Park is an urban green area which shows mixed use of native and exotic species usually planted in Australian urban forest. The layout and mix of species are typically English, with a design that could be described as “urban pastoral”. Three species were selected for this experiment: *Ulmus procera*, *Eucalyptus microcorys* and *Ficus macrophylla* (Figure 4.2). The first is an exotic species brought from Europe to integrate into the Victorian landscape during the 19th century (Lefoe 2008). The other two species are Australian natives, but more commonly found in Queensland and New South Wales regions (*Atlas of living Australia* 2018). All species are well adapted to Melbourne weather conditions. The selection of trees for this study ensured variability in the canopy characteristics, using trees with an isolated canopy, mature age and common use in urban forests. Additionally, logistical and safety issues were considered.

Ulmus procera, commonly known as English elm, is a deciduous tree native to northern Europe that can reach 30 m in height. The light-green leaves present an oblong shape with dentate edges interspersed with white hairs. Older branches and the trunk are covered in a thick, rough bark presenting corky wings, while young branches present smooth, grey-brown bark. The species is commonly employed in urban areas, mainly as street and park trees (Brodie and Lang 2016).

Eucalyptus microcorys, commonly known as tallowood, is an evergreen tree native to Australia prevalent in the states of New South Wales and Queensland. Their leaves have a lanceolate form and are covered in wax. New branches and part of the trunk are covered with smooth bark, while old parts have a thick and stringy dark-brown bark. It flowers in summer between December and January, producing terminal creamy-white inflorescences ("Atlas of Living Australia" 2018).

Ficus macrophylla, commonly known as Moreton Bay fig, is an evergreen tree native to north-eastern parts of Australia that can reach 60 m in height. The tree presents large, leathery oblong leaves which are smooth. The branches and trunk are covered in a smooth grey bark ("Atlas of Living Australia" 2018).

Figure 4.2. Selected trees for this study. A) *E. microcorys*; b) *F. macrophylla*; c) *U. procera*.

4.2.3. Throughfall collection

Throughfall was measured at the same time for the three trees selected using four under-canopy tipping buckets to quantify rainfall interception across a gradient of rainfall magnitudes and intensities. This collection method is based on the system employed in forest throughfall measurement for the isolated tree (King & Harrison 1991; Park & Cameron 2008). The rainfall tipping gauges were placed 1.5 m from the trunk in each cardinal point direction and were levelled on the ground surface to stay aligned with a horizontal plane (Figure 4.3). However, the gauges were removed from the park after the rain ceased. The collecting points were marked with a wood stake on the ground, ensuring the data was collected at the same points in different events. All rain gauges were set to start registering data after the first tipping.

Figure 4.3. Arrangement of tipping buckets.

Two tipping rain gauges were placed away from the canopies and set to record gross precipitation data. The gross precipitation was calculated from the average rainfall collected in the two buckets placed away from the projected canopy area. The total volume of throughfall collected underneath each tree for individual events was calculated by using an average of the total number of tips registered in each gauge. Canopy interception was calculated as the difference between gross precipitation and throughfall.

The experiment was designed to work as a mobile set-up, as it was not permitted to keep equipment permanently in the park. All equipment (except the wooden stakes left in the ground) was stored in the office and the weather conditions were checked regularly. When a rain event of more than 2 mm was forecast, the rain gauges were set to start and were placed in storage boxes, allowing me to carry them to the park in a cargo bike (Figure 4.4). After each rain event ceased, all equipment was packed and carried back to the office. The time and date of every tipping were retrieved from the rain gauge data loggers. From this data, it was possible to calculate the total amount of each event, as well as the intensity.

Figure 4.4. Cargo bike used to transport the equipment to Yarra Park.

Rainfall events considered in this analysis presented gross precipitation of at least 2 mm and a minimum of four hours without precipitation between events (Asadian and Weiler 2009). This data has allowed us to create cumulative rainfall graphs, which provide an overview of throughfall accumulation over the event duration. Based on the data collected in the outside gauges, the time when throughfall started under every tree could be estimated, considered the throughfall delay, in other words the temporal attenuation of the runoff effect.

Environmental condition data, such as average wind speed and direction, temperature and humidity, were acquired from a weather station located 1 km from the study area (Bureau of Meteorology 2017).

4.2.4. Tree measurements via ALS and TLS data

Trees were scanned aerially and terrestrially. Aerial laser scanning (ALS) was done during January 2017 (Figure 4.5). A LiDAR sensor (AL3-16, Phoenix Aerial Systems Inc., Los Angeles, California, USA) was attached to a drone which reached 60 m in height.

Figure 4.5. Drone with LiDAR sensor used to capture points cloud from plan view.

Terrestrial laser scanning (TLS) was done using the ZEB1 device and a similar method as described in Chapters 2 and 3. Target trees were walked around three times, which provided point clouds scanned from ground level. TLS data was collected in early April 2017, which should not have shown a significant difference in leaf density compared to the January drone data collection as trees usually start to lose their leaves around mid-April.

Additionally, the ALS data presents an accurate estimation of tree metrics from a top-down perspective. However, depending on the penetration index of trees, this can hinder the features under the canopy cover. On the other hand, TLS data provides a good view from the side and bottom views but, depending on the height of the tree, the top layer of the tree is underestimated. Combining both data was the solution in order to get the most out of the scanning data and improve the accuracy of the estimated metrics. Detailed methods for combining such data are presented in Parmehr et al. (in preparation). Tree height, projected canopy area and volume were estimated from combined point clouds.

The disadvantage of combining ALS and TLS data is that the density of points must be normalised across both collection methods. This step reduces the volume density of points in the cloud and does not permit the same analysis described in Chapter 3. The points are therefore not at a high enough resolution to estimate plant area metrics.

4.2.5. Tree measurements

Trees had their DBH and height directly measured. Canopy volume and projected area were estimated via a combination of ALS and TLS data. The concave method hull (described in Chapter 3) was selected, as it provides a more accurate estimate of volume and area based on the shape of the tree.

All three trees had their plant area index (PAI) and canopy cover estimated by hemispherical photographs. Photographs were taken during the early morning or on cloudy days, and analysed accordingly (Macfarlane et al. 2007). Each specimen received a value of 0.5 for the coefficient of extinction (k) (Bréda 2003). This is considered "the fraction of total one-sided leaf area projected onto a horizontal plane" (Hopkinson et al. 2013).

4.2.6. GASH model

The adapted model for sparse forests by Gash (1995) was used to calculate the storage capacity and interception of the trees in Yarra Park.

In Chapter 2, I explored the rainfall interception process in a more detailed approach, as the settings allowed me. There, storage capacity was directly measured for the studied trees. In this present chapter, storage capacity was estimated from throughfall data using the Gash model. Firstly, the model efficiency was tested in predicting throughfall by comparing results with field observations. As the output, the model calculated the interception volume for each rain event, which has been used to calculate the interception rate per tree.

Mean storage capacities used for calculation were based on results for *U. procera* and *C. maculata* in the indoor experiment (Chapter 2), and for *U. procera* and *E. microcorys*, respectively, and Xiao and McPherson's (2016) results for broad-leaved evergreen trees (0.78 mm) for *F. macrophylla* in the park.

The root mean square error (RMSE) was calculated for testing the accuracy of the Gash model to predict storage capacity (P_i) in relation to the observed data (O_i) (Eq. VII).

$$RMSE = \sqrt{\frac{\sum_{i=1}^{n}(P_i - O_i)^2}{n}} \qquad \text{(VII)}$$

Finally, the predicted values of storage capacity were used to estimate the amount of stormwater reduced by the trees in Yarra Park. The results were compared with calculations based on the average of the volume of water stored in one cubic metre during the rainfall simulations. The average volume stored was calculated for mature trees in Yarra Park based on the ratio of water volume (L) to canopy volume (m^3).

4.3 Results

4.3.1 Canopy measurements

Measurements of Yarra Park trees showed similar values of DBH for all *F. macrophylla* (FM) and *U. procera* (UP) trees and *E. microcorys* (EM) (Table 4.1). The projected canopy area ranged between 180.5 m^2 for an *U. procera* and 246.5 m^2 for an *E. microcorys*. Canopy volume ranged between 798.4 m^2 for a *F. macrophylla*, and 1693.7 m^2 for an *E. microcorys*. Estimates of PAI were highest for *U. procera*, followed by *F. macrophylla*, and then *E. microcorys* (Table 4.1).

Table 4.1. Description of measured diameter at breast height (DBH), height (H), canopy area (CA), canopy volume (CV), plant area index (PAI), literature-based extinction coefficient (k) and calculated canopy cover faction (C) for trees in Yarra Park.

Tree ID	Species	DBH (m)	Height (m)	Canopy area (m²)	Canopy volume (m³)	PAI	Extinction coefficient (*k*)	Canopy cover (*c*)
EM	*Eucalyptus microcorys*	0.76	16.70	246.50	1693.68	5.84	0.50	0.77
FM	*Ficus macrophylla*	0.71	9.90	183.97	798.43	6.09	0.50	0.95
UP	*Ulmus procera*	0.74	13.50	180.53	1141.22	7.36	0.50	0.97

4.3.2 Rainfall event description

From January 2017 to April 2017, 7 discrete events were counted for rainfall events with more than 2 mm depth (Table 4.2). A total of 50.4 mm of rainfall was collected during an overall period of 30.6 hours. The rainfall intensity ranged from 0.8 to 15.5 mm/h and the average rainfall intensity was 3.8 mm/h. Air temperature ranged from 11.1 to 23.2 °C. The highest average wind speed was recorded as 41 km/h during event 7.

Table 4.2. Rainfall characterisation and environmental conditions for each event measured in 2017.

Event	Date	Gross rainfall (mm)	Duration (h)	Intensity (mm/h)	Time since last rainfall (h)	Average temperature (^{0}C)	Average wind speed (km/h)	Predominant wind direction
1	20/03	2.4	1.9	1.3	>24	22.6	7.6	SSW
2	21/03	2.2	1.6	1.4	6.0	20.2	2.5	NE
3	21/03	9.0	0.6	15.5	6.5	23.2	6.8	NE
4	29/03	3.4	1.9	1.8	>24	11.1	7.7	SSW
5	8/04	7.6	4.0	1.9	>24	18.1	17.1	N
6	9/04	14.4	17.8	0.8	9.0	11.7	21.2	WSW
7	10/04	11.4	2.8	4.1	4.5	13.6	41.0	S
Avg		7.2	4.4	3.8		17.2	14.8	
Total		50.4	30.6					

The average throughfall volumes for each species across all events were 4 mm, 3.1 mm and 3.8 mm for *E. microcorys*, *F. macrophylla, and U. procera*, respectively. Throughfall rates presented averages of 46.4%, 35.7% and 45.1%, for *E. microcorys*, *F. macrophylla*, and *U. procera*, respectively. The interception was calculated and, along with stemflow (not measured), presented average rates of 53.6%, 64.3% and 54.9% for *E. microcorys*, *F. macrophylla*, and *U. procera*, respectively. *F. macrophylla* presented the highest interception rate, followed by *U. procera* and *E. microcorys* (Table 4.3).

Throughfall average start time was longest for *U. procera*, starting 33 min after rainfall had begun. Next, *E. microcorys* throughfall started after 24 min 36 s and *F. macrophylla* started after 24 min 24 s (Table 4.3). In other words, the average amounts of rainfall necessary before throughfall was registered were 1.0 mm, 0.7 mm and 0.95 mm for *U. procera*, *E. microcorys*, and *F. macrophylla*, respectively.

Table 4.3. Gross rainfall (GR), throughfall and interception + stem flow (SF), in % and mm, for each species (EM: *E. microcorys*; FM: *F. macrophylla*; UP: *U. procera*) and throughfall (TF) delay in all measured events.

Event	GR (mm)	Throughfall (mm; %)						Interception + SF (mm; %)						TF delay (min)		
		EM		FM		UP		EM		FM		UP		EM	FM	UP
1	2.4	0.8	33.3	0.7	29.2	1.1	43.8	1.6	66.7	1.7	70.8	1.4	56.3	20.0	20.0	45.0
2	2.2	0.6	25.0	0.5	22.7	0.4	18.2	1.7	75.0	1.7	77.3	1.8	81.8	87.0	95.0	80.0
3	9.0	5.6	62.2	5.1	56.7	8.6	96.1	3.4	37.8	3.9	43.3	0.4	3.9	4.0	5.0	5.0
4	3.4	0.9	25.0	0.3	7.8	0.6	18.8	2.6	75.0	3.1	92.2	2.8	81.3	22.0	4.0	43.0
5	7.6	3.1	40.8	2.3	30.3	1.8	23.7	4.5	59.2	5.3	69.7	5.8	76.3	5.0	18.0	13.0
6	14.4	5.5	38.2	5.9	41.0	4.7	32.6	8.9	61.8	8.5	59.0	9.7	67.4	16.0	19.0	32.0
7	11.4	11.4	100.0	7.1	62.3	9.4	82.5	0.0	0.0	4.3	37.7	2.0	17.6	18.0	10.0	13.0
Avg	7.2	4.0	46.4	3.1	35.7	3.8	45.1	3.2	53.6	4.1	64.3	3.4	54.9	24.6	24.4	33.0

Curves for cumulative rainfall from data collected in two events show the different rates for each species and the delayed times for throughfall start (Figures 4.5 and 4.6). In the example, cumulative rainfall is shown for 30 min periods for two distinct events: a low-intensity (event 6) and a high-intensity (event 3) rain event. Black lines represent the average cumulative rainfall collected in an open area (Out), the dotted line represents *E. microcorys*, dash-dotted lines represent *F. macrophylla,* and the dashed line represents throughfall under *U. procera*. The complete curves for all events are presented in Appendix A.

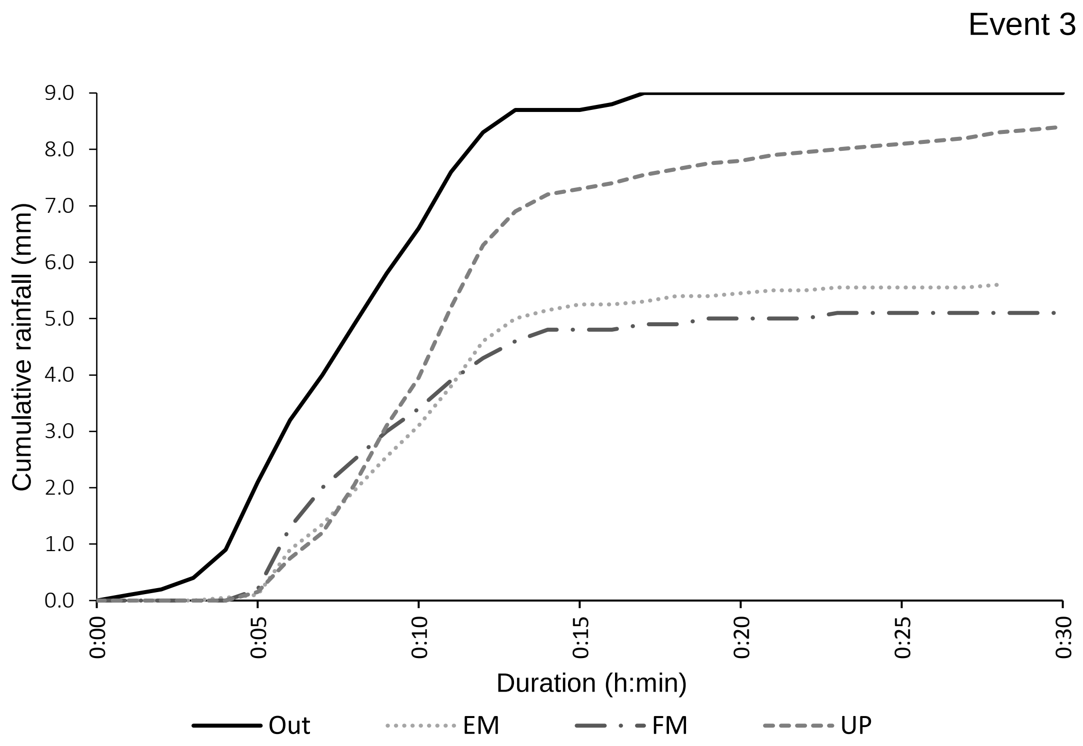


Figure 4.6. Curves for cumulative rainfall for outside and under-tree measurements during event 3.

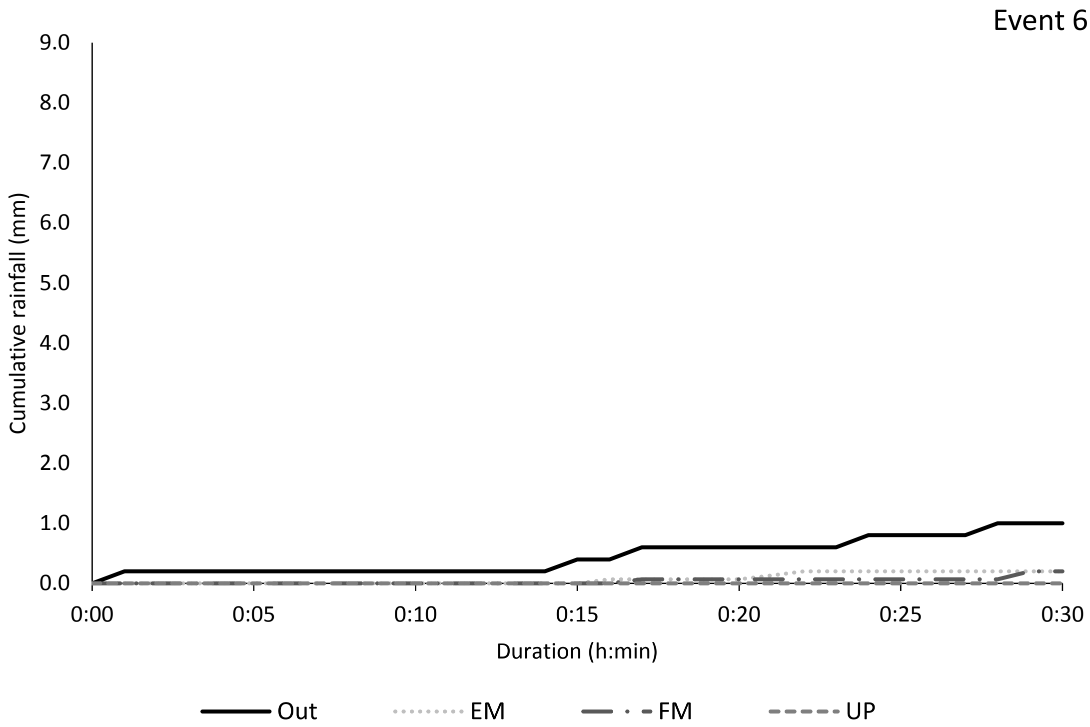


Figure 4.7. Curves for cumulative rainfall for outside and under-tree measurements during event 6.

Throughfall volume as a function of gross precipitation was compared for each species (Figure 4.7). There is a strong linear correlation between gross rainfall and throughfall, with values of R^2 = 0.96 (p-value <0.05) for *E. microcorys,* R^2 = 0.85 (p-value <0.05) for *F. macrophylla*, and R^2 = 0.84 (p-value <0.05) for *U. procera*. The difference among these species is greater for high-magnitude events.

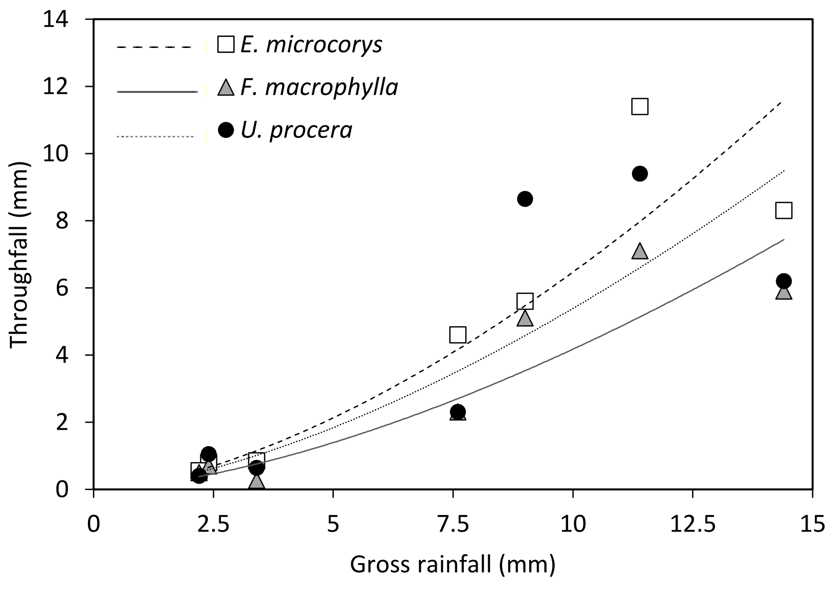


Figure 4.7. Throughfall depth (mm) collected under all trees (*E. microcorys*, *F. macrophylla, U. procera*) as a function of gross precipitation (mm) (N=7).

Throughfall and intensity present a weak correlation for all three species (R^2 = 0.33 for *E. microcorys*, R^2 = 0.22 for *F. macrophylla*, and R^2 = 0.16 for *U. procera*; all p-values < 0.05). Additionally, the relationship between wind speed and throughfall varied between species; *E. microcorys* presented R^2 = 0.69, *F. macrophylla* presented R^2 = 0.22 and *U. procera* presented R^2 = 0.49 (all p-values <0.05).

4.3.3 Prediction of rainfall interception using Gash (1995) model

The ANCOVA analyses results show that there was no significant difference between species (p = 0.28, p-value <0.01). Predicted and collected throughfall present a relatively strong relationship (R^2 = 0.65, p-value <0.05; Figure 4.8). Predicted throughfall was slightly overestimated when compared to collected results, mainly for collected throughfall greater than 5 mm, with a variance of 14% between collected and predicted data. The calculated RMSE is 3.04 mm.

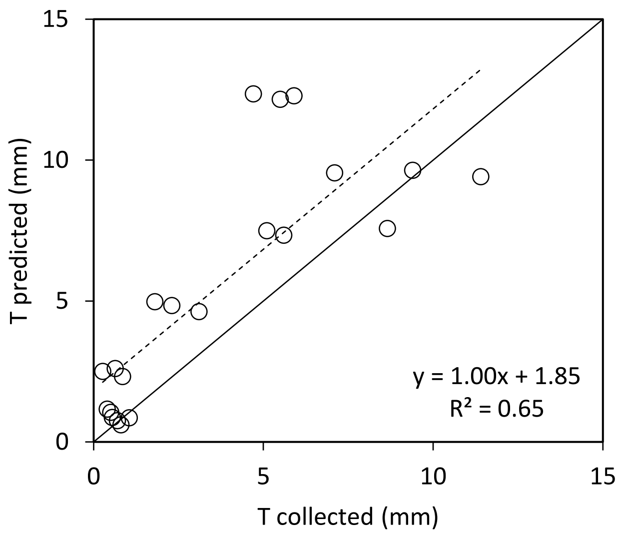


Figure 4.8. Correlation between collected and predicted throughfall (N=21). Solid line indicates the ideal fit to the model (1:1) and dashed line represents the trendline that best fits the model.

Interception losses were predicted for all events using the Gash model. Average values for interception rates are 0.8, 0.9 and 0.8 mm for *E. microcorys*, *U. procera* and *F. macrophylla*, per canopy area, respectively. From the predicted rates, the volume of runoff reduced by each tree was calculated. On average, *E. microcorys* intercepted 10.4% of rainfall, *U. procera* intercepted 12.3% and *F. macrophylla* intercepted 11.1%.

4.4 Discussion

4.4.1 Rainfall partitioning

The throughfall rate is a combination of both rainfall passing through gaps in the canopy and canopy dripping (Xiao et al. 2000). For this reason, throughfall rates are connected to canopy characteristics such as leaf and branch density, and leaf and branch inclination in relation to the ground (King and Harrison 1998). The significant difference between throughfall collected under different trees indicates distinct canopy characteristics that may be influencing throughfall dynamics. Additionally, differences in throughfall rates are greater for high-magnitude events.

In this study, the cumulative rainfall curves show distinct behaviour depending on the species and rainfall conditions. In an outdoor experiment, many environmental factors can affect the interception process, such as rainfall intensity and magnitude, although the relationships between rainfall magnitude and intensity with interception are still controversial. In several controlled studies, greater rainfall magnitude and intensity increased throughfall rate (Aston 1979; Li et al. 2016; Xiao and McPherson 2016). Higher throughfall rates were observed in this data collection for two events with higher rainfall rates (events 3 and 7). Higher rainfall magnitude and intensity may present characteristics that influence the kinetic energy of drops and decrease the potential for drops to stick to the surfaces (Nanko, Hotta and Suzuki 2006).

Li et al. (2016) found different effects of rainfall intensity variation on storage capacity. Only one of the four studied species, *P. tabulaeformis*, presented a significant increase in storage capacity as the intensity increased, while for the three other species the highest values of C_{max} and C_{min} were not achieved at the highest rainfall intensity tested (150 mm/h). The highest values of total leaf area and LAI may have influenced those cases, as their storage capacity was higher. In other words, when the rainfall intensity increases, the amount of stored water will also increase, but only until it reaches its C_{max}. So what really drives the amount of intercepted water is the plant surface area and its characteristics.

Trees delay throughfall from reaching the ground by detention storage and water travel time on plant surfaces (Xiao et al. 2000). For this reason, trees may delay throughfall initiation, which decelerates flooding effects through the interception process (Bolund and Hunhammar, 1999; Pataki et al. 2011). As mentioned in Chapter 2, greater values of PAI indicate a larger surface area within the projected canopy area where water may be stored. Trees with higher PAI values may delay water from reaching the ground by a few more minutes. In this study, rainfall took more time to pass through the *U. procera* canopy compared to the other species, as water may have found more obstacles to pass through and fewer gaps when compared to the other species. On the other hand, *E. microcorys* presented greater inclination angles for branches and leaves, which may have sped up the time water took to flow down. The roughness of the canopy surfaces may also have influenced the delay in throughfall start. Leaves can be rougher because of the presence of hairiness or wrinkles, which can increase the capacity of water to attach to the surface (Holder 2013).

The temporal aspect of interception is important as trees slow down the amount of water reaching the ground, consequently reducing the speed of runoff water. However, the benefit of trees may be limited as the rainfall magnitude and intensity are often high during flood events and rates of interception are minimum after the canopy surface is saturated (Xiao and McPherson 2002).

Data collected beneath the *E. microcorys* canopy recorded throughfall equal to gross rainfall in event 7. This effect was reported in other studies and has been connected to fog drip and wet canopies at the start of the event (Styger et al. 2016). Because event 7 was measured 4.5 hours after event 6, the canopies could have been partially wet and the additional rain would have contributed to throughfall. Another possibility is that the water captured in the buckets under the tree accumulated from different layers of leaves and branches, which may have caused a funnelling effect (Xiao et al. 2000). Because the buckets were receiving water from a larger incident area, it surpassed the amount of gross rainfall captured in an open area.

Studies conducted for isolated trees in the last 10 years show great variation between results. Trees in tropical regions seem to intercept much more water compared to other regions. Interception rates of 80.4% were reported for *Calophyllum antillanum* (Nytch et al. 2018) and 82.4% for *Tipuana tipu* (da Silva et al. 2008), both studies conducted in tropical regions. However, Alves, Formiga and Traldi (2018) reported interception rates of 48% for *Mangifera indica*, 44% for *Pachira aquatica*, 43% for *Lichania tomentosa* and 28% for *Caesalpinia peltophoroides*. Differences were mainly attributed to the canopy volume and leaf size.

The results of my research are closest to findings in temperate and semi-arid regions. The conifer trees *Pseudotsuga menziesii* and *Thuja plicata* presented interception rates of 49.1% and 60.9%, respectively (Asadian and Weiler 2009). *Ficus benjamina* intercepted only 4.8% less than the studied *Ficus macrophylla,* although the tree in this study was approximately 40% bigger (Guevara-Escobar et al. 2007). Because (Guevara-Escobar et al. 2007) collected the throughfall under the total crown projection area this must suggest an underestimation of interception rates in this present study. On the other hand, *E. microcorys* presented higher interception rates (53.6%) when compared to *E. nicholii* and *E. saligna* (44% and 29%, respectively) and the differences may be attributed to PAI, as *E. microcorys* presented a PAI of 5.84 in contrast to 3.03 and 3.88 for *E. nicholii* and *E. saligna* respectively, and to plant surface roughness such as the rougher bark of the *E. microcorys* compared to *E. saligna* (Livesley, Baudinette and Glover 2014).

Wind speed shows a stronger correlation with throughfall rate under the *E. microcorys* compared to the other two species. The stronger influence of wind on the throughfall of the *E. microcorys* may be explained by the openness of the canopy and canopy height. Because wind-driven rainfall causes the incident angle to change from a mostly vertical path and modifies the rainshadow (Herwitz and Slye 1995), the shape and height of the canopy may play a role in the rainfall incident area. The same study reported an influence of wind-driven throughfall under rainfall with high wind speed (Herwitz and Slye 1995), which may mean overestimation of the volume of throughfall in the gauges placed on the opposite side of the predominant wind direction. Wind speed and direction may affect the redistribution of throughfall and cause such inconsistency in the throughfall results. However, this experiment could not properly capture this variation in throughfall redistribution because the number of gauges was limited to four per tree.

The influences of wind speed and direction on interception loss still need to be better understood. There is some evidence that high wind speed may decrease interception rates, as the air turbulence increases the movement of leaves and branches (Jackson, 1975). However, the combination of high wind speed with high temperature and low air humidity may favour evaporation, as raindrops hit the plant surfaces and rapidly evaporate.

4.4.2 Prediction of storage capacity

Prediction models have been successfully employed to predict interception parameters for isolated trees (Pereira et al. 2009; Huang et al. 2017). In this study, the predicted results were overestimated for all events when compared with observed results. Similarly, overestimated results were found when applying the models to predict interception losses in isolated trees of *Quercus ilex*, where predicted interception losses were 3.5% larger than observed, but differed from results for *Q. pyrenaica*, which were 5.5% smaller than the observed losses (Hassan, Ghimire and Lubczynski 2017).

Predicted throughfall has shown significant correlations with collected throughfall in the park. However, predicted values of throughfall were slightly overestimated when compared to measured ones and shown to be more sensitive to lower amounts of gross precipitation. On the contrary, Huang et al. (2017) found that the model underestimated interception for isolated Western red cedar and Douglas fir, with variances of 19% and 6%, respectively. The differences between predicted and collected data could be explained by the generalisation in the measurements of air temperature, wind speed and relative humidity (Huang et al. 2017). In addition, the Gash model is a generic model basing interception prediction on PAI data only. The different tree characteristics that are not accounted for in the model, such as canopy shape and leaf morphology, may lead to variation in storage capacity.

Yet, some errors in this study may derive from oversimplification of the interception process, as the model assumes that evaporative loss and rainfall intensity are constant during a rainfall event. Huang et al. (2017) found some evidence when testing the sensitivity of the model in relation to three different main parameters: storage capacity (*S*), canopy gap fraction (*p*) and evaporation/intensity rate (*Ec/R*), varying the values by ±10%, ±20% and ±30%. *Ec/R* was the most sensitive parameter in the model compared to *S* and *p*. A decrease in this parameter led to a reduction in interception loss, showing the greater influence of rainfall intensity (*R*) compared to evaporative rate (*Ec)*. Simplifying complex interactions may be useful for understanding part of the process, but oversimplifying may also obscure other important aspects and details that are crucial to acquire accurate data.

4.4.3. Balance of evergreen and deciduous trees

In Chapter 2, an approximation of the contribution of evergreen and deciduous species to rainfall interception was made based on C_{max} and C_{min} data for trees in their full canopy and no leaf treatment. It is important to highlight that this approximation considered trees with equivalent volumes. For the purpose of comparison in Chapter 2, *C. maculata* was estimated to store 0.09 L per m^3 of canopy and *U. procera* to store 0.15 L under a 2.5 mm/h rainfall. Considering the similarity between *C. maculata* and *E. microcorys* canopies, *E. microcorys* trees were estimated to be 375 times bigger than *C. maculata* trees used on the simulation and so would store up to 195 L of water in similar conditions. Based on the same logic, *U. procera* trees in the park were estimated to be 170 times bigger than *U. procera* trees used in the simulation and so would store up to 177 L of water in similar conditions.

In the park experiment, the evergreens, *E. microcorys* and *F. macrophylla*, have intercepted as much water as the deciduous, *U. procera*. The canopy volume plays a significant difference in this situation. Because the trees were growing in a park without much constraint on their development, they could display their full mature size. Comparatively, *E. microcorys* trees need a 60% larger canopy to store the same amount of water as a *U. procera*. On the other hand, *U. procera* trees need a 15% larger canopy to store the same amount of water as a *F. macrophylla*. For this reason, species adaptability plays an important role in the selection of a tree. Storage capacity cannot be the only criterion, because a greater storage capacity per volume or area will not matter if the species cannot develop fully in face of the many constraints present in the urban environment.

The use of volume improved the results as it considered the whole canopy interaction. However, the upscaled results may not translate well to mature trees, as trees modify their characteristics along with their development. One of the reasons may be the underestimation of branch biomass, as this develops more after the tree has reached a certain age. Likewise, bark roughness is an important aspect that influences the interception process and changes along a tree's life. For example, for *U. procera*, stem bark is relatively smooth in its first years, while in mature age it presents a furrowed appearance.

4.4.4. Limitations

Because this experiment was designed to work as a mobile set-up, it allows greater flexibility as it can be replicated in any open space. Previous studies collecting throughfall in urban areas needed to rely on locked areas or additional material to keep rain gauges fixed and protected (Guevara-Escobar et al. 2007; Asadian and Weiler 2009). On the other hand, the mobile set-up posed some limitations to data collection. Although it is recommended to use a high number of gauges to minimise the effects of variation in collected throughfall (Zimmermann and Zimmermann 2014; Voss, Zimmermann and Zimmermann 2016), the number of gauges under a canopy was reduced to four. Otherwise, it would have been impossible to place, remove and carry all the equipment, thus losing the flexibility of data collection. The use of troughs to increase the area of collection (Voss, Zimmermann and Zimmermann 2016) was considered but carrying a trough on a bicycle is not practical and there was no place to safely store it.

The mobile framework for data collection has also limited the number of events. The experiment would be set every time that a rainfall of more than 2 mm was forecast at a 40% probability. During the collection period, two rain events of more than 2 mm were missed because of misjudgement in rainfall forecasts.

Vandalism is also one of the reasons people choose to collect data in locked and fixed set-ups (Van Stan, Levia and Jenkins 2014; Nytch et al. 2018). In this experiment, one of the gauges went missing after a rainfall event during the night (event 4), restricting the gross rainfall data collection to one gauge only for the following events (events 5, 6 and 7).

4.4.5. Potential contribution to runoff reduction

Similarly, in Chapter 2 a practical application has been undertaken to calculate the impact of urban tree species selection on runoff reduction in a hypothetical scenario (50 x 5.5 m street; covered in asphalt; 50 x 2.5 m concrete footpath) with a total impervious area of 525 m^2. The volumes for reduction of stormwater runoff was calculated for the three species studied in the park, *E. microcorys*, *F. macrophylla*, and *U. procera* based on observed throughfall data.

The same rainfall conditions were assumed: 5 mm/h^{-1} 1-hour duration rainfall event received across the 525 m^2 surface area that would produce 2625 L of water. The first 1 mm of incident rainfall was assumed to be stored on the hard surfaces and was not calculated as runoff (Boyd, Bufill and Knee 1993), generating 2100 L of runoff. In each scenario, four trees each with a 10 m wide canopy were planted on the footpath, producing a combined tree canopy area of

192 m^2. Excluding the fraction of the canopy that was not sheltering the impervious public area (38.8%), the canopy area would receive a total of 961.3 L of rainfall (with the remaining rainfall volume falling on the impervious surface outside the tree canopies).

Based on the interception results observed in this chapter, the water storage for a 5 mm rainfall event for *E. microcorys*, *F. macrophylla* and *U. procera* is approximately 518.2, 618.1 and 527.8 L, respectively. This represents a 24.7%, 29.4% and 25.1% reduction in runoff, respectively.

4.5. Summary

This chapter has compared different methods to estimate rainfall interception in an urban park. For this purpose, throughfall was collected for isolated trees in an urban park and the interaction between throughfall and rainfall condition was analysed. Because all trees were subject to the same rainfall conditions, the significant differences between throughfall collected under different trees indicate distinct canopy characteristics that may be influencing throughfall dynamics.

However, the differences between collected throughfall were not consistent throughout all events. These results warn of the complexity of measuring throughfall in an outdoor set-up, as many different factors may influence the interception process. The variation between events also highlights the importance of creating a standard for throughfall measurements, making results more reliable and more comparable between studies.

The use of the Gash model simplified the complexity of the process. Yet, the results of interception prediction in this chapter present overestimated results when compared to observed results. The Gash model may be used with restrictions because for some species, such as the *E. microcorys*, it is not taking important tree traits into account, and so may estimate interception incorrectly.

Results show the importance of mature trees in rainfall interception in urban areas. Although urban trees have a shorter mean life span compared to trees in the natural habitat (Konijnendijk et al. 2005), practices to extend the life of mature trees should be encouraged in management planning. The restriction of land area in cities also limits the number of new trees to compensate for the loss of the volume that a single large tree occupies. Practices aiming to decrease the number of tree removals may improve interception rates, as trees in their mature size store more water compared to new plantings.

Chapter 5. Urban trees and stormwater management

This thesis has studied the role of trees in stormwater management in urban areas. The potential reduction of runoff by storing rainwater in tree canopies has been also calculated from the measures. However, previously the role of trees has been treated as secondary as an option to reduce runoff and flood risk in urban landscapes. Part of this problem may be due to the uncertainty and complexity of the canopy interception process, which has made it hard to make assumptions and model this ecosystem service.

In this thesis, I have investigated in detail the rainfall interception process, focusing on understanding the variation in canopy storage capacity of different tree species and of different canopy densities within the same tree species. The novel approach used in this study has allowed me to quantify variations in storage capacity according to differences in tree characteristics between species, and within the same tree species, depending on the levels of canopy health and leaf density a tree possesses.

Another problem in recognising the role of tree canopies in stormwater runoff reduction is the ease and level of accuracy in the assessment of tree canopy traits and surface areas. As new technologies emerge, remotely sensed data has the potential to be used to improve the assessment of tree area metrics that are directly correlated with canopy water storage potential at a species level. Within this, there is now some evidence to suggest that terrestrial laser scanning (TLS) data can be used for measuring plant area metrics and, from this, there is future potential to use remotely sensed data to predict canopy interception parameters.

The relevance of the findings of this thesis to each question will be discussed in this chapter. Following, several recommendations to incorporate the role of tree interception in stormwater management policies are presented. In particular, the research in this study has focused on five research questions:

- How much does the variation in plant area affect the storage capacity of individual trees?
- Are laser scanning metrics a good predictor of storage capacity for an individual tree?
- Can we describe the effect of leaf and branch density on the redistribution of throughfall of individual trees?
- What are the differences when estimating interception for different scales and using different methods?
- How can all of the above information be incorporated into stormwater management policies?

The relevance of the findings of this thesis to each of these questions is discussed below.

Based on the findings of this research, a few recommendations are made that will contribute to more effective measurement of tree traits and quantification of interception estimates in the urban context.

5.1 How much does variation in plant area metrics affect the storage capacity of individual trees?

This thesis has shown that urban trees have the potential to play a larger and more direct role in the mitigation of runoff. However, to date urban trees have not been greatly considered as an effective tool in the management of stormwater and flood risk. These findings show that tree metrics such as leaf, branch and canopy areas are key to better understanding the process of water storage in tree canopies.

The morphological differences between studied species have influenced these metrics. Yet, plant area density may vary within a single tree in a real urban scenario as a result of its habit (deciduous trees), changes in the environmental conditions, such as droughts, heat waves and biological attack, or even direct human interventions, such as pruning under overhead power lines or adjacent major roadways.

In Chapter 2, canopy water storage capacity was measured in an indoor rainfall simulation experiment, to understand the potential for water retention by different tree species with different canopy characteristics, but also within a tree species for canopies of different densities or levels of foliar defoliation. The maximum (C_{max}) and minimum storage capacity (C_{min}) were measured directly during a rainfall simulation for three tree species commonly used as street trees in the city of Melbourne, Australia: *Ulmus procera*, *Platanus* x *acerifolia* and *Corymbia maculata*. Trees were progressively defoliated between events, allowing comparisons of C_{max} and C_{min} between species and various degrees of defoliation.

The findings in Chapter 2 indicate that canopy area metrics show varying responses to rainfall storage depending on species and extent of defoliation (canopy density), decreasing canopy storage capacity up to 62%, 90% and 87% for *C. maculata*, *P. acerifolia*, and *U. procera*, respectively. This highlights the importance of understanding the rainfall interception process and how storage capacity varies when surface area metrics vary between species and individuals. Consequently, managers need to consider important differences between species when planning urban forests for flood mitigation, such as leaf and branch area, roughness and angle.

Although the trees in this study stored most of their water on their leaves, the results also acknowledge the contribution of woody surfaces to the canopy storage capacity. For *U. procera* and *P. acerifolia* water storage on woody components represented approximately

13% and 10% of the total canopy stored volume, respectively, whereas for *C. maculata* the water volume stored on the woody surface area was approximately 40%. The area of woody surfaces and their roughness may vary between species depending on their life phase and growth pattern. Therefore, large and rougher barked trees may play a greater role in woody water storage.

Additionally, it is important to acknowledge differences in canopy storage capacity when reflecting on the balance between deciduous and evergreen species. Deciduous trees may remain leafless for long periods, suggesting that planting evergreen trees will provide greater interception over time. But in this study, *C. maculata* (an evergreen) presented a smaller storage capacity compared to the other two (deciduous) species.

Finally, acknowledging the variation in a volumetric approach with the help of laser scanning (LS) technology has allowed us to understand the dynamics of canopy storage capacity on a small scale, and therefore in more detail. The findings suggest that urban foresters should consider the density of leaves per canopy volume, as well as leaf and woody surface characteristics, to enhance storage of rainfall if this is a requirement of urban tree plantings. This volumetric approach is relevant in the urban environment, where the development of a tree may be restricted by spatial limitations. Urban foresters must also keep in mind that, at any life stage, trees may suffer a reduction in their canopy due to pathogen attacks, insect herbivory or climate impacts, e.g. severe drought or heat waves. Such reductions in canopy surface area will directly affect their water storage capacity.

5.2. Are laser scanning metrics a good predictor of storage capacity for an individual tree?

Chapter 3 investigated the relationships between spatial distributions of throughfall and interception parameters with LS-derived metrics. Rainfall was simulated above small trees (~3 m tall) for three different species in a controlled indoor environment. Tree canopies were assessed using terrestrial LS (TLS) to generate point clouds to relate to directly measured canopy area metrics: number of points (NP), number of points per projected canopy area (NPA, m^2) and number of points per canopy volume (NPV, m^3). The trees were then destructively sampled and plant area was measured. The derived metrics were tested as parameters to predict tree water storage capacity via TLS data.

As interception rates depend on tree surface metrics, those TLS metrics were correlated with measured tree metrics: PSA, PAI and PAD. After validation, TLS-derived metrics were correlated with measured intercepted water (C_{min}).

Retrieving plant area metrics from TLS data has shown a significant correlation between directly measured and remotely sensed data. However, the regressions in Chapter 3 have also shown important differences in the slope and level of association between TLS data and plant area metrics of different tree species. In other words, practitioners should exercise caution in making assumptions based on TLS data without considering the species being managed. For example, for a given number of TLS points, a very different plant area metric or C_{min} would be predicted for each of the three tree species in our study.

In addition, the estimate of plant surface metrics may be an underestimation for species with smaller leaves, such as *U. procera*. Yet, the strong relationship between surface area metrics and the number of TLS points confirms the connection between those parameters within a given tree species, encouraging further exploration of TLS data to estimate critical morphological parameters in future studies.

As in the previous chapter, I have also investigated the effect of leaf area variation on water storage capacity, aiming to understand how the use of remotely sensed data can be implemented in the evaluation of tree area metrics, and possibly used to then predict simple interception parameters.

The use of point cloud density as a parameter to estimate tree metrics simplifies the use of TLS data in practical analyses. However, the use of TLS to predict interception parameters may be limited by leaf characteristics such as leaf angle and size. Leaf size and angle are crucial features for evaluating the quality of TLS to predict interception because they affect the chance of the leaf being reached by the laser beam. Other metrics derived from TLS data may be applied and additional studies may help to understand how to apply LS technologies in the context of urban forestry.

5.3. Can we describe the effect of leaf and branch density on the redistribution of throughfall of individual trees?

In Chapter 3, the redistribution of rainfall under the tree canopy was studied on a sub-canopy scale. For this purpose, the scanned data was converted into maps of point density, representing the plant density of the whole canopy. Throughfall was collected using a grid of vials and a map of throughfall distribution was created from this data. Throughfall maps and plant density maps were correlated; however, the relationships did not appear significant.

The throughfall redistribution maps showed an interesting pattern for *P. acerifolia* and *U. procera*, showing zones of concentration of throughfall where values were higher than the incident precipitation and zones where throughfall was reduced. These zones seemed to be correlated with higher plant canopy density values as indicated by TLS data and, for this purpose, the collected throughfall was categorised into "reduction" and "concentration" zones, and these categories were correlated to the plant density map. For *P. acerifolia* and *U. procera*, high plant density was shown to be more correlated to reduction zones, while no significant correlation was found for *C.maculata*.

Despite throughfall rates and plant density showing a weak correlation in regressions, the zones of reduction in throughfall were associated with the presence of a denser canopy zone. These results compared to previous ones suggest that point clouds are predictive at the canopy scale (good predictor for PSA, PAI and PAD), but not at the sub-canopy scale.

Understanding the patterns of throughfall distribution may help to guide the selection of species, use of understory vegetation and type of ground cover used under urban trees. Considering trees' specificities in the selection of species is a key factor that should be taken into account to achieve a potential rate of rainfall interception when planning to use trees for stormwater management. This initial investigation complements previous studies on the complexity of rainfall redistribution after reaching the tree canopy, but now on a small scale.

From the point of view of urban forestry, the amount and physical characteristics of raindrops reaching the surface are important when considering the kind of surface a tree is growing over. A great part of ground surfaces in city centres is covered by asphalt and cement, which presents limited permeability or none. Information on sub-canopy interception and throughfall could be considered in the design of the shape and level of permeability underneath the canopy.

5.4. What are the differences when estimating interception for different scales and using different methods?

Chapter 4 investigated how canopy water storage capacity can be predicted for a tree under realistic rainfall conditions. Throughfall was collected for isolated trees in an urban park and the interactions between throughfall and natural rainfall events were analysed with regards to rainfall characteristics (duration/intensity). As a result of data collection in 7 different events, throughfall rates presented averages of 46.4%, 35.7% and 45.1% for *E. microcorys*, *F. macrophylla*, and *U. procera*, respectively. Because all trees were exposed to the same rainfall conditions, the significant differences between throughfall collected under different trees indicate that distinct canopy characteristics may be influencing throughfall dynamics. Yet, the data collected may not represent species traits, as there was not enough individual tree for each species to be compared.

The differences in throughfall rates between trees were not consistent throughout the different types of rainfall events. For example, in a high-intensity event (I = 15.5 mm/h, GR = 9 mm) *U.*

procera presented 96% throughfall, whereas *E. microcorys* and *F. macrophylla* presented 62% and 57%, respectively. In a low-intensity event (I = 1.9 mm/h, GR = 7.6 mm), *U. procera* presented 24% throughfall, whereas *E. microcorys* and *F. marcophylla* presented 41% and 30%, respectively. These results demonstrate the complexity in understanding interception dynamics in a realistic scenario, as many other factors are influencing the canopy storage in addition to the trees' characteristics.

Prediction models like the Gash model (1995) may help to estimate interception without directly measuring throughfall. The differences between observed and predicted interception suggest that the use of such prediction models simplifies the complexity of the canopy interception processes. However, the interception rates predicted by the Gash model were slightly overestimated when compared to the observed values. As this calculation used the storage capacity measured in the previous indoor experiment, this may suggest that the results from the smaller trees may not translate well to larger, more mature trees, as canopy shape, bark surface and branch size change along with tree development.

Runoff reduction was calculated in a hypothetical scenario in this study using collected data from the two different setups. In Chapter 2, the interception was directly calculated for *C. maculata*, *P. acerifolia* and *U. procera* in the indoor setup. Based on these results, for a 5 mm rainfall event, the reduction in runoff is approximately 5%, 20% and 26%, respectively. On the other hand, in Chapter 4, the interception was calculated indirectly after throughfall collection for *E. microcorys*, *F. macrophylla* and *U. procera* in the outdoor setup. Based on these results, for a similar rainfall event, the reduction in runoff is approximately 25%, 29% and 25%, respectively. The results observed for *U. procera* in both experiments are comparable, presenting a difference of 1% only. Even for different broadleaves species, *P. acerifolia* and *F. macrophylla*, the difference is approximately 9%. Difference is great between *C. maculata* and other species. Differences in runoff reduction rates may be attributed to the method of data collection, size and age of the studied trees.

Chapter 6. Recommendations and conclusion

Based on the findings of this research, some recommendations can be made that will contribute to more effective use of trees in stormwater management.

6.1. Urban forest management

Urban forest needs to be a diverse ecosystem which provides benefits for a diverse range of needs. In a streetscape, for example, the main role in stormwater management is the attenuation of runoff in impervious area. According to this study, trees must offer a higher plant surface within a given volume to present better results, which allows the trees to provide more interception on an impermeable surface (asphalt and concrete).

Monitoring trees is a crucial element in good management, as it is important to “benchmark the forest, set future targets and measure change over time” (City of Melbourne 2012). The urban forest management strategies for the City of Melbourne emphasise the importance of monitoring “tree health, species composition, canopy cover and useful life expectancy”. Monitoring practices and policies focus on canopy cover as their unit. However, according to my results, improving and maintaining the quality of the canopy are as important as increasing canopy cover area.

Measuring and monitoring the ecosystem services provided by a tree in the urban environment are challenges because of the great geographical and temporal variability. For this reason, the use and development of new technologies are important demands for urban foresters. The use of LS data is viable from the point of view of reliability and accuracy when compared with collected data. To effectively use new tools, cities must invest in equipment and training as necessary.

To maximize the benefits of trees for stormwater management, planners need to guarantee the good health of the trees in the city. Because storage capacity is dependent on canopy surface area, trees will provide their maximum interception potential when they grow without constraint. For growing to their maximum expression, trees have three basic needs: water, nutrients and light. Unfortunately, in the urban environment these resources may be limited by surrounding grey structures, such as impervious pavements and buildings. These limitations may hinder their potential to fully develop their canopy, and so limit the benefits that depend on leaf area, as a reduction in runoff. As a recommendation, planners should focus on noting what is limiting the full development of trees in the urban environment, removing the constraint when possible or mitigating the effects on the urban forest.

The competition for space in cities has increased with the densification of urban centres. Spatial availability is a key element for sustaining healthy tree development in an urban area.

In this context, aerial development is physically restricted by grey infrastructure (buildings, poles, signs, etc.), traffic (mainly the passage of large vehicle as buses and trucks) and users' preferences when pruning trees for aesthetic reasons.

Root development is also restricted by grey infrastructure such as building foundations and sewer systems. A reduction in tree size has been associated with a decrease in the permeable area around trees (Sanders and Grabosky 2014) and tree health condition has been negatively connected to the presence of impervious surfaces (Just, Frank and Dale 2018). This may also limit the service of trees in the urban environment, as the root system may damage infrastructure. Therefore, policies to increase the pervious areas in new developments and rebuild established areas to allow greater space for root development underground are crucial to keep trees in a good health and grey infrastructure in good condition. The choice of suitable species is also essential to avoid future problems such as aerial roots breaking into footpaths because space is not sufficient.

Directly connected to the availability of space, the condition of the urban soil is an important constraint on proper tree development. Urban soils are known for their poor biochemical and physical quality (Scharenbroch, Lloyd and Johnson-Maynard 2005). Soil compaction is an aggravator in urban areas, as heavy traffic of vehicles and people, and buildings decrease the porosity of the soil, making it hard for the root system to spread and penetrate to lower layers of soil. Compaction is also an issue for tree development because compacted soil will hinder water's ability to penetrate, consequently decreasing the availability of water and nutrients to the roots and impeding gas exchanges (Jim and Ng 2018). Applying techniques of rehabilitation of urban soil to increase soil porosity may help the growth of the root system, leading to an increase in aerial systems (Layman et al. 2016; Somerville, May and Livesley 2018) and consequently increasing the interception and evapotranspiration rates.

Water availability is an issue that has intensified with climate change in diverse cities and, considering the future scenarios of climate change, trees will have harder growing conditions in cities. Temperature increases, longer periods of drought and higher occurrences of extreme events are creating a different challenge for the management of urban forests. Climate projections in North America have predicted a huge loss of trees and decreasing growth rates in the coming years (Lanza and Stone 2016; Nitschke et al. 2017). Additionally, defoliation induced by heat waves and drought decreases the canopy storage capacity. Therefore, the selection of species adapted to the region will support the growth of healthier and more resilient forests in the face of climate change. Current urban trees would need special care including irrigation to thrive in a more hostile environment.

As well as the changes in climate, human activities may have a direct negative impact on the quality of a tree canopy. Pruning is a common practice in urban areas to maintain a healthier canopy (remedial) or to reduce the height and/or spread of the tree (reduction). This can reduce drastically the total canopy surface area and, consequently, the potential canopy storage capacity. A study has shown that trees that were pruned over a longer interval (3 to 4 year cycle) and in a less intensive removal intercepted 54% and 35% more water for mature sweetgum and camphor, respectively, compared to trees that were pruned over a shorter cycle (1 to 3 years) in a more intensive removal (Xiao and McPherson 2002). Therefore, it is recommended to have less frequent and less intensive pruning of urban trees because this may increase rainfall interception rates.

Biological attacks by pests and pathogens can reduce canopy cover drastically. The susceptibility to a pathogen may have a genetic reason, but a great part of it may be connected to environmental conditions. Trees under heat or drought stress are more vulnerable to insect attack and diseases (Véle and Horák 2018; Long, D'Amico and Frank 2019). The occurrence of pests and pathogens in urban areas may also be connected to the low diversity of species (Laćan and McBride 2008).

Additionally, greater diversity is fundamental in order to mitigate the effects of climate-related stress. The diversity of species has been proven to be beneficial for recovery from forest defoliation caused by a long period of drought (Sousa-Silva et al. 2018). In urban forests, planners have the advantage of selecting species. However, the low diversity is currently an issue in most cities. To solve this problem, urban forest planners must consider the balance between native and exotic species, as well as evergreen and deciduous species. A more diverse urban forest is more resilient to climate change consequences.

In Australia, the use of native trees has been encouraged because of their natural adaptation to the climate. Native trees are also related to a sense of pride, connection and memories. However, many native species, such as the *Corymbia maculata* and *Eucalyptus microcorys* studied in this research, present contrasting features required for improvement in storage capacity. For this reason, the location and arrangement are important. For example, the use of some species should be restricted to parks and pervious areas. Trees with more open canopies should be associated with understory vegetation, which would help to intercept the excess water passing through the canopy. Also, the use of tree pits and green foothpaths must be encouraged when applicable because it not only has the benefit of increasing infiltration, but also improves the quality of the canopy (Grey et al. 2018a 2018b).

The ecological services provided by trees should be also considered in the management of the urban forest. Gustavsson et al. (2005) describe two different ways of addressing management. First, there is a long-term level, which can be denominated strategic management. At this level, activities consider a period of 10 years or more. Second, operational management focuses on annual or biannual activities. Both involve maintenance and developmental actions, and must be aligned with policies and planning objectives and targets, to maintain management as a dynamic and creative process (Gustavsson et al. 2005).

Therefore, the management of urban forests must involve a multidisciplinary approach due to the complex character of urban forest resources. It should take into account the care of trees and vegetation, but also meeting human demand and preferences, and dealing with interactions among different natural elements and built components (Gustavsson et al. 2005).

6.2. Stormwater management policies

Limitations regarding technical and administrative aspects have constrained more sustainable stormwater management. Roy et al. (2008) identified that “uncertainties in performance and cost, insufficient engineering standards and guidelines, fragmented responsibilities, lack of institutional capacity, lack of legislative mandate, lack of funding and effective market incentives, and resistance to change” are the major barriers to implementing sustainable solutions.

Policies to increase tree canopy cover are common in urban planning nowadays. Increasing tree canopy cover is an easily measured parameter to guide policies and progress. But as results in this thesis have shown, the quality of the urban forest canopy is also important for determining the canopy water storage and interception capacities. Therefore, considering tree species characteristics when selecting trees for rainfall water interception is a key factor in urban forest planning. Additionally, increasing canopy cover is not only about increasing interception and canopy water storage, as the benefits of urban trees for stormwater management also involve evapotranspiration and improvement of ground surface infiltration.

The early stages of planning an urban development should include policies of runoff targets “and/or to purchase the right to discharge stormwater from other parcel owners in a watershed” (Berland et al. 2017). Similarly, there should be targets for establishing a minimum area of impermeable surface and incentives to stimulate tree planting. Some policies already focus on increasing established impermeable areas. However, these measures need to be applied with caution, because increasing permeability may raise groundwater levels, consequently causing floods and undesirable returns from the sewage system (Endreny and Collins 2009; Berland et al. 2017).

Cities may provide more incentives to increase the number of trees on private properties. This may improve the interception capacity of an area. Across the City of Melbourne’s public and private realms, canopy cover is estimated at 11%. This means 89% of the municipality is without natural shade. Tree canopy covers about 22% of Melbourne's public streets and park areas, while canopy cover in private land is only about 3% (City of Melbourne 2012). Initiatives like reducing the level of property taxes for those growing trees and maintaining more pervious areas on their land should be applied to new developments and adapted to established areas.

Additionally, new developments and retrofitting of existing areas should apply techniques used in rain gardens and other green infrastructure planned to infiltrate stormwater. These techniques aim to increase the amount of runoff collected, such as considering planting water-tolerant trees in concave designs (Berland et al. 2017).

Policies should focus on extending the life span of urban trees and on monitoring trees' long-term health. Although their life span is often far shorter than for trees growing in a natural forest, practitioners should aim to improve site conditions for new plantings (Konijnendijk et al. 2005) and then to monitor the health of that urban forest in the long term (FAO 2016).

Finally, incorporating the management of trees for runoff reduction into stormwater management policies is complicated because it is an inter-institutional issue (Conway, Shakeel and Atallah 2011). As this requires integrated planning between the agencies responsible for trees and for water management, the different stakeholders must ensure good communication and collaboration to overcome the challenges of conflicting agendas.

There is not one perfect solution to maximise rainfall interception by urban trees and, consequently, reduce runoff rates in cities. Planners should consider a combination of good practices to increase canopy volume and maintain the quality of the trees, and should create policies to guarantee these practices are incorporated into the management of urban forests.

6.3. Future research opportunities

This thesis has attempted to estimate interception rates using both indoor and outdoor approaches. However, the investigation of rainfall interactions within the urban forest is still a relatively new field of study and there are some valuable opportunities for further research in this area.

- Investigating secondary tree characteristics that affect canopy storage capacity

It is clear from this study that the surface area of leaves is the main driver of canopy storage capacity. However, significant differences between species may be attributed to secondary characteristics, such as leaf angle, hydrophobicity and branch inclination. Although these have not been investigated in this study, previous research acknowledged the effects of such traits in the interception process (Goebes, Bruelheide, et al. 2015; Holder and Gibbes, 2016). Future investigation of the effects of these characteristics will help to better inform the potential for runoff reduction when selecting tree species for stormwater management.

- Investigating other benefits of trees for stormwater management

This study has focused on the interactions between rainfall and plant surfaces. The main objective was to understand the canopy storage capacity and how much water does not reach the ground to become runoff. However, this is only part of the role of trees in the urban hydrological cycle.

The relationships among rainfall, trees and soil offer important benefits for stormwater management. Trees can reduce runoff water by providing an area for water to infiltrate, and afterwards the available water may be absorbed by their roots (Grey et al. 2018; Szota et al. 2019). The trees' physiological aspects may be an important characteristic in selecting species to use for infiltrating and absorbing rainfall water.

The contribution of stemflow (SF) also needs to be better understood in the urban context. Although SF was not measured in this study, previous research has shown that, for certain species, SF may be a large contributor to redistribution of water under the canopy (Carlyle-Moses and Schooling 2015; Schooling and Carlyle-Moses 2015). The SF flux presents a potential benefit for improving water availability, contributing to tree establishment and runoff reduction when associated with good infiltration around the tree (Grey et al. 2018).

- Developing tools to better inform stakeholders

The applicability of this and similar studies is still limited by the complexity of interactions. Developing simplified applications which model the interception and predict scenarios in a more accurate way would give more confidence in adopting the use of trees in stormwater management. The reduction of runoff is the key outcome from interception studies for stormwater management. If we improve the way we are calculating runoff reduction in cities, we may be able to better calculate the potential economic benefits.

The use of laser scanning data should be further investigated. Significant correlations between directly measured and scanned metrics encourage the use of this technology, which is easily accessible to city planners these days. However, the use of this type of data is still limited. Further investigations should consider developing the use of LS data to urban forest planning, facilitating the applicability of this kind of data to assessing trees and calculating benefits.

6.4. Final considerations

Comprehending the interception process and the canopy storage capacity is essential to advance studies of urban hydrology and the benefits of urban trees for stormwater management. The findings of this thesis validate leaf density as the main driver of canopy storage capacity. Therefore, this should be the main characteristic when selecting trees for the purpose of reducing runoff in urban areas.

Additionally, greater plant density has been correlated with sheltering zones under the canopy. Understanding the redistribution of throughfall under the canopy may help to minimise errors when collecting data and allow standardisation of methods for studying throughfall. Further research in this area would contribute to significant improvement in the way that throughfall is accounted for in stormwater management.

LS metrics showed a significant correlation with direct measurements of plant area. The findings of this study support the use of LS data in the assessment of trees. The use of LS data may improve the accuracy of tree assessment, simplifying and decreasing the time we take to collect tree information. New methods to calculate runoff reduction should be developed from this data.

The limitations of the Gash model to predict interception relate to the fact that the model acknowledges only canopy cover in interception predictions. This may miscalculate the benefits because the urban forest is often a patchwork of species, ages and arrangements. Thus, understanding the processes in detail would allow us to better evaluate predictions and trust results even when simplified.

The uncertainty regarding trees' performance has limited the development of policies and the use of trees as part of the integrated solutions to managing stormwater in our cities. Yet, there is some evidence to suggest that policies have started to incorporate such findings about interception research by acknowledging the importance of trees in the urban hydrological cycle and making recommendations about better management of them. However, with increased occurrence of flood in urban areas, these results will be only significant if practices and policies to increase canopy cover and improve its quality are adopted in time.

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APPENDIX A

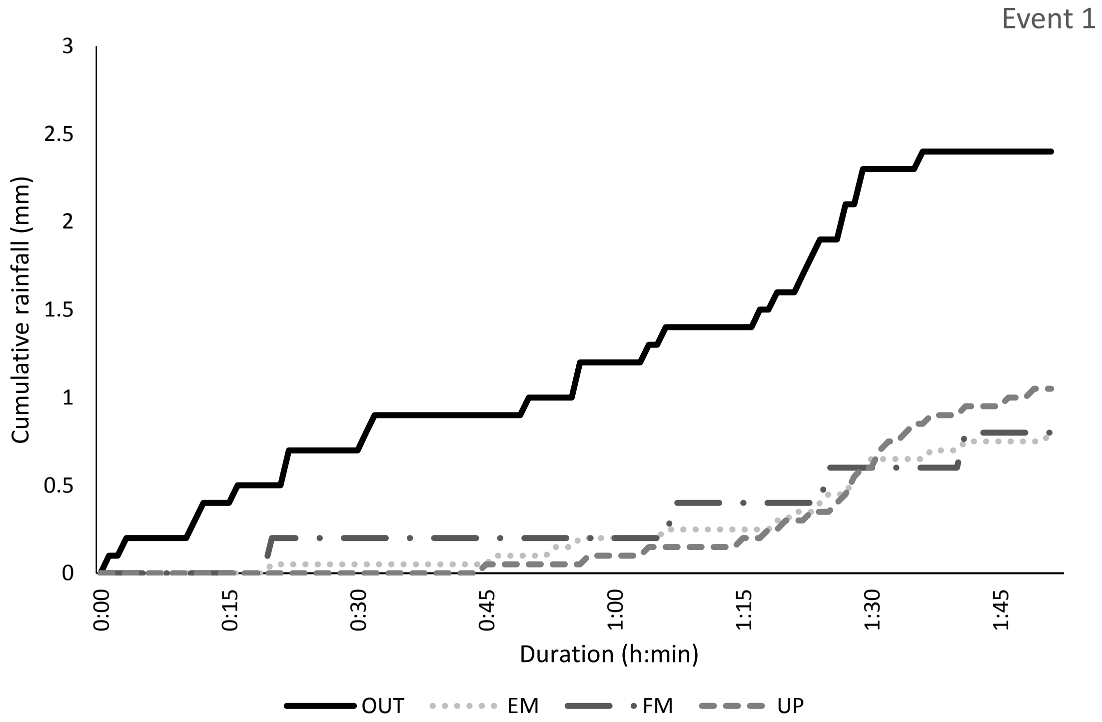

Figure A1. Curves for cumulative rainfall for outside and under-tree measurements during event 1.

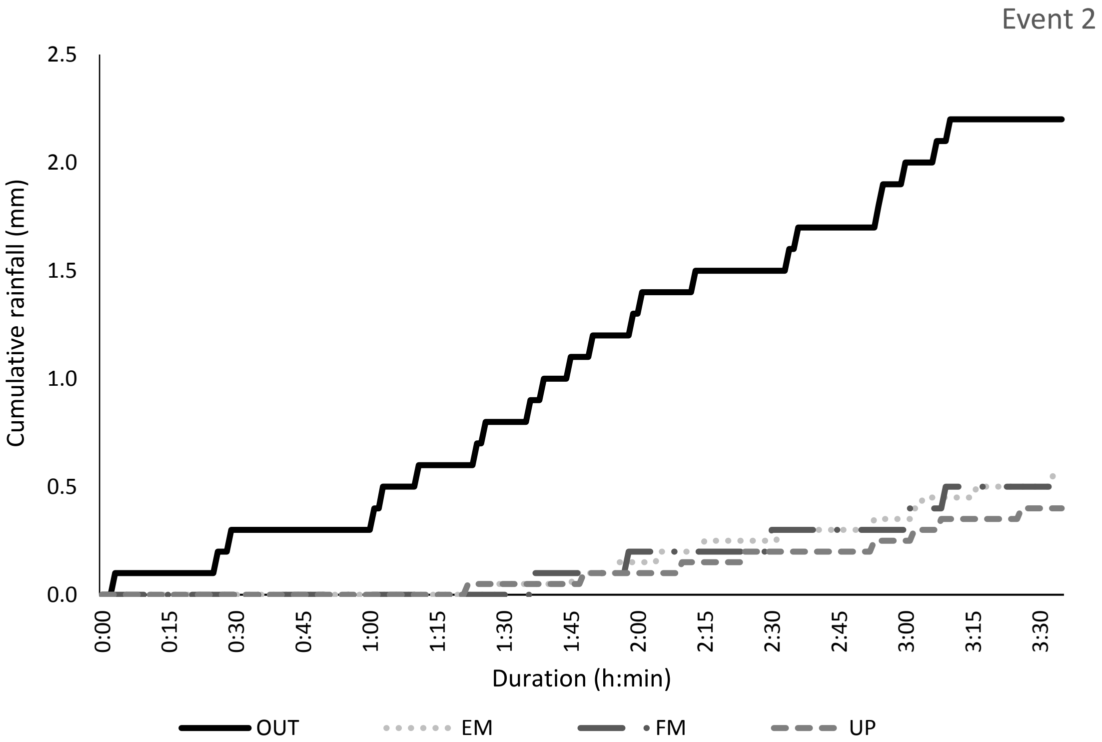

Figure A2. Curves for cumulative rainfall for outside and under-tree measurements during event 2.

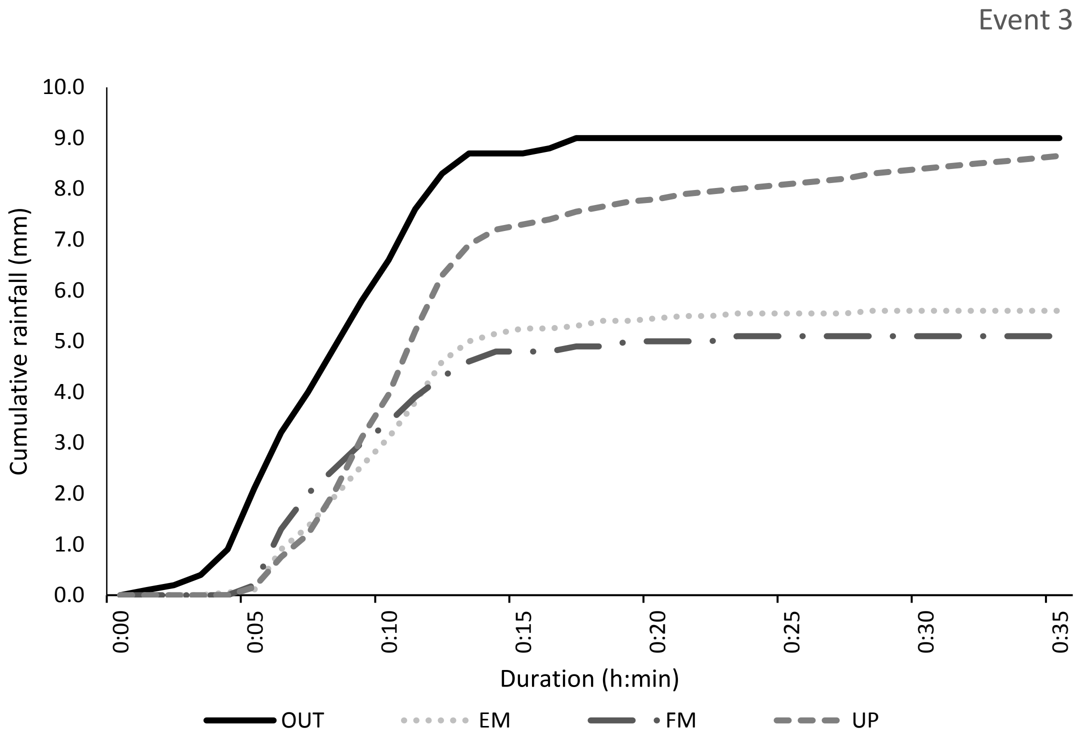

Figure A3. Curves for cumulative rainfall for outside and under-tree measurements during event 3.

Event 4

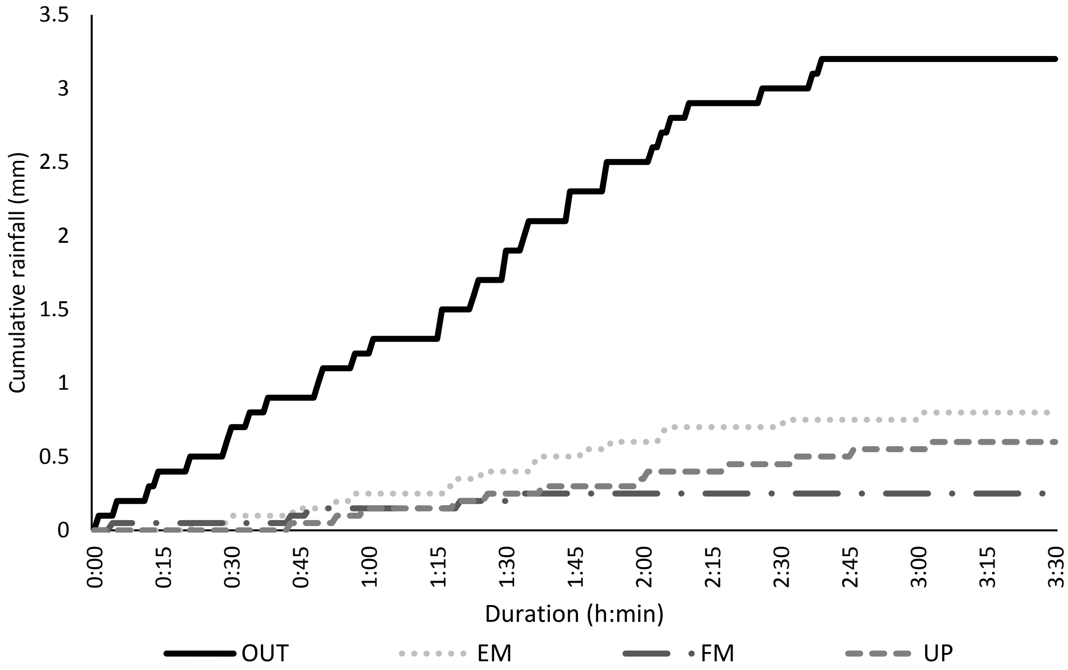

Figure A4. Curves for cumulative rainfall for outside and under-tree measurements during event 4.

Event 5

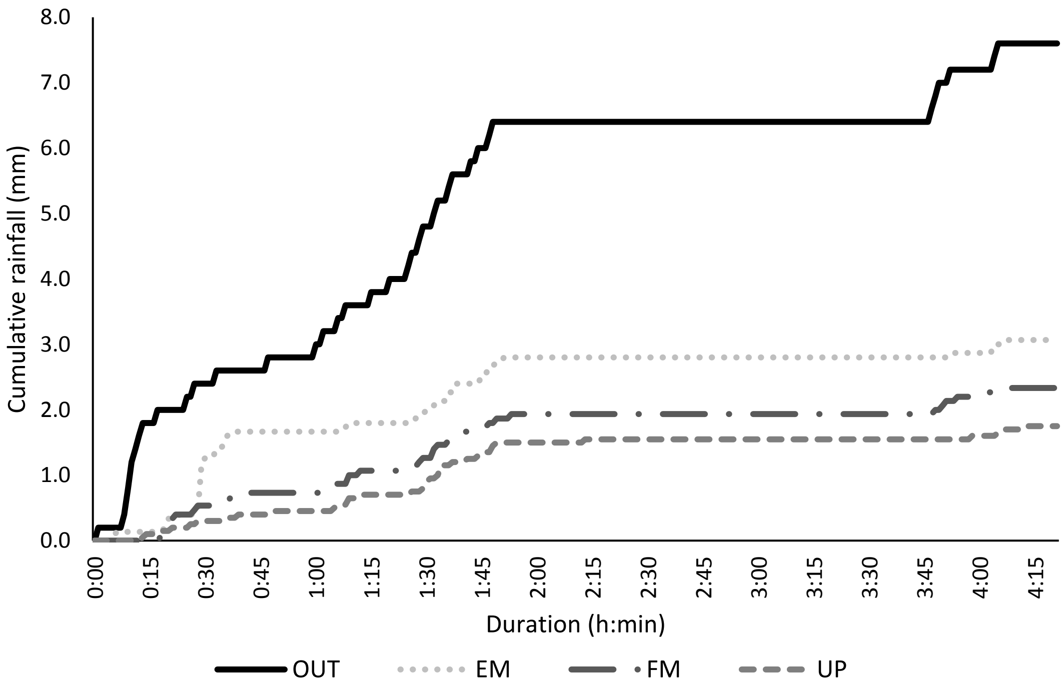

Figure A5. Curves for cumulative rainfall for outside and under-tree measurements during event 5.

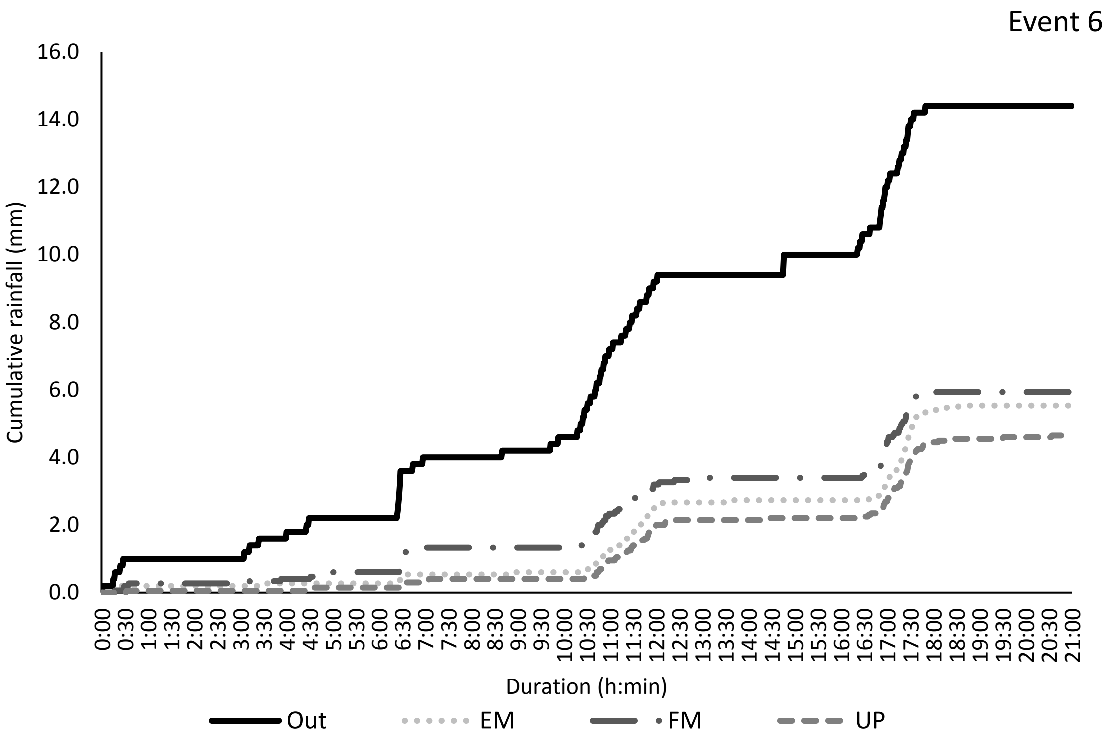

Figure A6. Curves for cumulative rainfall for outside and under-tree measurements during event 6.

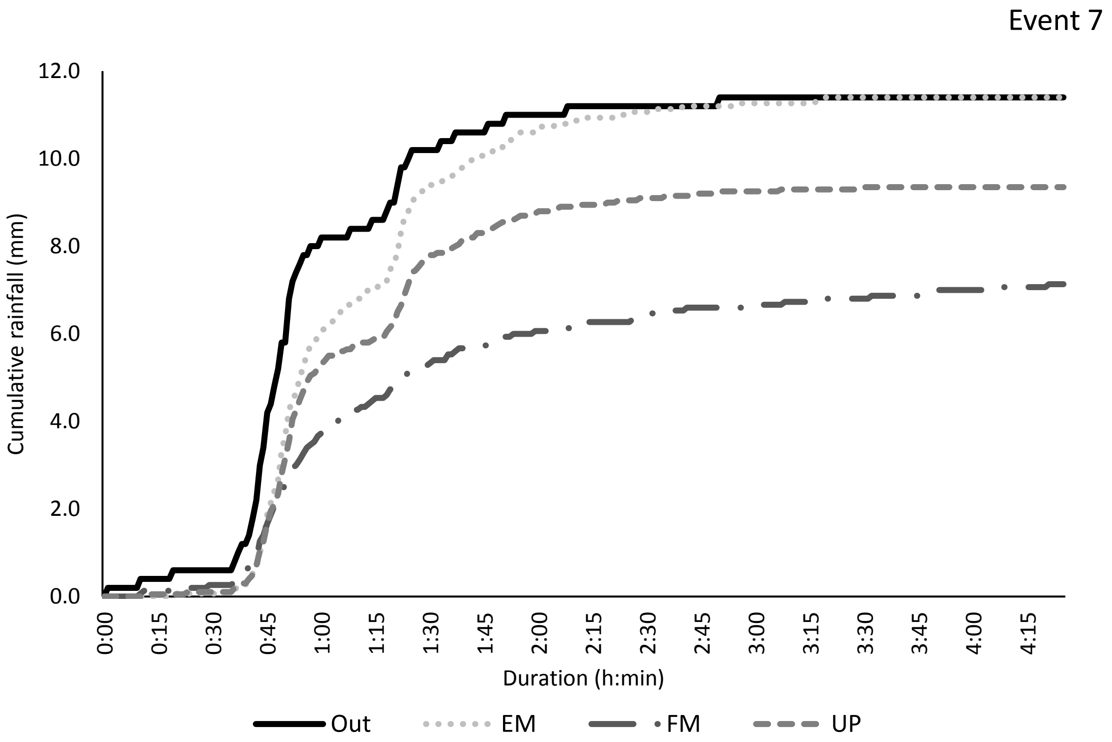

Figure A7. Curves for cumulative rainfall for outside and under-tree measurements during event 7.