

Minerva Access is the Institutional Repository of The University of Melbourne

Author/s:

Orozco Aguilar, Luis Alberto

Title:

Assessing growth rates and standing biomass yield of urban trees

Date:

2018

Persistent Link:

<https://hdl.handle.net/11343/219973>

Terms and Conditions:

Terms and Conditions: Copyright in works deposited in Minerva Access is retained by the copyright owner. The work may not be altered without permission from the copyright owner. Readers may only download, print and save electronic copies of whole works for their own personal non-commercial use. Any use that exceeds these limits requires permission from the copyright owner. Attribution is essential when quoting or paraphrasing from these works.

Assessing growth rates and standing biomass yield of urban trees

Luis Alberto Orozco Aguilar

A thesis submitted in total fulfilment of the requirement for the degree of
Doctor of Philosophy

October 2018

School of Ecosystem and Forests Sciences

Faculty of Science

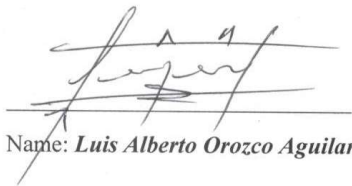
The University of Melbourne, Australia

ORCID: 0000-0002-2731-3563

Declaration

This is to certify that:

- i. The thesis comprises only my original work towards the PhD except where indicated in the preface,
- ii. Due acknowledgement has been made in the text to all other material used,
- iii. The thesis is fewer than 100,000 words in length, exclusive of tables, figures, maps, references and appendices.



Name: *Luis Alberto Orozco Aguilar*

Abstract

Currently models used to quantify tree carbon stocks and growth rates do not consider the unique issues inherent in urban tree growth and management. This research addresses these knowledge gaps in urban forestry by examining: 1) the reliability of a faster method for assessing growth rate, 2) the extent of decayed wood in urban trees and its effect on stored carbon and; 3) canopy structure and standing volume distribution of several urban tree species in the city of Melbourne, Australia. Assessing the accuracy of resistance drilling (RD) to perform ring analysis on *Quercus robur*, *Ulmus procera*, and *Platanus x acerifolia* trees was done by comparing core-derived growth series with the corresponding resistance-drilled growth series. This research confirmed the ability and reliability of RD to measure average growth rate at population level but was unable to detect the interannual growth pattern at tree level. Hence, RD cannot be used to replace dendrochronology for growth-climate studies of urban trees. Decay is a common issue in urban forests which deteriorates wood structure and tree vitality over time yet, its effect on standing biomass yield has been overlooked. An existing theoretical model of decay infection was combined with an expert system to quantify the extent of internal decayed wood in 43 trees of three species (*U. procera*, *P. x acerifolia* and *Corymbia maculata*). This study demonstrated a substantial reduction of tree stem volume of *U. procera* sampled trees due to decayed wood and reported the occurrence of decay in a wide range of stem diameter and tree vitality. This study suggested the application of a species-decay factor, rather than a standard factor, for a more accurate calculation of stored carbon in urban forests. Understanding standing biomass yield of several tree structural parts and the subsequent development of allometric equations may aid in reducing the error in whole tree volume estimations. Full tree measurements and non-destructive approach namely randomized branch sampling were used to estimate standing volume, capture canopy structure, assess biomass distribution and further develop allometric equations of 45 trees comprising three species (*U. procera*, *P. x acerifolia* and *C. maculata*). This research reported significant differences in biomass distribution among sampled trees which also differed from published data for other urban trees. This PhD study provided a set of allometric equations and quantitative inputs on tree structure and dimensional relationships which can be used for tree growth modelling.

Preface

A substantial part of this PhD thesis has been published in peer-review journals as multiauthor papers. The papers are as follows:

1. Orozco-Aguilar, L.; Livesley, J. Stephen; Nitschke, R. C; Brack, C.; Johnstone, D. 2018. Testing the accuracy of resistance drilling to assess growth rate and the relationship with past climatic conditions. An edited version of this manuscript has been published in the journal *Urban Forestry & Urban Greening*. This paper appears as **Chapter 3** in this Ph.D thesis.
2. Orozco-Aguilar, L.; Johnstone, D.; Livesley, J. Stephen.; Brack, C. 2018. The overlooked carbon loss due to decayed wood in urban trees. An edited version of this manuscript has been published in the journal *Urban Forestry & Urban Greening*. This paper appears as **Chapter 4** in this Ph.D thesis.
3. Orozco-Aguilar, L.; Livesley, J. Stephen.; Brack, C. Johnstone, D. 2018. Standing volume distribution, canopy structure and allometric relationships of urban trees. An edited version of this manuscript has been submitted to the journal *Urban Forestry & Urban Greening* and is currently under review. This paper appears as **Chapter 5** in this Ph.D thesis.

The original research proposal for these studies was developed by my supervisors Denise Johnstone and Steve Livesley. However, these studies were primarily the work of **Luis Orozco Aguilar** who, in collaboration with his supervisors further developed the design of the individual studies, conducted the research, collected, analyzed, and interpreted the data, and wrote the manuscripts. Dendrochronological data from a previous study (Nitschke, C. R., Nichols, S., Allen, K., Dobbs, C., Livesley, S. J., Baker, P. J., & Lynch, Y. (2017). The influence of climate and drought on urban tree growth in southeast Australia and the implications for future growth under climate change. *Landscape and Urban Planning*, 167, 275-287. doi:10.1016/j.landurbplan.2017.06.012) was used with permission from the authors to compare with resistance drilling data in Chapter 3, and was not physically collected by Luis Orozco Aguilar. However, the afore mentioned core samples were visually re-analyzed by Luis and the remaining data was collected during the course of his PhD.

Acknowledgements

The special thanks to The University of Melbourne for giving me the opportunity to complete my PhD and for the financial sponsorship given to enjoy the world's most liveable city.

I gratefully acknowledge the support of the Melbourne City Council, specially to David Callow, for the logistic and financial support provided without which I would not have been able to sample park and streets trees.

I would also like to thank the Frank Keenan Trust Fund and the Madeleine Selwyn Smith Memorial Fund Scholarship for the research funds granted.

Special gratitude to Dr. Craig R. Nitschke for providing academic guidance, field work inputs and technical training to conduct the comparative annual increment analysis of urban trees. The provided raw data set derived in one experimental chapter and one publication in this thesis.

I would like to acknowledge the support of my supervisors; Dr. Denise Johnstone, Assoc. Prof. Stephen J. Livesley and Assoc. Prof. Cris Brack. Your guidance and encouragement throughout my PhD journey and the production of this thesis have been priceless and highly esteemed.

I would like to acknowledge the help and enthusiasm of Australian arboriculturalists William Dunlop, William Maccabee and, Chis Wright for the valuable assistance and knowledge shared during the field work campaign.

I would also like to acknowledge the help, support and inspiration of my family, my wife Arlene Lopez Sampson PhD and my daughter Melissa Orozco Lopez, without whom this thesis would never have been completed.

Table of contents

DECLARATION.....	II
ABSTRACT.....	III
PREFACE.....	IV
ACKNOWLEDGEMENTS	V
TABLE OF CONTENTS	VI
LIST OF FIGURES	X
LIST OF TABLES	XIII
CHAPTER 1. INTRODUCTION.....	1
1.1 Research Aims.....	2
1.2 Research Approach.....	2
1.3 Thesis structure.....	3
CHAPTER 2. LITERATURE REVIEW.....	6
2.1 Introduction.....	6
2.2 Urban tree benefits	7
2.3 Assessing growth rate in an urban context.....	9
2.4 Measuring wood decay in the urban landscape	14
2.5 Biomass loss due to wood decay in urban trees.....	16
2.6 Allometric relationships of urban trees	19
2.7 Stored carbon in urban trees	23
2.8 Conclusion	29
2.9 Species evaluated in this study.....	29
CHAPTER 3. TESTING THE ACCURACY OF RESISTANCE DRILLING TO ASSESS TREE GROWTH TRENDS IN URBAN FORESTS	31
3.1 Abstract.....	31

3.2 Introduction.....	32
3.3 Materials and Methods.....	36
3.3.1 Study site	36
3.3.2 Background silvics of the three species	36
3.3.3 Tree measurements and resistance drilling	37
3.3.4 General overview of ring analysis process.....	42
3.3.5 Data analysis	42
3.4 Results	44
3.4.1 Annual increments values between methods.	44
3.4.2 Accuracy of annual increment measurements among species	46
3.4.3 Age calculation between methods and species	48
3.4.4 Identification of pointer years at population level	50
3.4.5 Identification of event years at tree level	51
3.4.6 Series intercorrelation, mean sensitivity and cross dating index.....	53
3.5 Discussion.....	54
3.5.1 Scope and limitation of resistance drilling (RD) for ring analysis.....	54
3.5.2 The strength of resistance drilling (RD) and the effect of ring width on ring analysis	57
3.5.3 Mean intercorrelation values, wood anatomy and cross-dating index	59
3.5.4 Resistance drilling (RD) has limited use for climate-growth studies.....	61
3.6 Conclusion	62
 CHAPTER 4. THE OVERLOOKED CARBON LOSS DUE TO DECAYED WOOD IN URBAN TREES	 63
4.1 Abstract.....	63
4.2 Introduction.....	64
4.3 Materials and Methods.....	69
4.3.1 Study site	69
4.3.2 The CODIT model for describing and assessing wood decay	70
4.3.3 Tree measurements and vitality assessment.....	70
4.3.4 Stem volume calculation.....	72
4.3.5 Tree stem micro-drilling	72
4.3.6 Terms and definition used for decay assessment	73
4.3.7 Assessing wood decay	75
4.3.8 Decayed wood area and volume loss calculation.....	77
4.3.9 Data management and statistical analysis	77
4.4 Results	78
4.4.1 Occurrence of decay among species	78
4.4.2 Decay distribution within species	80
4.4.3 Relationship between vitality index and decayed wood	81
4.4.4 Stem volume loss	85
4.4.5 Relationship between vitality index (VVI), diameter and stem volume loss	86
4.5 Discussion.....	88
4.5.1 Decay distribution patterns along the stem	88
4.5.2 Decay affects a wide range of stem tree diameter.....	89
4.5.3 Vitality index as a reliable proxy for stem volume loss calculation.....	92

4.5.4 Scope and limitations of internal decayed volume loss calculation	93
4.5.5 Decay classes, tree parts and C contents	95
4.6 Conclusions.....	96
 CHAPTER 5. STANDING VOLUME YIELD, CANOPY STRUCTURE AND ALLOMETRIC RELATIONSHIPS OF URBAN TREES.....	 98
5.1 Abstract.....	98
5.2 Introduction.....	99
5.3 Methodology	103
5.3.1 Study site	103
5.3.2 Tree measurements and vitality assessment.....	104
5.3.3 Full tree measurement and stem volume calculation	105
5.3.4 Application of randomized branch sampling	106
5.3.5 Data analysis	109
5.3.6 Terms and definitions	110
5.3.7 Allometric relationships.....	110
5.3.8 Factor in the overlooked decayed wood loss	112
5.4 Results	112
5.4.1 Section 1: Canopy structure and branching pattern among species	112
5.4.2 Section 2: Standing volume distribution among species.....	115
5.4.3 Section 2.1 Volume estimations using full tree measurements and branch sampling.....	117
5.4.4 Section 3: Allometric relationships among species and canopy structure.....	121
5.4.5 Section 4. Factor in volume loss due to decay in standing trees	125
5.5 Discussion.....	127
5.5.1 Canopy structure and branching ratio among species	127
5.5.2 Volume distribution among species.....	129
5.5.3 Allometric relationships of tree structural parts.....	130
5.5.4 Suitability and reliability of RBS to estimate standing volume	132
5.5.5 Factor in decayed wood loss into stored carbon calculations	135
5.6 Conclusions.....	135
 CHAPTER 6. GENERAL DISCUSSION AND SYNTHESIS.....	 137
6.1 Introduction.....	137
6.2 A novel way to assess growth rate of urban trees	140
6.3 Assessing the occurrence and extent of decay in urban trees	142
6.4 Improving standing volume estimates and allometry of urban trees.....	146
6.5 Research outcomes.....	149
 REFERENCES.....	 151

APPENDICES	176
-------------------------	------------

List of Figures

- Figure 3.1 Steps taken in the process for ring analysis from core-sampled and resistance drilled trees. Photos and figures from the author. 41
- Figure 3.2. Average growth rate (mm year^{-1}) as estimated by the core measurements (Core) and resistance drilling readings (Resi). Presented values include both N and W drill axes data. 45
- Figure 3.3. Relationships between paired annual increment values (mm) series as measured by resistance drilling (Resi) and core sampling (Core) for north-south (N) and west-east (W) drill axes. Associated statistical values were as follow: *Q. robur*: N- ($y = 0.9279x + 0.2161$, $n = 2545$, $R^2 = 0.95$, $p < 0.0001$, RSE: 0.08), W- ($y = 0.9243x + 0.2225$, $n = 2555$, $R^2 = 0.96$, $p < 0.0001$, RSE: 0.09), *P. x acerifolia*-N- ($y = 0.9488x + 0.2958$, $n = 1595$, $R^2 = 0.94$, $p < 0.0001$, RSE: 0.23), W- ($y = 0.9482x + 0.2588$, $n = 1618$, $R^2 = 0.92$, $p < 0.0001$, RSE: 0.42) and *U. procera*-N: ($y = 0.8167x + 0.3251$, $n = 2846$, $R^2 = 0.83$, $p < 0.0001$, RSE: 0.23), W: ($y = 0.7975x + 0.4051$, $n = 2781$, $R^2 = 0.78$, $p < 0.0001$, RSE: 0.27). RSE: Residual standard error. 46
- Figure 3.4. Differences of annual ring width (mm) calculations as measured by core-sampling (Core) and resistance drilling (Resi) for *Quercus robur* ($n = 25$ trees, $n = 2555$ rings), *Platanus x acerifolia* ($n = 29$ trees, $n = 1618$ rings) and *Ulmus procera* ($n = 24$ trees, $n = 2845$ rings). Annual ring width presented from North (N) and West (W) axes. 47
- Figure 3.5. Annual ring width (mm) series of the oldest tree per species as measured by the core measurements (core) and the resistance drilling readings (Resi). Annual ring width series presented for two drill axes North (N) and West (W). 49
- Figure 3.6. Bar plot of mean growth deviation in *Quercus robur* ($n = 25$), *Ulmus procera* ($n = 25$) and *Platanus x acerifolia* ($n = 29$) calculated by pointer.rgc, and plotted for the period 1870–2010 with the rgc.plot function. Pointer years are highlighted in dark grey and an asterisk on the top. Applied Cropper value of > 0.75 SD for both axes. 51
- Figure 3.7. Ring-porous genera (A-*Quercus* spp.), semi-porous genera (B-*Ulmus* spp.) and diffuse-porous genera (C-*Platanus* spp) showing strong and no-association between the pores and the ring boundaries in a cross-section view. Sourced with permission from: InsideWood-2017. Published on the Internet. <http://insidewood.lib.ncsu.edu/search> [accessed on August-28, 2017]. The readers are advised to visit the website <http://insidewood.lib.ncsu.edu> for more details on the wood anatomy of sampled species. 60
- Figure 4.1. Overview of sampled trees of different size class and tree vitality index (VVI): A) *Corymbia maculata*, VVI= 25, B) *Platanus x acerifolia*, VVI=22 and C) *Ulmus procera*, VVI= 21.5. (Photos taken by Luis Orozco Aguilar). 74
- Figure 4.2 Overall methodology followed in this study to assess the occurrence and calculate the extent of decayed wood along the trunk of *Platanus x acerifolia*. The left picture (A) shows the arborists micro-drilling at the tree's live crown position. The right picture (B) displays the decay assessment done using IML PowerDrill® tools. The drilling profile shown here has 40 cm in length and corresponds to the live crown position (N axis). Drilling height and stem diameter at this position were 5.3 m and 83.5 cm, respectively. (Photo taken by Luis Orozco Aguilar). 76
- Figure 4.3. Box plots of the cross-sectional area of decayed wood in urban trees (*Ulmus procera*, *Platanus x acerifolia*, *Corymbia maculata*) growing in the city of Melbourne,

Australia. Decayed wood was measured at four points up the stem: Base= 0.3 m above ground, DBH= 1.3 m, Trunk= 2.3 m and Crown+ variable mid-crown position (3.3-6.8 m).	80
Figure 4.4. Tree vitality index versus the proportion of decayed wood (%) along the stem of <i>U. procera</i> trees in parks of the city of Melbourne, Australia. Regression values and related statistics were: (A)-Base: $R^2 = 0.0568$, $p = 0.3924$, $n = 15$. (B)-DBH: $R^2 = 0.2447$, $p = 0.0608$, $n = 15$. (C)-Trunk: $R^2 = 0.2571$, $p = 0.0536$, $n = 15$. (D)-Crown: $R^2 = 0.1329$, $p = 0.2441$, $n = 12$	82
Figure 4.5 Tree vitality index versus the proportion of decayed wood along the stem of <i>P. x acerifolia</i> trees growing in parks of the city of Melbourne, Australia. Regression values and related statistics were: (A)-Base: $R^2 = 0.6628$, $p = 0.0010$, $RSE: 1.564$, $n=15$, (B)-DBH: $R^2 = 0.6422$, $p = 0.0007$, $RSE: 1.975$, $n=15$ (C)-Trunk: $R^2 = 0.6803$, $p = 0.0005$, $RSE: 2.201$, $n=15$, (D)-Crown: $R^2 = 0.4415$, $p = 0.2190$, $RSE: 2.073$, $n=7$	83
Figure 4.6. Tree vitality index versus the proportion of decayed wood along the stem of <i>C. maculata</i> trees growing in parks of the city of Melbourne, Australia. Regression values and related statistics were: (A)-Base: $R^2 = 0.07379$, $p = 0.1393$, $RSE: 1.158$, $n=15$, (B)-DBH: $R^2 = 0.3037$, $p = 0.0351$, $RSE: 1.086$, $n=15$, (C)-Trunk: $R^2 = 0.1741$, $p = 0.1303$, $RSE: 1.324$, $n=15$, (D)-Crown: $R^2 = 0.3531$, $p = 0.0538$, $RSE: 1.417$, $n=10$	84
Figure 4.7. Diameter at breast height (stem DBH) versus stem volume loss (m^3) for <i>U. procera</i> trees growing in parks in the city of Melbourne, Australia. Regression coefficients and related statistical values were as follow: $Y = 0.0074x - 0.1279$ ($R^2 = 0.8006$, $p = 0.0046$, Residual standard error-RSE: 0.1424) where: Y is volume loss (m^3) and X is stem DBH (cm).	86
Figure 4.8 Correlation matrix of stand and tree attributes with potential effect on the predictability of volume loss (m^3) in standing <i>U. procera</i> park trees, Melbourne, Australia. Blue colour represents a positive correlation between paired variables and red colour denotes otherwise. The bigger and darker the colour of the circles, the stronger the correlation. Matrix's variables were: VVI (visual vitality index), C-Density (crown density), C-size (crown size), Crown-H (crown height), Total.Vol (total stem volume), Vol.loss (volume loss due to decay), C-position (crown position), Competition (number of trees within 10 m radius), D-Branche (dead branches retained within the canopy), Epicormics (presence of epicormics along the trunk and canopy), Dead-T-class (overall dead tree class).	87
Figure 5.1 a) Hierarchical classification of canopy structural parts of a fully measured <i>P. x acerifolia</i> tree, b) Randomized branch sampling (RBS) with 20 segments and 29 possible paths to be followed in this study (Photos taken by Luis Orozco Aguilar).	108
Figure 5.2 Standing volume distribution (%) as per structural part of 18 fully measured trees. Stem: tree main stem, Scaffolds: scaffolds branches, Branch-1: 1 st order branches, Branch-2: 2 nd order branches, Branch-3: 3 rd order branches. Notes: Species and Tree size class: CS, CM and CS: <i>C. maculata</i> large, medium and small trees, respectively. UL, UM and US: <i>U. procera</i> large, medium and small trees, respectively. PL, PM and PS: <i>P. x acerifolia</i> large, medium and small trees, respectively.	116
Figure 5.3 Effect of species and tree size class (S: small, M: medium, L: Large) on volume calculations using randomized branch sampling RBS-3-parths and RBS-5-paths as compared to full tree measurements (Full tree).	118

Figure 5.4 Relationships between branching ratio and relative estimation error (RSE) of volume estimates derived from the application of randomized branch sampling on fully measured trees R^2 values for RBS-3 paths on <i>C. maculata</i> , <i>P. x acerifolia</i> and <i>U. procera</i> were 0.05, 0.55, 0.62, respectively. R^2 values for RBS-5 paths on <i>C. maculata</i> , <i>P. x acerifolia</i> and <i>U. procera</i> , were 0.03, 0.42 and 0.47, respectively). All relationships were not significant $p = \geq 0.05$	119
Figure 5.5 Allometric relationships of whole tree, main stem and canopy structure of <i>Ulmus procera</i> trees. Graphs display allometric relationships following the hierarchical order of canopy measurements: 1) diameter-whole tree volume, 2) diameter-tree stem volume, 3) diameter-scaffolds volume, 4) diameter-1 st order branch volume, 5) diameter-2 nd order branch -volume and 6) diameter-3 rd order branches-volume.....	123
Figure 5.6 Allometric relationships of whole tree, main stem and canopy structure of <i>Platanus x acerifolia</i> trees. Graphs display allometric relationships following the hierarchical order of canopy measurements: 1) diameter-whole tree volume, 2) diameter-tree stem volume, 3) diameter-scaffolds volume, 4) diameter-1 st order branch-volume, 5) diameter-2 nd order branch -volume and 6) diameter-3 rd order branches-volume.	124
Figure 5.7 Allometric relationships of whole tree, main stem and canopy structure of <i>Corymbia maculata</i> trees. Graphs display allometric relationships following the hierarchical order of canopy measurements: 1) diameter-whole tree volume, 2) diameter-tree stem volume, 3) scaffolds diameter-volume, 4) 1 st order branch diameter-volume, 5) 2 nd order branch diameter-volume and 6) 3 rd order branches diameter-volume.....	125
Figure 5.8 Standing volume of six fully measured <i>U. procera</i> trees (Full tree) by tree size class (S: small, M: Medium and L: Large) from this study. Full tree volume estimates which included tree stem volume loss due to internal decay wood (Decay factor of 13%) and standing volume yield as predicted by the published urban equation (USA-model) for <i>U. americana</i> . Model and values of the allometric equation used was: $V = a * (DBH)^b$, where V: standing volume (m^3), a: 1.8 E-03 and b: 1.869, $R^2 = 0.92$, RSE: 0.268 (McHale et al., 2009).	126

List of Tables

Table 2.1. Mean annual growth rates of urban trees as reported in various studies by core sampling or remeasurements overtime.	11
Table 2.2. Set of selected urban tree predictive models from published literature spanning different locations, tree age and diameter ranges.....	21
Table 2.3 Carbon stocks and sequestration rate of urban trees as reported by several studies across cities, land uses and methodologies.	27
Table 3.1 General dimensions, location and wood anatomy features of 78 stem cored and then resistance drilled trees in parks and streets of the city of Melbourne, Australia. The $\pm$ symbol indicates standard deviation of each reported value.	38
Table 3.2 Number of event year class shared by the core measurements (Core) and resistance drilling (Resi) for <i>Quercus robur</i> , <i>Platanus x acerifolia</i> and <i>Ulmus procera</i> and their corresponding Jaccard similarity index.	53
Table 3.3 Dated ring width series, mean intercorrelation indices (MI), average mean sensitivity and fraggged segments as yielded by COFECHA and per method (core sampling-Core- and resistance drilling-Resi-) and the specie's assigned cross dating index (CI).	54
Table 4.1 Number of individuals, tree attributes and wood properties of three urban species (<i>Ulmus procera</i> , <i>Corymbia maculata</i> , <i>Platanus x acerifolia</i>) included in the study.	71
Table 4.2 Summary statistics of internal decayed volume loss in urban trees (<i>U. procera</i> , <i>C. maculate</i> and <i>P. x acerifolia</i>) growing in parks in the city of Melbourne, Australia.	85
Table 5.1 Number of individuals, tree attributes and vitality index of three urban species included in the study.	105
Table 5.2 Mean values of canopy structural parts of sampled trees in parks, Melbourne, Australia. Data derived from 18 fully measured trees.	114
Table 5.3 Whole tree standing volume distribution (stem, scaffolds and branches) of sampled urban trees. Data from 18 fully measured trees. Six trees per species, two trees per size class.....	115
Table 5.4 Relative estimation errors (REE-expressed in %) of randomized branch sampling (RBS) volume estimates for 18 trees as a function of the number of paths carried out on the same tree. Volume for full tree (Full), RBS-3-Paths and RBS-5-Paths are expressed in m ³	120
Table 5.5 Statistics of the best fitted models (based on AIC/BIC) to predict diameter-volume relationships for all measured tree structural parts.	122
Table 6.1 Knowledge gaps addressed in each experimental chapter and main findings and research/management implications.	139

Chapter 1. Introduction

An increasing body of research documents the various social and environmental benefits of urban forests across several countries and in both temperate and tropical regions (Escobedo et al., 2008; Jim et al., 2008; Livesley et al., 2016; Nowak et al., 2002b). Most of the urban forests' functions and benefits such as the provision of shade, rainfall interception and runoff distribution and stored carbon are linked to tree size, tree growth rates, canopy traits and vitality status of a given tree population (Dwyer et al., 2003; McPherson et al., 2012). In general terms, tree growth rates are critical data regarding site index assessment, monitoring long term health, population dynamics and stand yield prediction (Hu et al., 2018; Stephenson et al., 2014; Worbes et al., 2003). In particular, tree attributes and growth rate are an important input for allometry construction and valuation of urban tree benefits (McHale et al., 2009; McPherson et al., 2012). Assessing tree growth trends over time is a central but challenging aspect of urban forest management (Bowman et al., 2013; Rogers et al., 2014). Nevertheless, the potential damage caused by invasive devices used in dendrochronological analysis is a common concern among urban foresters (Gao et al., 2017; Wessels et al., 2011). Thus, the development of a less-invasive method to assess growth rate faster and reliably is clearly beneficial for tree growers.

Urban trees are credited as suitable tools to aid climate change mitigation within cities, hence accurate estimation of above-ground biomass is a crucial factor in accounting for carbon stocks (Churkina et al., 2010; Escobedo et al., 2010; Hutyrá et al., 2011; McPherson et al., 2013). Decay is a common issue which deteriorates wood structure and tree vitality over time; yet its effect on above ground biomass yield has been overlooked (Johnstone et al., 2010a; Koeser et al., 2016; Luley et al., 2009). Models currently used to quantify the aboveground biomass do

not take into account either differences in biomass/volume distribution between urban and rural trees or the biomass loss due to internal decay (Brazee et al., 2010; Marra et al., 2018).

Forest-based allometric equations assess reasonably well tree biomass distribution (the partitioning and amount of biomass in roots, stems, stem, branches, foliage, etc) and allometry patterns (the dimensional relationships between tree attributes) of forest trees (Peper et al., 2014) but they are not as reliable when applied on urban forests (Dutca et al., 2014; Jenkins et al., 2004; McHale et al., 2009). Consequently, developing species-specific allometric equations is the most recommended approach to quantify carbon stocks of trees outside forests (Chaojnacky et al., 2014; Jenkins et al., 2003; Lefsky et al., 2008; Schnell et al., 2015).

1.1 Research Aims

The aims of this research are;

1. to evaluate a quick, reliable and semi-invasive method for estimating tree growth rates.
2. to factor in the overlooked volume loss due to decayed wood in stored carbon calculations and.
3. to develop a set of allometric equations for several urban tree species.

1.2 Research Approach

In order to meet the research aims some prerequisites of this study were: 1) selecting urban trees grown under similar conditions. In this regard, four common tree species in the city of Melbourne were sampled (*Quercus robur*, *Ulmus procera*, *Platanus x acerifolia* and *Corymbia macualta*) (Dobbs et al., 2013; Frank et al., 2006; Moore, 2012). One sampled species was

native to Australia and the remaining three species were exotic but widely planted in Europe and USA, therefore the scope, limitations and, implications of research's findings are relevant to other locations, 2) selecting subject trees from a wide range of tree diameter and tree size resembling the un-even age structure of the city's urban forest. In order to explore potential links between tree internal decay along the trunk and a visual vitality index, a third requirement of this research was the inclusion of individuals displaying a range of tree vitality, from poor to high vitality but growing in similar conditions, like parks. This study does not include street trees; therefore, no contrasting decay assessment can be done. Based on the Melbourne's Urban Forest Strategy, the city's urban forest contains a large number of mature and over mature *U. procera* trees; hence, many sampled trees were likely to be affected by wood decay. A fourth requirement of this study was sampling individuals with no evidence of heavy pruning which in turn may alter species' canopy structure. A final condition limiting the scope of this study was sample size. Due to financial and time constraints only 15 trees per species and six trees per size class (small, medium and large) were measured thus restricting the applicability of developed allometric equations. Limitations of each individual study will be discussed further in Chapter 6.

1.3 Thesis structure

This thesis consists of six chapters, one introductory chapter (Chapter 1) that briefly presents the research framework, approach and scope. Another thematic chapter which summarizes relevant literature and describes the context and research background (Chapter 2) and, three experimental chapters (Chapters 3, 4 and 5) which contain the quantitative research undertaken. Finally, there is a synthesis chapter concluding the significance of this thesis (Chapter 6).

Chapter 2 is titled “***Literature Review***” which is aimed at examining past and current research on the unique issues inherent in urban tree growth and management. Chapter 2 debates on several approaches followed to track tree growth rate in urban settings. Chapter 2 also examines the incidence, frequency and severity of decay and reviews current literature in relation to available techniques for assessing tree vitality and decay calculation in standing trees. Lastly, Chapter 2 covers techniques employed to estimate above-ground biomass, stored carbon and, urban tree growth modelling.

Chapter 3, the first experimental chapter, is titled “***Testing accuracy of resistance drilling to assess tree growth trends in urban forests***”. The aim of Chapter 3 is to develop a novel method, which is fast and reliable, to assess growth rate and age of three urban tree species namely *Ulmus procera*, *Platanus x acerifolia* and *Quercus robur*. A combination of techniques was used and gathering of available data was a prerequisite. A set of previously core sampled trees were visually scanned and compared with drilling profiles obtained with a resistance drilling device to perform annual increment analysis. Chapter 3 explains the steps taken and discusses generated outcomes of this approach; addresses several issues faced during the development of the method and, at the same time; evaluates its suitability and reliability in urban forestry field.

Chapter 4, the second experimental chapter, is titled “***The overlooked carbon loss due to decayed wood in urban trees***”. The aim of Chapter 4 is to evaluate the distribution pattern of decay along the stem of urban tree species (*U. procera*, *P. x acerifolia* and *Corymbia maculata*) and explore potential links with a visual vitality index. Chapter 4 applies an “expert system”, successfully used in plantation trees (Johnstone et al., 2007); to calculate the extent of internal decay in standing trees. Chapter 4 describes steps taken and limitations faced in the process.

Chapter 4 explores possible correlations between tree and site attributes which can aid in developing a predictive equation of volume loss due to decayed wood in standing urban trees.

Chapter 5, the third experimental chapter, is titled “**Standing volume distribution, canopy structure and allometric relationships of urban trees**”. The aim of Chapter 5 is to construct allometric equations for a set of abundant tree species (*U. procera*, *P. x acerifolia* and *C. maculata*) growing in the City of Melbourne (Frank et al., 2006). Chapter 5 employs randomized branch sampling to calculate standing volume and map tree canopy structure to account for above-ground volume distribution and allometric relationships among canopy structural parts of urban trees. Chapter 5 assesses whether tree allometry varies according to crown structural part and species within an urban environment.

Each experimental chapter (Chapters 3, 4 and 5) was written in journal article format to facilitate journal submission and indeed two experimental chapter (Chapters 3 and 4) have been published in the international peer reviewed journal “Urban Forestry & Urban Greening”. In addition, an edited version of Chapter 5 has been submitted for publication in the international peer reviewed journal “Urban Forestry & Urban Greening” and is currently under review. Therefore, some repetition of text from among experimental chapters is expected. Finally, Chapter 6, “**General discussion and synthesis**”, summarizes implications and limitations of research’s findings with references to previous studies and draws guidelines for further research to advance the assessment of urban tree benefits.

Chapter 2. Literature review

2.1 Introduction

An increasing awareness of the potential effects of climate change on citizens' wellbeing has led to a growing body of research on urban tree benefits in general and, stored carbon and growth rates in particular (Dobbs et al., 2011b; Poudyal et al., 2011; Russo et al., 2014; Steenberg et al., 2017; Stoffberg et al., 2010; Strohbach et al., 2012b; Zhao et al., 2010). Urban forest functions and benefits are significantly influenced by urban forest structure and management, which in turn, determines the economic worth of any particular function (Kendal et al., 2014; Kermavnar et al., 2017; Weissert et al., 2014; Yao et al., 2017).

Young fast-growing trees store carbon quicker than slow-growing individuals but mature and healthy trees store carbon longer, and, some species, like *Platanus x acerifolia* sustain good stock carbon for probably 80-100 years (Koeser et al., 2017; Nowak et al., 2002a; Ruiz-Peinado et al., 2012). In addition, retaining older senescent trees may be essential for the provision of habitat for local fauna (Harper et al., 2005; Isaac et al., 2014). Species' carbon storage capacity can be either improved or limited by site conditions and tree maintenance, therefore; enhancing growth rates of young trees and monitoring overall health of older trees to delay their senescence is an important way to make urban tree benefits more sustainable (Davies et al., 2017; McPherson et al., 2013; Mullaney et al., 2015; Pretzsch et al., 2017).

2.2 Urban tree benefits

In general terms, trees outside forest play a pivotal role in providing essential benefits and services to a growing urban population (FAO, 2013; Schnell et al., 2015). In particular, urban trees enhance city liveability throughout shade provision, rainfall interception, channeling of run-off, removal of air pollutants, energy savings by cooling buildings, offering shelter and food for local biodiversity and delivering green outdoor areas for residents' enjoyment (Escobedo et al., 2011; Livesley et al., 2016; McPherson, 2003; Nowak et al., 2013). Urban trees also provide less "measurable" aids such as aesthetic/visual amenity and psychological benefits to the community, including stress reduction, improved work attitudes, reduction of domestic violence, and creating 'more profitable' retail environments (Chen et al., 2015; Cho et al., 2014; Pandit et al., 2013; Price, 2003; Schroeder et al., 2006; Zhou et al., 2018). Nevertheless, growing trees within cities is not entirely beneficial for residents and local authorities. Researchers have reported collateral expenditures and conflicts with infrastructure, allergies and pollution due pollen deposition (Davies et al., 2017; Escobedo et al., 2011) and by emitting hazardous volatile organic compounds (Peñuelas, 2003; Peñuelas et al., 2010). Overall, urban forests are conspicuous elements for modern cities which ensure citizen's contact with nature within the build environment (Dobbs et al., 2011a; Kendal et al., 2014).

Most published studies labelled urban trees as being important carbon pools but also argued that methodologies aimed at assessing stored carbon need to be improved since carbon sequestration rates vary according to species' growth rate, population dynamic and, overall health condition (Escobedo et al., 2010; McPherson, 1998; Nowak et al., 2013). The greatest quality and quantity of environmental services and social benefits are given by large and healthy trees and varies over time (McPherson et al., 2012; Moser et al., 2015; Silvera Seamans,

2013). For instance, the provision of shade increases as trees grow and reaches maturity, afterwards, tree vitality declines, and both shading intensity and shade cover is reduced. Biomass accumulation thus, stored carbon, and sequestration rate increases rapidly as trees grow, then as trees get older growth rates decrease, the storage capacity is maintained; unless there is wood decay, but sequestration rates is reduced (Moser et al., 2015).

Urban forests are not currently considered under the Kyoto protocol framework for carbon sequestration purposes, primarily due to issues regarding the verification of data and the relatively small scale of urban plantings compared to forest stands or plantations (Diaz-Porrás et al., 2014; Frank et al., 2006; McHugh et al., 2015; Moore, 2009). However, given the proximity of urban forests to emission sources their carbon storage potential should not be overlooked (McHale et al., 2007; McHugh et al., 2015; Nowak et al., 2006).

Urban forests are also considered a source of saw timber, raw material for biofuels and even as a strategy for forest tree migration (MacFarlane, 2007; MacFarlane, 2009; Woodall et al., 2010). However, since tree care and park maintenance involve using oil-based tools and machinery, a life cycle approach has been proposed to elucidate the net carbon balance of urban forests. In some cases, urban trees are carbon pools, and in other cases, they become carbon sources as widely unexpected (Kuittinen et al., 2016; McPherson et al., 2015; Nowak et al., 2013; Steenberg et al., 2017; Strohbach et al., 2012a). Ultimately, the land being cleared to give way to urban development will eventually dictate whether there is a net-gain in carbon stock per unit area of urban land (McPherson et al., 2013; Nowak, 2006; Strohbach et al., 2012a; VLSAC, 2011).

2.3 Assessing growth rate in an urban context

Monitoring tree growth patterns in both forests stands and trees outside forests is a vital but challenging task (Bowman et al., 2013; Yue et al., 2014). Tree growth varies according to species and growing conditions, and assessing those trends is influenced by the variable measured overtime (Clark et al., 2007; Way et al., 2010). There are currently two main ways to evaluate growth rate in trees: 1) by recurrent measurements and 2) dendrochronology (Table 2.1). The former provides a more accurate measure of tree increments since the interval between recurrent measurements is known and can be applied in trees where annual rings are not readable (Mbow et al., 2013; Rogers et al., 2014). The later, by stem-coring and subsequent annual increments assessment, allows for cross-dating analysis and can be done over a single tree or a sample tree population where recurrent measurements have not been made over time. However, the application of dendrochronology is limited to those regions where trees show recognizable annual increments (Cherubini et al., 2003; Heinrich et al., 2013).

Researchers and arborists support the theory that urban environments place numerous constraints affecting tree growth performance (Ostberg et al., 2013; Swoczyna et al., 2010) and may consequently impair the extent of benefits and services provided by urban trees (Mullaney et al., 2015; Tubby et al., 2010). Tree growth rate are linked to biophysical and socioeconomic factors within a particular growing environment (Iakovoglou et al., 2001; Stravinskienė et al., 2015), poor-quality planting material (Huyler et al., 2014; Searle et al., 2012), delayed tree maintenance (Horn et al., 2015; Koeser et al., 2014), unsuitable site conditions (Cienciala et al., 2016; Day et al., 2010; Nowak et al., 2004), neighbourhood status, and even residents attitude towards nearby trees, which in combination, might lead to highly variable survivorship

rates (Ko et al., 2015; Roman et al., 2014), vitality status (Dobbertin, 2005; Johnstone et al., 2012; Vogt et al., 2015) and tree lifespan (Moser et al., 2017).

There is a general assumption that urban trees underperform as compared to conspecifics in natural settings (McPherson et al., 2012; Quigley, 2004), yet published research on tree growth rate either support or contrast this general debate (Pretzsch et al., 2017; Volgusheva et al., 2011). Overall, both early and recent research illustrates the difficulty associated with forecasting tree growth rate in urban environments due to many confounding effects in a given location (McPerson et al., 2012).

Table 2.1. Mean annual growth rates of urban trees as reported in various studies by core sampling or remeasurements overtime.

Method	Species	Diameter growth rate (cm year ⁻¹)	Reference
Core sampling	<i>Acer rubrum</i> , <i>A. saccharinum</i> , <i>Fraxinus</i> sp., <i>Gleditsia triacanthos</i> , <i>Platanus x acerifolia</i> , <i>Quercus palustris</i> , <i>Tilia</i> spp.	0.4-0.8	Vrecenak et al. (1989)
	<i>Platanus occidentalis</i> , <i>Acer rubrum</i> , <i>A. saccharum</i> , <i>Quercus alba</i>	0.8-1.2	Quigley (2004)
	<i>Q. robur</i> , <i>F. excelsior</i> , <i>Acer pseudoplatanus</i> , <i>Fagus sylvatica</i> .	0.35-0.55	(Rogers et al 2014).
	<i>Acer platanoides</i> , <i>A. pseudoplatanus</i> , <i>Q. petraea</i> , <i>Q. rubra</i> and <i>P. x hispanica</i>	0.28-0.33	Gillner et al. (2014)
	<i>A. pseudoplatanus</i> , <i>F. excelsior</i> , <i>Fagus sylvatica</i> and <i>Q. robur</i> .	0.25-0.55	(Rogers et al., 2014)
	<i>Q. robur</i> , <i>Ulmus procera</i> , <i>Ulmus</i> spp. and <i>P.x acerifolia</i>	0.25-0.32	(Nitschke et al., 2017)
	<i>Platanus x hispanica</i>	0.25-0.65	(Cedro et al., 2006)
	<i>A. pseudoplatanus</i> , <i>Betula pendula</i> , <i>F. excelsior</i> and <i>Q. robur</i>	0.66-1.16	(Vaz Monteiro et al., 2017)
	<i>Quercus macrocarpa</i>	0.13-0.17	(Catton et al., 2007)

	<i>A. platanoides</i> , <i>C. occidentalis</i> , <i>Gleditsia triacanthos</i> , and <i>Tilia</i> spp	0.17-0.15	(North et al., 2017)
	<i>Abies sachalinensis</i> , <i>Picea glauca</i> , <i>T. cordata</i> , <i>P. x hispanica</i> , <i>R. pseudoacacia</i> , <i>Q. robur</i> , <i>Khaya senegalensis</i> , <i>Araucaria cunninghamii</i> , and <i>Q. nigra</i> .	Urban trees grew faster than natural trees (14%–25%).	(Pretzsch et al., 2017)
	<i>Liquidambar styraciflua</i>	0.6-1.6	Kjelgren and Clark (1992).
Remeasurements	<i>P. x acerifolia</i> , <i>Fraxinus excelsior</i> , <i>Prunus avium</i>	0.9-1.3	Bühler et al. (2007).
	<i>Quercus bicolor</i> , <i>Q. phellos</i> .	8-15	Grabosky & Bassuk (2008).
	<i>Juniperus virginiana</i> , <i>Q. virginiana</i> , <i>Lagerstroemia indica</i> , <i>Celtis laevigata</i> , <i>Ostrya virginiana</i> , <i>L. styraciflua</i> , <i>Acer rubrum</i> .	0.36-1.24	(Lawrence et al., 2012)
	<i>Quercus laurifolia</i>	1.69	(Templeton et al., 2003)
	<i>Liquidambar styraciflua</i> and <i>Quercus virginiana</i>	0.90-1.3	(Staudhammer et al., 2011)
	<i>Ulmus</i> spp.	2.2-2.7	(Costello et al., 2004).
High precision dendrometer and core sampling	<i>Tilia cordata</i> .	0.26-0.52	(Moser et al., 2017)

Source: Author's based on literature review.

So far, dendrochronology is the most popular method used for assessing growth in urban settings where no recurrent measurements have been made (Bartens et al., 2012; Helama et al., 2012; Quigley, 2004; Rogers et al., 2014). Recent research conducted by Gillner et al. (2014) found species-specific differences in growth rate response of mature trees (*Acer platanoides*, *A. pseudoplatanus*, *Quercus petraea*, *Q. rubra* and *P. hispanica*) to climatic variability over time. Radial growth of most species was strongly influenced by temperature and water availability during the current growing season and in summer and autumn of the previous year. Similarly, Nitschke et al. (2017) found that *Quercus robur*, *Ulmus procera*, *Ulmus* spp. and *Platanus acerifolia* were sensitive to past climatic variability. Radial growth of all four-species in a given year was negatively impacted by arid conditions in the previous autumn and arid conditions in the spring or early summer of current year. Finally, Cedro et al. (2006) reported that precipitation, particularly that in late winter-early spring and in the summer months, influenced radial growth of *Platanus x hispanica* street trees.

The potentially damaging effect of using invasive devices (core borer and resistance drilling) to conduct dendrochronology assessments is a constant concern among urban foresters (Dolwin et al., 1998; Gao et al., 2017; Smith, 2006). Experts state that such devices penetrate and break reaction zones which limit the propagation of wood decay within trees; yet research in this regard is both scattered and contrasting. Early research supported the argument that coring holes and stem wounds may play a role in decay infection since the drilling itself creates a channel for decay fungi entry into sound wood protected by tree's natural defense (Laplamme, 1979; Lorenz, 1949; Schwarze et al., 2006). Later, Kersten et al. (2005) found that after 8 months, the frequency and extent of decoloration and decay within sapwood of *Platanus x hispanica* were greater after wounding with a resistance drill than with an increment borer. The authors linked differences to micro-environmental conditions created by drilling holes' size,

tightly packed wood shavings are retained within resistance drill holes, whereas holes created by the increment borer do not provide a moist and food-rich environment for microorganisms.

Recent research provides new insights into the impact of coring on tree mortality and decay infection in forest stands. For instance, van Mantgem et al. (2004) found no differences in mortality rates between 825 cored and 525 uncored *Abies concolor* and 104 cored and 66 uncored *Abies magnifica*. Similarly, Wunder et al. (2011) compared 551 trees cored in 1965 with an uncored control set and found not significant effect of coring on tree mortality of *Picea abies*. In a subsequent study, Wunder et al. (2013) using electric tomography found that increment coring of *P. abies* does not cause a significant increase of tree decay frequency 45 years post coring in undisturbed high-elevation forest stands. However; authors cautioned that species in different environments may prove to be more sensitive to coring and additional studies are required to test the generality of their findings. The risk of wood decay infection is aggravated in the urban environment and the full effect of coring and drilling on decay infection of several species of urban trees remains untested.

2.4 Measuring wood decay in the urban landscape

Decay in trees is a fungi-assisted process which decomposes the structural integrity of wood into simpler forms to provide nutrients for their growth and development (Harris et al 2004). Wood strength loss in urban trees frequently leads to hazardous situation such as falling trees or branches due to strong winds or tree failure in public places (Johnstone et al., 2013; Kane et al., 2003). Moreover, the presence and progression of wood decay in standing trees is aggravated in urban environments due to several stressors such as mechanical injury, drought

and the urban heat island effect which deteriorate wood structure and tree vitality overtime (Dobbertin, 2005; Koeser et al., 2016; Luley et al., 2009).

The science of decay assessment has evolved considerably overtime. A comprehensive review of methods, tools, instruments and, a sound discussion of their appropriateness and limitations to locate and calculate the extend of wood decay in trees is provided elsewhere (Dolwin et al., 1998; Gao et al., 2017; Johnstone et al., 2010a; Leong et al., 2012). A summary of the two main groups of decay detection tools/techniques is presented hereafter.

Visual and basic screening: wood decay in urban trees can be visually assessed by identifying external sings of decay (cankers, cracks, wounds and, fungi fruiting bodies) and basic screening such as the use of sounding hammers and portable wood drills (Johnstone et al., 2010b). Visual assessment can give an idea of the state of a tree's general decay infection but may not always predict the extent of internal decay accurately (Gao et al., 2017; Kennard et al., 1996). Visual inspection has been largely questioned since trees may lack signs of internal defects and external symptoms of decay can often be confusing (Koeser et al., 2017). A sound assessment of wood decay relies on arborist's experience and can improve with feedback (Fink, 2009; Terho, 2009). For instance, Koeser et al. (2016) found that a visual decay factor (VDF) encompassing all visual indicators of decay was effective (70% of predictability) in identifying decay in *Quercus* spp with diameter range of 45-75 cm. However, this VDF did not perform well for lower tree diameter. If concern still exists when assessing a tree for decay without using a sounding hammer, the use of more sophisticated methods of assessment is suggested.

Sophisticated screening tools: In response to the need to more accurately predict the extent of wood decay and hollow in standing trees, several sophisticated tools have been developed in the past few decades. Non-intrusive methods such as electrical conductivity meter, stress wave timers or X rays are designed to detect the presence of decay with minimal damage to the tree (Larsson et al., 2004; Rabe et al., 2004; Wang et al., 2004; Yamaguchi et al., 2001). Intrusive methods include simple tools, such as drills or increment corers, and more advanced devices such as the Resistograph, electronic hammer and computerised tomography, are widely used today (Axmon et al., 2004; Baietto et al., 2010; Barrett et al., 1987; Leong et al., 2012). Each of these methods have their own drawbacks. Intrusive methods wound trees and may allow spread of decay into uninfected parts (Kersten et al., 2005; Weber et al., 2006). Constant feed drills, computerized tomography and radar measurements has been frequently tested with both promising and contrasting findings (Castello et al., 1999; Gilbert et al., 2004; Gilbert et al., 2016; Johnstone et al., 2010b; Lin et al., 2015; Nicolotti et al., 2003; Sambuelli et al., 2003; Schmidt et al., 2012). In general, decay assessment devices vary in their invasiveness, reliability, practical of use, cost, and interpretation (Gao et al., 2017; Johnstone et al., 2010a).

2.5 Biomass loss due to wood decay in urban trees

A large body of research had documented the occurrence and extend of decay in urban trees. For instance, Castello et al. (1999), based on resistance drilling profiles, reported moderate incidence of advanced decay in 16 *Eucalyptus globulus* and five *Ulmus glabra* street trees. Using sonic tomography, decay wood was found to affect a wide range of tree diameter of *Quercus alba* (21-50 cm) and *Carya* Spp (27-40 cm) growing in parks (Gilbert et al., 2004). Likewise, Terho et al. (2007) assessed the presence of decay in 194 aging trees comprising three species (*Tilia* spp. *Betula* spp. and *Acer* spp) in Helsinki, Finland and reported that over

57% of sampled trees had hollows and 35% showed advanced decay. In a subsequent study, Terho et al. (2008) detected central columns of decay up to 6 m along tree stem affecting between 25% to 75% the cross-sectional area of evaluated trees.

Decay is usually believed to be linked with aging trees, nevertheless; urban foresters report otherwise. For instance, Luley et al. (2009) demonstrated that decay was frequent and severe in street trees of a wide range of diameter (30-80 cm). Overall, 58.3% of the sampled trees had some amount of decay and incidence was highest in *Acer saccharium*. This study suggests that decay initiates early in the life of street trees but is most severe in larger diameter trees that compartmentalize decay poorly. Similarly, Koeser et al. (2016) found that 57% of tested street trees in Tampa, Florida, USA had some level of decay, though decay incidence was higher in *Quercus virginiana* (67.4%) than in *Q. laurifolia* (29.4%) across tree size and locations.

Using different devices and approaches available, recent research confirmed a widespread occurrence and severity of wood decay along the trunk of several urban and peri urban tree species including *Casuarina equisetifolia* (Lin et al., 2016), *Platanus x acerifolia* (Robles et al., 2015) and, *Picea abies* (Oliva et al., 2011) and over an ample list of tropical and temperate forest trees (Cousins et al., 2015; Frank et al., 2018; Gilbert et al., 2016; Marra et al., 2018).

The study of plant vitality is essential to aid arborist in the maintenance of a more healthy, diverse and resilient tree population within urban landscapes (Hermans et al., 2003; McPherson et al., 2018; Ryder et al., 2013). Tree growth, health and vitality are dependent on the physiological processes of photosynthesis, nutrient assimilation and maintenance of a

consistent water balance within the plant (Diaz et al., 2016; Olson et al., 2018). Tree vitality can be therefore defined with reference to the environmental stress to which a plant has been exposed. A tree displaying traits corresponding to high vitality will respond positively to treatment designed to ameliorate physiological stress, while a tree of low vitality will not respond, and in some cases will continue to decline until death (Callow et al., 2018; May et al., 2013; Meir et al., 2015; Steenberg et al., 2017).

Tree vitality is a complex trait to measure and requires a combination of methods to be reliably assessed (Dobbertin, 2005; Johnstone et al., 2013). For instance, Martinez-Trinidad et al. (2010) found a positive but weak relationships between glucose values and vitality groups (poor, fair and good) for 36 *Quersu virginiana* of standing trees. In summary, wood decay is a common issue in urban forest which usually deteriorates wood structure and may or may not cause a decline in tree vitality over time (Dobbertin, 2005).

Decay wood rates in forests have been applied to the modelling of tree benefits, but measurements of existing decay in urban trees have not been used to improve tree biomass calculations (Brazee et al., 2010; Cousins et al., 2015; Russell et al., 2015). Improving the assessment of wood decay wood in urban trees may assist urban foresters in justifying the retention and pruning of exiting trees, rather than their removal (Johnstone et al., 2010a; Koeser et al., 2016; Luley et al., 2009).

2.6 Allometric relationships of urban trees

The development and utilization of allometric equations is an emergent approach for modelling urban tree growth (McPherson et al., 2012; Muukkonen, 2007; Steenberg et al., 2017). During the last decade, considerable research has been done in the field of allometry for urban trees in various climatic regions (Blood et al., 2016; Pretzsch et al., 2015; Vaz Monteiro et al., 2016). Urban forest researchers have developed allometric equations for trees in urban environments, but their range of application and predictive power are limited owing to small sample sizes, few species, young trees only, excellent-condition trees only, and narrow geographic region (McHale et al., 2009; McPherson et al., 2012; Peper et al., 2014). For instance, Yoon et al. (2013) developed allometric equations to estimate above-ground volume for five major urban trees growing in Daegu, Korea. The authors also provided a generalized allometric model for a wider use elsewhere. Likewise, Peper et al. (2001) evaluated 12 species, including *Zelkova serrata*, *Platanus x acerifolia* and *A. saccharinum*, in Modesto, California, USA. They found a strong correlation between total height, crown diameter, and leaf area with DBH for many species and weaker correlations between crown height and DBH. Similar results were reported in a subsequent study for *Ficus macrocarpa*, *Jacaranda mimosifolia*, and *Magnolia grandiflora*, in Santa Monica, California (Peper et al., 2001).

In addition, Larsen et al. (2002) used tree age to develop allometric equations for tree height, trunk height, crown base height, DBH, and crown radius from 251 urban trees (*Tilia cordata* and *T. europaea*) growing in shaded and unshaded conditions. Regression analysis showed strong quadratic relationships between age and size variables. Correlations between age and crown radius for both unshaded and shaded trees showed that crown diameter increases with age, revealing that shade may influence crown radius of trees older than 45 years. Likewise,

Stoffberg et al. (2008) studied allometric relationships of *Combretum erythrophyllum*, *Sersia lancea*, and *Searsia pendulina* growing in the City of Tshwane, South Africa. Logarithmic functions provided a good fit to the data on age against tree height and age against crown diameter.

In another study, Troxel et al. (2013) reported strong relationships for DBH, age, tree height, crown diameter and crown volume across all ten sampled species (1474 trees, age range 4-16 years). The study established species-specific allometric relationships allowing urban forest managers to more accurately project tree growth city-wide. A compilation of available tree growth model and allometric equations for several urban trees is presented in Table 2.2. In order to better reflect the contents of Table 2.2 some terms and definitions are provided below.

Terms and definitions

- ***Allometry***: is a principle that describes the ontogenic development of individuals, i.e the growth of trees. Allometry is also the proportionality relationship between relative increases in plant dimensions (Gayon, 2000). It is also defined as the linear or non-linear correlation between increases in tree dimensions.
- ***Allometric equation***: is a formula that quantitatively formalizes the relationship between plant dimensions (FAO, 2012). An allometric equation represents the statistical relation on a population scale between two size characteristics of the individuals in this population.
- ***Growth model***: Tree growth models project the growth and development of forest ecosystems by increasing the size of each simulated tree in the forest on an annual or greater periodic basis (Dale et al., 1985).

Table 2.2. Set of selected urban tree predictive models from published literature spanning different locations, tree age and diameter ranges.

Location	Number of Species (# trees)	Predictive variable	Response variable	Range of DBH (cm)	Range of age (years)	Reference
<i>Allometric models</i>						
Chicago, Illinois, USA	Six species (43 trees in total)	DBH, crown parameters.	Leaf area/biomass	11-53	Not given	(Nowak, 1996)
Northern California, USA.	Three species (8 open-grown trees)	Comparison of methods against published models.	Foliar- and above-ground biomass	12.9-19.4	Not given	(Peper et al., 1998)
Modesto, California, USA.	Seven species (341 individuals, 30 trees/species)	Tree age and DBH	DBH, height, crown diameter, crown height, and leaf area	5-65	3-89 after planting	(Peper et al., 2001)
Fort Collins, Colorado, USA.	15 species (10-25 trees/species).	DBH/crown volume.	Volume, biomass and carbon storage.	Wide range	Not given	(McHale et al., 2009)
University of Helsinki, Finland.	<i>Two species</i> (5-12 trees/species)	Annual shoot and branch basal area	Crown structure and tree leaf area.	8.2-10.8/6.7-11	2-7/1-6	(Riikonen et al., 2011)
Daegu, South Korea	Five species (10 trees/species)	DBH	Tree height, crown area and volume.	10-50	Not given	(Yoon et al., 2013)
Santiago de Chile	11 common tree species citywide	DBH	Above-ground biomass and leaf area.	6-80	Not given	(Dobbs et al., 2011b)
Gwangju metropolitan city of Korea.	Six species (10-40 trees/species)	DBH	Above-ground volume, Crown basal area	10-62	Not given	(Kim et al., 2016).
Parco Nord Milan, Italy	10 street species (50-120 trees/species)	DBH	Tree height, tree growth, crown	5-45	10-25	(Marziliano et al., 2013)
The city of Helsinki, Finland.	One species (12 trees)	DBH	Above-ground biomass	13-33	20-55	(Tanhuanpää et al., 2017)
Chapultepec Park, Mexico City.	One species (46 trees)	DBH, branch basal area	Above-ground biomass	10-100	Not given	(López-López et al., 2017)

Gainesville, Florida, USA	Three species (65/species)	DBH	Aboveground biomass and crown volume change	11-60	Not given	(Timilsina et al., 2014)
<i>Tree growth models</i>						
City of Tshwane, South Africa	Three species (70-100 trees/species)	Age, DBH.	Tree height, crown dimensions.	Not given	1-47, 1-32 and 3-15.	(Stoffberg et al., 2008)
Canberra, Australia	340 parks and street trees.	Species, crown health, crown width, age.	DBH, growth rate and canopy dimensions.	Not given	Not Given	(Banks et al., 1999)
Santa Monica, CA	16 species (481 individuals, 30 trees/spp and age class).	Age and DBH.	DBH, height, crown diameter, crown height, and leaf area.	5 - 70	Grouped into four age classes of 10 years intervals.	(Peper et al., 2001)
Copenhagen, Denmark.	Three species (total of 251 trees)	Age	Tree height, crown dimensions and DBH.	5 -63	1-112	(Larsen et al., 2002)
Botanical gardens, Tohoku University, Japan	11 species dominated (27-40 trees per specie)	DBH, Crown exposure index.	Tree height, DBH and trunk DBH.	Not given	5-45	(Osada, 2012)
Auburn, Alabama, USA	Three species (100-300 trees/species)	DBH	Crown width	3-30	Not given	(Martin et al., 2012)
Oakville, Ontario, Canada	Two species (27-75 trees/species)	Age and DBH	DBH, tree height, crown dimensions.	5-52/4-102	1-48/2-84	(Peper et al., 2014)
North eastern USA	Ten species (1474 trees).	DBH and age.	Tree height, crown dimensions and volume.	3.4-38.8	4-16	(Troxel et al., 2013)
Several cities in Great Britain, UK	Eight species (22-45 trees/species).	Age and DBH	Tree height or crown width/dimensions.	10-70	2-25	(Vaz Monteiro et al., 2016)
München and Würzburg, southern Germany.	Two species (64 and 84 trees, respectively).	Age and DBH	Tree height, crown width and crown volume.	10-100	3-25	(Moser et al., 2015)
South-eastern USA	97 species (regional data set)	DBH	Tree height, crown width.	Wide range	Not given	(Blood et al., 2016)

Source: Author's based on literature review.

Despite the benefits and constraints being identified in academia, little quantitative data exists to improve tree growth prediction and to demonstrate the full benefits provided by urban trees in Australia (Brack, 2006; Moore, 2012). For instance, Banks et al. (2003) determined relationships between species, crown health status, diameter at crown break, age, crown diameter and tree height to estimate growth and canopy dimensions of 340 street tree species in Canberra, New South Wales. They assumed sigmoidal growth curves and used regression analysis to determine allometric relationship of tree dimensions.

The sigmoidal curve implies all species will experience a period of rapid growth when juveniles, a slowing of growth when semi-mature or at middle age; and then at maturity, a stepping point in tree increment is experienced (Semenzato et al., 2011). Nevertheless, due to unsuitable conditions in urban settings, many trees do not follow this growth pattern, therefore, equations based on this assumption may not accurately model tree growth. The authors developed a set 12 predictive equations for tree height which constituted the foundation to develop a modelling software used for local planting programs (Brack, 2006).

2.7 Stored carbon in urban trees

Most allometric equations currently available were developed to estimate above-ground biomass and timber yield for both managed forest and plantations, thus their application and predictive power in urban settings is limited (Jenkins et al., 2003; McHale et al., 2009). Typically, above-ground biomass yield of urban trees is calculated using either a generalized or species-specific forest-based equation developed in a location with similar climatic zone

(Chaojnacky et al., 2014; Jenkins et al., 2004). Then, under the statement that forest trees grow better and consequently yield greater above-ground biomass than urban trees, a ‘discount’ factor of 0.8 is applied to the resulting biomass estimates (McPherson et al., 1997; McPherson et al., 2013; Nowak et al., 2002a). As a result, most published research so far provides an overview of the actual above-ground biomass and storage carbon potential of urban trees (Lefsky et al., 2008; Stephenson et al., 2014).

A rich body of research supports the fact that urban forestry research need to develop species-specifics equations to more accurately predict biomass yield (Kermavnar et al., 2017; Kuittinen et al., 2016; McHale et al., 2009; McPherson et al., 2012; Moser et al., 2015; Peper et al., 2014; Velasco et al., 2016; Yao et al., 2017). For instance, Jenkins et al. (2004) compiled biomass equations for several hardwood and softwood species and developed equations to estimate component of biomass as a proportion of total tree above-ground biomass. These equations showed that hardwoods, as compared to softwoods, distribute more biomass to their branches than to stems, especially for trees with smaller stem diameters. Furthermore, McHale et al. (2009) compared predictive equations developed from ‘natural forests’ against those constructed from terrestrial LiDAR of urban trees and found that forest-based predictive models yielded significant estimation errors ranging from 60 to 300% at tree level. The authors suggested that in the absence of locally-calibrated equations, using a generalized equation rather than species-specific equations from forest stands is favored, since biomass estimation errors is lower at tree population scale.

Destructive sampling used to collect data required to generate allometric equations is restricted in urban environments, therefore less-destructive techniques has been implemented.

Alternative approaches for tree volume and biomass estimation includes on-field measurements of tree components or entire trees (Fernández-Sarría et al., 2013; López-López et al., 2017), randomized branch sampling (Chirici et al., 2014; Dobbs et al., 2011b; López-López et al., 2017), airborne devices to capture tree canopy structure (Alonzo et al., 2015; Hess et al., 2015; Kato et al., 2009) and the application of terrestrial LiDAR (Chen et al., 2015; Lefsky et al., 2008; Xu et al., 2013). However; resulting biomass estimates should preferably be contrasted against actual biomass values obtained via destructive sampling for accuracy validation (Duan et al., 2015; Lovell et al., 2011; Shrestha et al., 2012).

Due to differences in tree architecture from natural stands and those grown in urban locations, allometric relationships vary widely overtime (Blood et al., 2016; McPherson et al., 2013). In addition, wood density values in branches are higher than stem wood density (Aiba et al., 2009; Henry et al., 2010), thus measuring both wood density and branch volume as a proxy for biomass estimation will probably indicate that reducing biomass yield of urban trees by 20% should be re-evaluated (Luley et al., 2009). Reliable above-ground biomass and carbon stock estimations can lead to a better understanding of the role of urban trees in climate change mitigation (Frank et al., 2006; Kuittinen et al., 2016; Moore, 2009; Poudyal et al., 2011). Overall, carbon stock, sequestration rates and storage capacity of urban forests vary according to species, population structure and management (Boukili et al., 2017). A compilation of selected carbon stock and sequestration rate of urban trees in presented in Table 2.3.

Terms and definitions as reported within the Table 2.3 are given below:

- ***Carbon stock:*** refers to the stored carbon in one place at a given time (Nowak, 1993).

- ***Carbon storage:*** refers to the accumulation of woody biomass as trees grow over time.

The amount of CO₂ stored at any one time by urban trees is proportional to their biomass and influenced by tree density and management practices (McPherson et al., 1997).

- ***Carbon sequestration:*** refers to the annual rate of storage of CO₂ in biomass over the course of one growing season. Sequestration depends on tree growth and mortality, which in turn depends on species composition and age structure (McPherson, 1998).

Table 2.3 Carbon stocks and sequestration rate of urban trees as reported by several studies across cities, land uses and methodologies.

Location	Methodology	Main reported findings	Source
<i>Carbon stock</i>			
Halifax, Nova Scotia, Canada.	Squared plots (20 x 20 m) to sample trees across land uses. Allometric equations applied over 1000 trees.	Carbon stocks ranged from 8.5 – 53 t h C ha ⁻¹	(Freedman et al., 1996)
Several cities across USA	Urban tree cover data from 10 cities was combined with allometric equations and computed in I-tree eco software.	Carbon stocks ranged from 19,300 to 1.2 million t C. Mean carbon stock in urban and forest stands was 25.1 tC/ha and 53.5 tC/ha, respectively.	(Nowak et al., 2002a).
Leipzig, Germany.	Stratified random sampling across 19 land cover classes. Published predictive equations were used over 4358 trees of 89 spp to calculate stored carbon.	Above-ground carbon stock and storage were 316,000 t/C at 11 t C/ha ⁻¹ , respectively.	(Strohbach et al., 2012b)
Lisbon, Portugal	A field inventory of 33,232 trees was combined with i-Tree STRATUM to quantify carbon stock/storage citywide.	Lisbon's street tree population stored over 21,030 t of C accumulated over time in its biomass.	(Soares et al., 2011)
Leicester city, UK	Quantities and spatial patterns of above-ground carbon stored was calculated by surveying urban vegetation.	Citywide, stored above-ground C was 231 521 t, equating to 3. 6 kg C m ² of urban area (97% of this C was stored by trees).	(Davies et al., 2011)
Seattle, WA region, USA	A total 154 sample plots were set to assess carbon stocks as a function of distance from the urban core and land cover.	Regionally, aboveground live biomass was 89±22 MgCha ⁻¹ with an additional 11.8±4 MgCha ⁻¹ of coarse woody debris biomass.	(Hutyra et al., 2011)
City of Tshwane, South Africa.	A total of 28 parking lots were sampled across six towns. Generalized models were used over 820 trees of 12 species.	Mean carbon stock per parking lot was 1390 (± 2503) kg ha ⁻¹ .	(O'Donoghue et al., 2013)
Orlando, Florida, USA	Carbon (C) stock changes and tree care-related C emissions were calculated by re-measuring a subsample of plots (2009 and 2011) + regional allometric equations.	Findings show 17.8 tC/ha in stocks and 1.2 tC/ha/year of net sequestration.	(Horn et al., 2015)
<i>Carbon storage</i>			
Canberra, Australia	The computer system— Decision Information System for Managing Urban Trees (DISMUT) was combined with input from field tree sampling (over 1500 trees sampled).	Mean stored C was 30 2 tC ha ⁻¹ . Predicted C storage (2008-2012) from 13000 to 17200 t C citywide.	(Brack, 2002)
Miami-Dade, and Gainesville, Florida, USA	Field data were spatially analysed to compare C sequestered by managed urban forests to equivalent amounts of CO2 emitted in urban areas.	Stored C ranged from 53-2000 kg per tree. Urban trees sequestration potential offsets CO2 emissions relative to total city-wide emissions.	(Escobedo et al., 2010)

Hangzhou, China	Urban forest inventory data combined with volume-predictive equations were used. Included bamboo forest.	C stock was 30.25 t ha ⁻¹ , estimated C sequestration rates were 166.5 t C/ year and 1.66 t C/ha/year.	(Zhao et al., 2010)
58 cities worldwide.	Below and above-ground C stocks for urban areas was calculated based on datasets reported by Nowak et al. (1996) and its updated version (Nowak et al., 2001).	C storage in vegetation and soils ranged from 11 and 26 PgC (mean of 18.5 PgC in 2000). Soils stored most of this value. Woody plants stored between 3-5 PgC.	(Churkina et al., 2010)
Shenyang, City, China	A total of 450 circular plots, field samples (569 trees) and urban forests data from QuickBird images.	City's C stock was 337,000 t with a sequestration rate of 29,000 t/yr.	(Liu et al., 2012)
Hamburg, Germany	Tree carbon was calculated via allometric equations, while soil organic carbon was analyzed with taken soil samples.	About 6 Mt of organic C are stored within the city, with 2 Mt in trees and 4 Mt in mineral topsoils.	(Dorendorf et al., 2015)
Carbon sequestration			
City of Rome, Italy	Ten trees of two species across growing sites were measured. Published allometric equations were used to calculate stored carbon and sequestration rate at city scale.	C sequestration rate ranged from 84 to 185 kg year ⁻¹ according to tree size and site. Polluted sites had peaks CO ₂ concentration of 432 ± 37 ppm.	(Gratani et al., 2006)
Florence, Italy.	Detailed information on surface areas, green spaces, tree richness and attributes as inputs for allometric equations.	C sequestration rates in built-up and peri-urban area were 13.5 kt y ⁻¹ 58.7 kt y ⁻¹ , respectively.	(Vaccari et al., 2013)
Bolzano, Italy	Aboveground C storage and sequestration rate was quantified using allometric equations and two existing C estimation models (UFORE and CTCC).	Annual C sequestration rates were 5.73 Mg/year from allometric equations, 8.27 Mg/year from CTCC and 5.82 Mg/ year from EUFORE model.	(Russo et al., 2014)
Auckland City, New Zealand.	Tree field survey using four parallel transects. Destructive sampling was used to develop local allometric equations.	C accumulation on a per-tree basis varied between 15 and 62 kg. C, mostly in tree stems (43.3%).	(Schwendenmann et al., 2014)
Canada's major urban areas	Carbon storage and sequestration rates were assessed using high resolution earth data and canopy cover data (27%).	Tree cover stored approximately 34,000 kt C. Annual sequestration rate was estimated in 2500 kt of CO ₂ .	(Pasher et al., 2014)
Cambridge City, Massachusetts, USA	Species and DBH were used to estimate C sequestration rates (kg year ⁻¹) using three approaches: 1) i-Tree Streets, 2) predictive equations and growth rates, and 3) empirically measured growth rates combined with allometric models.	At city scale, C sequestration rates differed significantly (49.2%-49.5%) among approaches and were highest for large trees.	(Boukili et al., 2017)

Source: Author's based on literature review.

2.8 Conclusion

Tree growth rate and allometry underpin tree growth modelling and consequently the assessment of urban tree benefits. Significant progress has been made to explore the relationships of urban tree dimensions and growing sites to further develop predictive equations. Although wood decay is reported as a frequent and severe issue in urban forests its detrimental effect on biomass yield calculation has been overlooked. Currently models used to quantify tree carbon stocks and growth rate do not consider the unique issues inherent in urban tree growth and management, therefore novel approaches are needed. Unlike forestry research, a few attempts have been made to assess 1) the suitability and reliability of resistance drilling to assess growth rate of urban trees (Lukaszewicz et al., 2005; Szewczyk et al., 2018), 2) the occurrence, extent and detrimental effect of decayed wood on biomass yield of standing trees (Koeser et al., 2016; Luley et al., 2009) and 3) the overall above-ground volume/biomass distribution patterns of urban trees and potential effects on allometric relationships among species (Dahle et al., 2014; Dobbs et al., 2011b). Filling these knowledge gaps is crucial to provide solid data on tree growth modelling and to more accurately assess urban tree benefits.

2.9 Species evaluated in this study

Full name of urban tree species evaluated in this study are provided below:

- 1) Species #1: botanical name: *Ulmus procera* (Salisb), common name: English elm, genus: *Ulmus*, Family: *Ulmaceae*.
- 2) Species #2: botanical name; *Platanus x acerifolia* (Ainton) Wild, common name: London plane tree, genus: *Platanus*, Family: *Platanaceae*.
- 3) Species #3: botanical name: *Quercus robur* L., common name: English oak, genus: *Quercus*, Family: *Fagaceae*.

- 4) Species #4: botanical name: *Corymbia maculata* (Hook) K. D. Hill & L.A.S Johnson.
common name: Spotted gum, genus: *Corymbia*, family: Myrtaceae.

Chapter 3. Testing the accuracy of resistance drilling to assess tree growth trends in urban forests

3.1 Abstract

Assessing tree growth trends over time is a central but challenging aspect of urban forest management. The potential damage caused by invasive devices used in dendrochronological analysis is a common concern among urban foresters. Thus, the development of a less-invasive and faster method for assessing tree growth rate that provides reliable results is clearly beneficial. In this study, resistance drilling (RD) profiles were compared with stem core assessments (Core) to estimate the growth rate of 78 trees of three species (*Quercus robur*, *Ulmus procera*, and *Platanus x acerifolia*). All trees studied were core-sampled in 2013 and then resistance drilled in 2015 at a stem height of 1-1.3 m in both north (N) and west axes (W). The dependency and accuracy of paired annual ring series (Core measurements and RD reading) was tested using descriptive statistics and regression analysis. In addition, point and event year tests were determined to confirm the accuracy of RD to assess growth trends at both population and tree level. Growth series from both methods were cross-dated to test the reliability of RD to relate historical tree growth to past climatic conditions. Mean ring width values and age of 70 out of 78 trees were statistically similar for both methods and similar for both sampled stem axes. Within each tree, regression analysis indicated significant correlation between cored ring datasets and paired resistance drilled ring datasets ($R^2 = 0.78 - 0.95$, $p < 0.05$) across species. RD reliably detected pointer years at population level for *Q. robur* only. For all species, RD could not adequately detect event years at tree level. Regardless of species and drill axes, RD was less accurate in measuring ring width below 1 mm. For all species, RD yielded lower intercorrelation indices and greater number of “A” flagged segments as compared to Core. Overall, RD can successfully estimate mean annual increment values to a comparable standard as conventional Core analysis. However, the RD device used in this study did not detect the inter-annual growth pattern to the same standard as stem Core analysis, so RD should not be used to replace dendrochronology in climate-tree growth studies.

Key words: ring analysis, dendrochronology, urban forests, drilling profiles, growth trends.

3.2 Introduction

Dendrochronology is the most used method to conduct tree growth-climate studies in urban, peri urban, plantations and natural forests worldwide (Dolanc et al., 2013; Gillner et al., 2014; Helama et al., 2012; Leal et al., 2015; Nitschke et al., 2017; Pretzsch et al., 2017; Rozendaal et al., 2010). Dendrochronology research first requires coring trees twice (two axes are needed to cross date the samples), second obtained cores need mounting, sanding, and last, annual increment delimitation demands careful measurement under the microscope, which overall is a time-consuming process. Therefore, the development of an alternative method to assess growth rates of standing trees which is reliable as dendrochronology but more rapid will be of great benefit to urban foresters and researchers.

Resistance drilling (RD) allows a rapid evaluation of wood properties in standing trees, presence of decay and cavities in poles and the assessment of wood density in both forest plantations and urban forests (Johnstone et al., 2007; Koeser et al., 2016; Luley et al., 2009; Oliveira et al., 2017; Orozco-Aguilar et al., 2018; Wang et al., 2008). For instance, Johnstone et al. (2011) and Isik et al. (2003) successfully used RD to predict mean wood density values of *Eucalyptus globulus* and *Pinus taeda* plantation trees, respectively. Both studies suggested RD as a suitable and far more time and cost-effective way than core sampling and traditional dendrochronology to assess trends in growth of forest grown and urban trees. The investigation in this chapter focus on developing an impartial test to determine whether RD is as accurate or as reliable as dendrochronology to perform ring analysis and further climate-growth studies.

The potential damage of using invasive devices (stem cores and resistance drills) to enable dendrochronology analysis is a constant concern among urban foresters and tree growers (Baum et al., 2007; Gao et al., 2017; Wessels et al., 2011). However, literature regarding the effect of stem coring and RD on tree mortality and the development of decay in trees is both scarce and conflicting. Early research supported the argument that the coring holes and stem wounds may play a role in wood discoloration and decay infection (Helliwell, 2007; Laplamme, 1979; Schwarze et al., 2006; Weber et al., 2006), yet recent research found no significant effect of coring on tree mortality and decay in undisturbed forest stands (van Mantgem et al., 2004; Wunder et al., 2013; Wunder et al., 2011). Species growing in urban environments might be more sensitive to coring and RD, but the current lack of long-term evidence means that both approaches may cause wood damage but are unlikely to hasten tree breakage or mortality. Overall, the comparative effect of coring or drilling on wood decay infection of urban trees remains untested.

Tree growth rates are critical inputs regarding site index assessment, long-term monitoring of tree health, population dynamics and stand yield prediction (Hu et al., 2018; Moser et al., 2017; Stephenson et al., 2014). Moreover, measuring tree growth rates may: 1) improve our assessment of the age structure of tree stands (Nikolova et al., 2011; Oldfield et al., 2015; Worbes et al., 2003); 2) improve our understanding of how different tree species grow in different sites (Cedro et al., 2006; Rogers et al., 2014; Searle et al., 2012); 3) advance our understanding of how different species respond to climatic variability (Gillner et al., 2013; Ordóñez et al., 2014); 4) help identify robust species that withstand extreme climatic events such as drought (Chen et al., 2010; Fahey et al., 2013; Sedmák et al., 2014) and, 5) assist our

ability to forecast and assess threats such as pests, diseases and wood decay associated with aging trees (Neil et al., 2006; Orozco-Aguilar et al., 2018; Tubby et al., 2010).

Variation of tree annual increments is influenced by management practices (planting density, thinning, pruning, fertilization and irrigation regimes) as well as climate (changes in temperature, water availability and CO₂ concentration over time (Moser et al., 2016; Scharnweber et al., 2011; Searle et al., 2012; Stravinskienė et al., 2015)). Several approaches, analytical tools and indices have been proposed to assess tree growth patterns as a natural response of climatic variability. Among these approaches, cross-dating is a standard procedure used to synchronize tree annual increments and date their exact calendar year of formation, and to elucidate whether past climatic information can be linked to growth records (Bartens et al., 2012; Gillner et al., 2013). A second approach is the identification of pointer years (synonymous with event years and signal years) which is used to statistically understand the impact of extremes climatic events, such as frost and drought events on tree growth (Eilmann et al., 2012; García-Suárez et al., 2009; Hartmann et al., 2015; Meir et al., 2015). Positive and negative pointer years are defined as remarkably wide or narrow annual increment frequently detected within the same group of trees (Bunn, 2008; Lara et al., 2015; Salzer et al., 2009). A third approach refers to component of resilience, which consists of a set of indices used to assess tree growth rate before, during, and after climatic events such as hurricanes, fire, frost and extended drought (Castagneri et al., 2014; Fahey et al., 2013; Vogt et al., 2017; Volgusheva et al., 2011).

To our knowledge, the first attempt to use RD for estimating growth rates of *Taiwania cryptomerioides* plantation trees was done by Wang et al. (2003). Later, Lukaszkiwicz et al.

(2005) evaluated 50+ *Tilia cordata* street trees of variable size and developed a regression model describing trends in the growth of trees whose age was known, but in many cases planting records are not available to support such an approach.

Lukaszkiwicz and colleagues found on-field limitations when using RD such as 1) drilling tangential to the ring structure, 2) internal decayed wood which affects the quality of RD profiles for annual increment analysis and, 3) limited length of the boring bit which restricts its utilization in large/mature trees. In addition, Ukrainetz et al. (2010) reported that resistograph readings are sensitive to various environmental and instrumental factors. On the contrary, Guller et al. (2012) revealed promising results of the usage of resistograph outputs for annual ring measurements of *Pinus brutia*. The aim of this study was to assess whether RD can be used to reliably assess growth trends of a sample population of urban trees. To this end the following research questions were addressed: 1) Are growth rates estimated from stem core measurements comparable to those from RD readings regardless of the tree species, 2) Are tree growth rates estimated from stem core measurements comparable to those from RD readings in the identification of pointer and event years; and, 3) Are tree growth series from stem core measurements and RD readings similar in the assessment of climate-growth patterns across species?

3.3 Materials and Methods

3.3.1 Study site

The research was carried out in the urban forest of the City of Melbourne, Australia (37°48'S, 144°57'E). The climate of Melbourne is temperate with an average annual rainfall of 656 mm with the wettest months being from September to December. Mean annual temperature is about 19.7°C ranging from a highest average in February (25.7°C) and the lowest in July (13.4°C) (www.bom.gov.au). This study sampled 100 urban trees from six parks and five streetscapes located across an elevation gradient between 12 and 49 m above sea level. Soil analyses (provided by the City of Melbourne) found six sampled parks (n = 32 soil samples) having predominantly loam-silt loam soils while streetscapes (n = 12 soil samples) showed predominately sandy loam – loam soils. Soils under street-based trees had significantly ($P < 0.05$) more sand, less silt, less organic matter and higher pH than soils under park trees. Differences between specific parks and streets were also found for clay, sand, silt and pH; however, no differences were found in soils under different tree species across sites (City of Melbourne, 2012; Nitschke et al., 2017).

3.3.2 Background silvics of the three species

The Melbourne's city council maintains ~70,000 trees in parks and streets with an average tree density of 26.5 ha⁻¹ (± 18 ha⁻¹) and a canopy cover of 12.3% (3-20%). The five most common species are *Eucalyptus camaldulensis*, *Platanus x acerifolia*, *Ulmus* spp. and *Corymbia maculata* which account for 29% of the total tree population. More than 50% of the species are native to Australia and most exotic species originated from Europe, followed by North America and Asia (Dobbs et al., 2013). Melbourne's urban forest includes an important population of approximately 6,500 European elms (*Ulmus procera*, *U. × hollandica*, *U. glabra*, and *U.*

minor) that have never been affected by Dutch elm disease (*Ophiostoma* spp.) (Frank et al., 2006). These elms, along with plane trees (*P. × acerifolia*) account for many of the large street trees in Melbourne and contribute character to many parks (City of Melbourne, 2012).

Melbourne's urban forest is undergoing unprecedented change and many trees are approaching the end of their lifespan due to a combination of factors, such as age, extended drought, extreme heat waves and water restrictions (City of Melbourne, 2012; May et al., 2013). A recent period of drought (1997-2009) and water restrictions triggered an irreversible decline for many trees, particularly planes trees, *Elms* spp. and *Populus* spp (May et al., 2013). In addition, a concomitant infestation of elm leaf beetle (*Pyrrhalta luteola*) may have contributed to the decline in tree health within this genus. A useful life expectancy (ULE) assessment undertaken on 35 000 street and park trees indicated that a substantial proportion of (23%) city' tree population will be at the end of its ULE within 10 years and 39% within 20 years. Moreover, 55% of elm trees were in a state of severe decline and will likely be removed from the landscape within the next 10 years (City of Melbourne, 2012; Moore, 2012). Regular tree care of sampled trees includes lifting of canopies to remove low branches, pruning, topping and mulch application if needed (Moore, 2009).

3.3.3 Tree measurements and resistance drilling

All studied trees (300 in total) were core-sampled in 2013 at approximately 1-1.3 m from the ground in two axes north-south (N) and west-east (W). The selection of trees to be core-sampled was pre-determined by the City of Melbourne based on trees having an estimated useful life expectancy of <20 years (City of Melbourne, 2012). Tree height from all obtained

cores and allowed to capture as many growth rings as possible without including distortion in rings related to any stem buttressing. All cores either included the pith or were close to pith, providing the longest ring-width series possible per tree (Nitschke et al., 2017). A subsample of 100 open-grown consisting of three species (*Q. robur*, *U. procera* and *P. x acerifolia*) were then remeasured and resistance drilled in summer 2015 (January-April). From sampled 100 trees only 78 trees were suitable for ring analysis due to the high incidence of decay. These trees were situated in parks and streets, and in general had stems >40 cm in diameter and a height between 15 and 20 m. General tree dimensions and wood anatomy features of evaluated tree species are given in Table 3.1. Sampled trees included over-mature *U. procera* and *Q. robur* individuals planted during 1880-1900 and mature and young *P. x acerifolia* trees planted in 1920-1950 and 1970-1980, respectively.

Table 3.1 General dimensions, location and wood anatomy features of 78 stem cored and then resistance drilled trees in parks and streets of the city of Melbourne, Australia. The $\pm$ symbol indicates standard deviation of each reported value.

	<i>Quercus robur</i>	<i>Platanus x acerifolia</i>	<i>Ulmus procera</i>
No. of trees	25	29	24
DBH (cm)	84 $\pm$ 12	38 $\pm$ 18	81 $\pm$ 11
Tree height (m)	14.7 $\pm$ 1.3	18.8 $\pm$ 3.4	15.5 $\pm$ 3.5
Establishment period*	1890-1930	1920-1950	1880-1900
Mean growth rate (mm year⁻¹)**	2.47 $\pm$ 1.47	3.74 $\pm$ 2.82	2.57 $\pm$ 2.42
Location	Parks	Parks/Streets	Parks/Streets
Wood anatomy features***	Ring-porous, inter-locking grain, low natural durability.	Diffuse porous, small to medium pores, straight grain, low natural durability	Ring-porous, straight grain, irregular or inter-locked, very good natural durability.

Notes: *Based on core-assessments done in 2013 on the same sampled trees. ** Calculated from raw chronologies done in 2013 on the same sampled trees. Source: (Nitschke et al., 2017).

***Wood anatomy features sourced from www.wood-database.com.

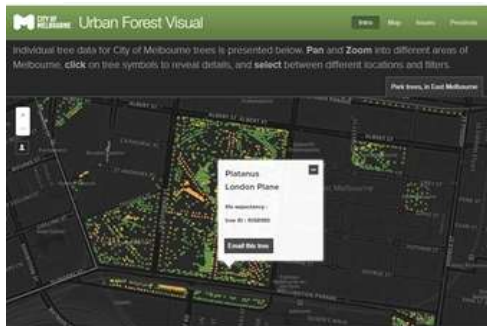
Trees were resistance drilled using an electrically recording IML-PowerDrill® PD-series (www.imlaustralia.com) with the following specifications: diameter needle shaft: 1.5 mm, diameter needle tip: 3.0 mm and 40 cm in length. Both the drill feed speed (penetration) and needle speed (rotation) were adjusted according to species' wood density (İÇEl et al., 2016). The defined settings were: 100 cm/min and 3000 rpm for *U. procera*, 50 cm/min and 4000 rpm for *Q. robur* and 25 cm/min and 5000 rpm for *P. x acerifolia*. Device settings need to be adjusted to capture the cleanest and longest drilling profiles from different sampled trees (Rinn, 2012). For instance, a slower penetration speed and higher rotation speed (revolutions) are necessary for trees with higher density wood, otherwise the drill cannot penetrate the tree stem and cannot provide complete drilling profiles (i.e. it gets stuck). But for lower wood density trees, a faster penetration speed and a slower rotation speed is required to capture meaningful data (Oliveira et al., 2017). The drill graphically measures both the drill resistance and the feed curve, which is the force needed to push the needle into the wood. The feed curve is only minimally affected by shaft-friction; hence the feed curve was used for ring analysis for all species (Guller et al., 2012; Wang et al., 2008).

Ring width analysis: In this study, raw increment series of core-sampled trees were collated and used for comparative ring analysis with their corresponding RD raw increment series. Core raw data came from Nitschke et al. (2017) who used standard dendrochronological procedures to visually cross dated cores to account for false or missing rings (Grissino-Mayer, 2001) and then statistically cross dated increment width series using the program COFECHA. Resistance drilled growth series were obtained as follows: 1) trees were identified and revisited using the city's data base (<http://melbourneurbanforestvisual.com.au/>), 2) each tree was then resistance drilled slightly above/below the core-sampling points in two axis (North-N, West-W), 3) core

samples from the same drilled trees and drilling points were scanned, 4) bark thickness from core sample was measured and discounted from the corresponding drilling profile, which in turn was used as the reference distance to further perform ring analysis on each drilling profile, and 5) paired images (scanned cores and RD profiles) were taken for ring analysis using installed IML PowerDrill® tools package (Figure 3.1).

Finally, ring delineation was done in a 2X amplitude screen to facilitate ring width viewing. In this study, an *annual ring* within RD profiles was considered as the distance between the middle point of two consecutive peaks. This assumption is equivalent to ring width from early wood to late wood of two adjacent annual increments when ring analysis is done onto core samples (Eilmann et al., 2012; Wang et al., 2003). The lowest reported value for annual increment delineation using RD profiles is 0.5 mm depending on wood anatomy and tree ring density (Rinn et al., 1996).

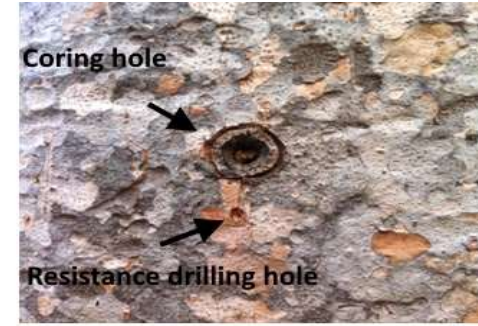
Age calculation: Available IML PowerDrill® ring analysis tool package back-records the age of a given tree once ring counting and width delineation is completed on each drilling profiles (Maxwell et al., 2011; Rinn, 2012). In this study, age calculation from RD profiles was done from bark to pith and was assumed as the total number of annual rings registered during ring analysis minus the two years interval between coring and RD field campaigns. According to Nitschke et al. (2017) age range of core-sampled trees was: *Q. robur* (1876-2012), *P. x acerifolia* (1878-2012) and *U. procera* (1873-2012).



Step 1: Trees were located and revisited



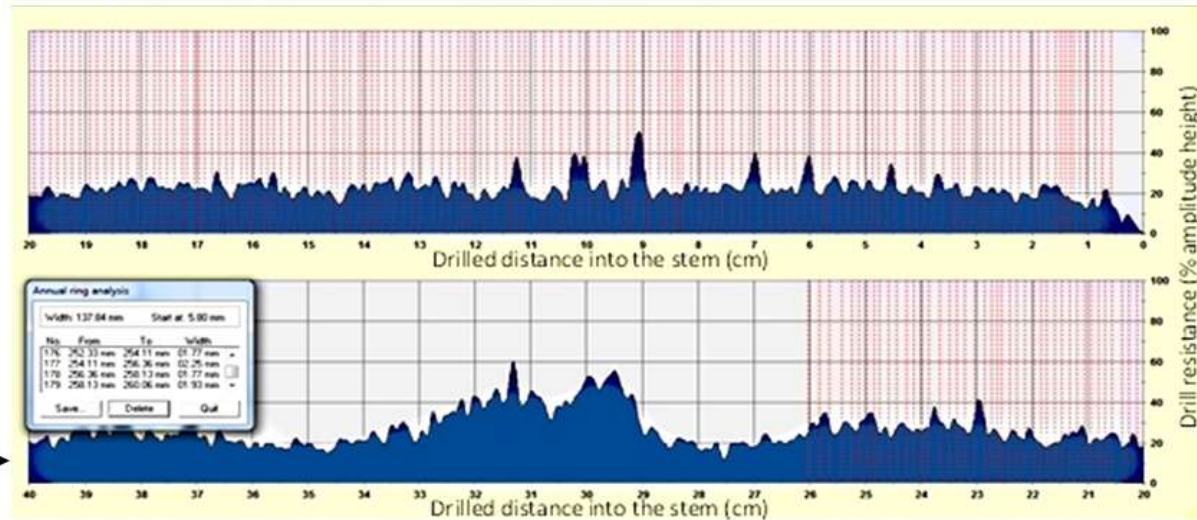
Step 2: Trees were microdrilled twice.



Step 3: Trees microdrilled slightly above and below the coring points

Step 4: Scanned cores and paired drilling images were used for ring analysis

Drilling profile →



Scanned core →



Figure 3.1 Steps taken in the process for ring analysis from core-sampled and resistance drilled trees. Photos and figures from the author.

3.3.4 General overview of ring analysis process

From 100 trees sample only 78 trees were suitable for ring analysis due to a high incidence of decay wood within the drilling profiles, especially in *U. procera* individuals. Ring analysis process began by scanning all core samples in a high resolution dendro-scanner to facilitate comparisons against corresponding drilling profiles, this task demanded between 15-20 minutes per core sample. Once trees were correctly identified and paired scanned cores were matched, ring analysis from bark to pith took place and lasted for about 45-60 mins. As the next step, resulting annual ring width series (expressed in 1/1000 mm within IML PowerDrill[®] analytical tools) were converted into standard units (mm).

As a final step, converted ring width series were exported to an Excel sheet and merged with paired core ring width series for further statistical analysis. Based on our field records, the overall process of identifying, resistance drilling and conducting ring analysis using an IML PowerDrill[®] demanded between 1.5 to 2 hours per tree to be completed. Nevertheless, estimated processing time of a given tree depends on stem diameter. For instance, ring analysis of trees with DBH between 30-50 cm (whose drilling profiles length from bark to pith was about half the diameter (i. e 16-26 cm), required up to 1 hour per tree. Ring analysis of trees with DBH greater than 50 cm (drilling profile length of ~ 30 cm) took between 1.5 to 2 hours.

3.3.5 Data analysis

Descriptive statistics were calculated to summarize annual increment values and age of all sampled trees and by method (core vs resistance drilling) following Maxwell et al. (2011).. Normal distribution of data was partially confirmed using a modified Shapiro-Wilks test, although normality is not a necessary assumption for analysis with high sample size (Stevens,

2013). Box plot graphs were generated to confirm statistical differences between average increment values and age estimated with both methods and for both drill axes (N and W). Regression analysis tested the dependence and accuracy of RD readings against core sampling measurements to conduct ring analysis for all species and across drill axes.

Tree increment width series produced by both methods (Core and Resi) were then used to conduct a pointer and event years analysis to detect trends in growth for all species at both population and tree level. The term pointer year refers to a notable growth change and/or response at population level whereas the term event year refers to years with remarkable growth change, either positive or negative, at individual tree level. R functions used to analyse pointer and event years were the `norm.plot` and `rgc.plot` to create a bar plot of either mean annual Cropper values or mean annual growth deviation (in percentage); which are directly derived from the output of `pointer.norm` and `pointer.rgc` commands, respectively. In these bar plots, pointer years are indicated with grey/dark fill colors (Bunn, 2008; van der Maaten-Theunissen et al., 2015).

The approach used to identify pointer and event years was the normalization technique proposed by Cropper (1979) which consists of four steps: 1) produce normalized individual tree-ring series, 2) set thresholds onto annual increment values which are typically the number of standard deviation (SD) that a tree population grow above or below the mean growth rate value. In this study a Cropper value of > 0.75 SD was applied, 3) a threshold of 75% as a benchmark of sampled trees showing a negative or positive pointer/event year was set and, 4) identification of a three intensity classes for event years (weak, strong and extreme) was adopted to detect trends in growth at tree level. The level of similarity between event year

classes marked by Core measurements and RD readings (Resi) was tested via Jaccard similarity index (Real et al., 1996).

Increment width series from both methods (Core and Resi) were cross-dated (within and between trees) using COFECHA version 6.06. In COFECHA, the following default analysis settings were used: 1) 32-year cubic smoothing spline with 50% wavelength cutoff for filtering, 2) examination of 50-year segments lagged 25 years, 3) autoregressive modelling turned on, 4) transformation of series to logarithms and, 5) a value of 0.3281 as critical level in the correlation analysis following Grissino-Mayer (2001). The comparative analysis (Core vs Resi) focused mainly on the following outputs: 1) tree-ring series correlations with the master chronology, 2) mean sensitivity, a measure of the year-to-year ring variability within a sample; and, 3) number of “A” flagged segments (i.e., 50-year sections of an individual tree-ring series with low correlation to the master chronology) as suggested by Maxwell et al. (2011). All statistical analysis was done in R (R Core Team, 2015).

3.4 Results

3.4.1 Annual increments values between methods.

A box plot test confirmed that mean increment values of *U. procera*, *P. x acerifolia* and *Q. robur* were similar using both methods and similar for both N-W drilling axes (Figure 3.2). For *U. procera* trees, five out of 24 mean increment values were statistically different. For the other two species only two mean increment values differed statistically (Appendix 1). The level of accuracy of average tree increments estimations was greater for *Q. robur*, followed by *P. x*

acerifolia and least accurate for *U. procera*. These findings indicated the ability and reliability of RD to assess average ring width values regardless of species and drill axes.

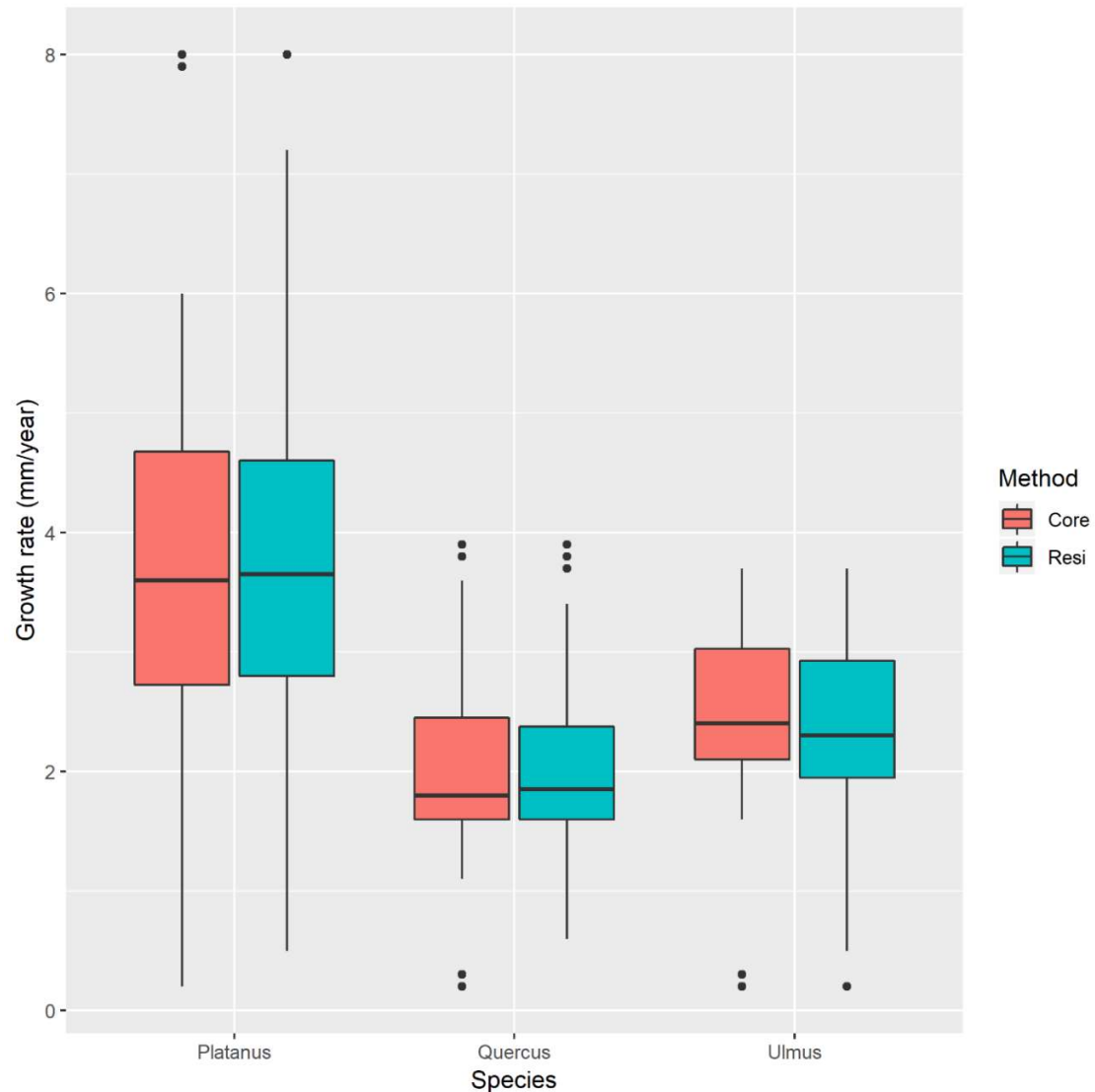


Figure 3.2. Average growth rate (mm year⁻¹) as estimated by the core measurements (Core) and resistance drilling readings (Resi). Presented values include both N and W drill axes data.

Regardless of species and drilling axes, linear regression analysis indicated a strong and significant relationships between paired core measurements and RD readings datasets ($R^2 = 0.78-0.96$, $p = <0.0001$) (Figure 3.3). The correlation (which indicates the level of similarity between methods) was stronger for *Q. robur*, followed by *P. x acerifolia* and least accurate for

U. procera. These findings indicated a satisfactory accuracy level of RD to assess average ring width values for all sampled species.

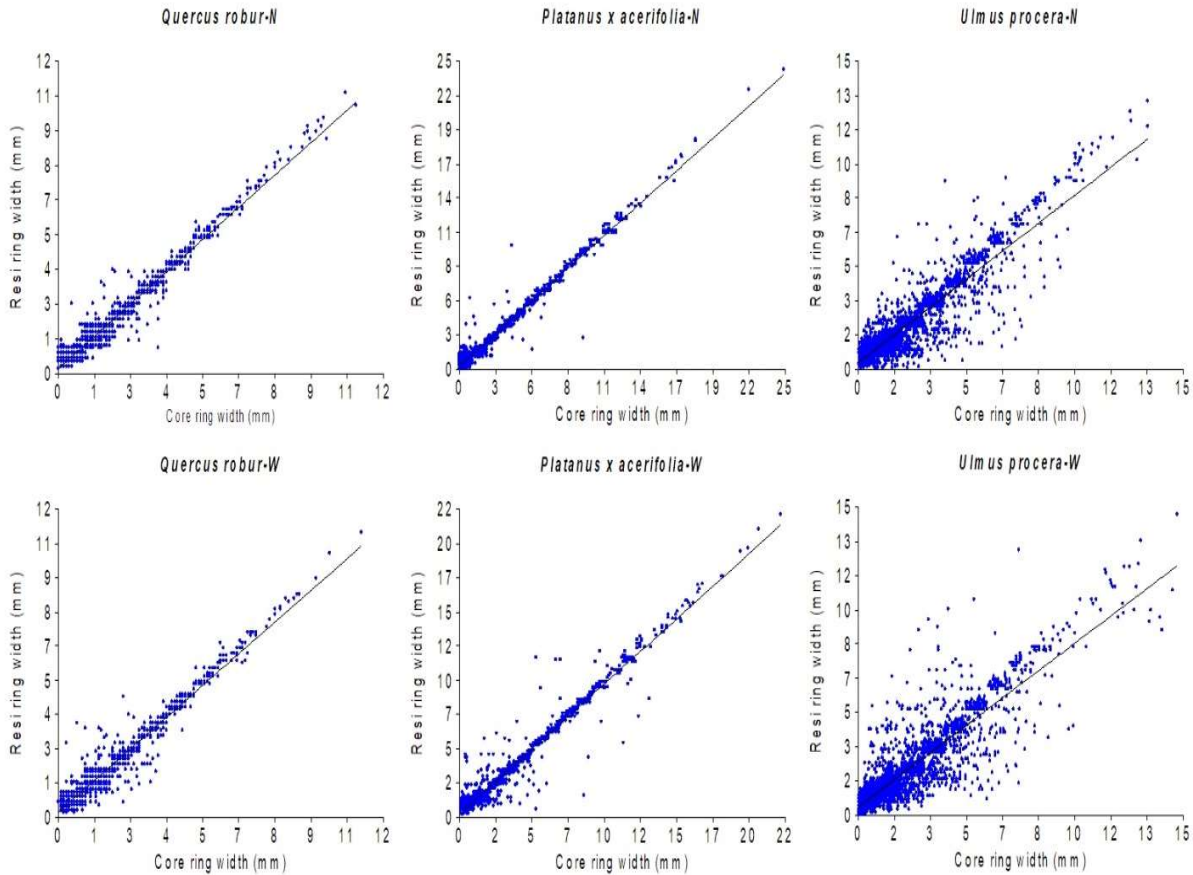


Figure 3.3. Relationships between paired annual increment values (mm) series as measured by resistance drilling (Resi) and core sampling (Core) for north-south (N) and west-east (W) drill axes. Associated statistical values were as follow: *Q. robur*: N-($y = 0.9279x + 0.2161$, $n=2545$, $R^2= 0.95$, $p= <0.0001$, RSE: 0.08), W-($y = 0.9243x + 0.2225$ $n=2555$, $R^2= 0.96$, $p= <0.0001$, RSE: 0.09), *P. x acerifolia*-N-($y = 0.9488x + 0.2958$, $n=1595$, $R^2= 0.94$, $p= <0.0001$, RSE: 0.23, W-($y = 0.9482x + 0.2588$, $n= 1618$, $R^2=0.92$, $p= <0.0001$, RSE: 0.42) and *U. procera*-N: ($y = 0.8167x + 0.3251$, $n=2846$, $R^2= 0.83$, $p= <0.0001$, RSE: 0.23, W: ($y = 0.7975x + 0.4051$, $n= 2781$, $R^2= 0.78$, $p= <0.0001$, RSE: 0.27). RSE: Residual standard error.

3.4.2 Accuracy of annual increment measurements among species

Overall, RD readings under or overestimated annual increment values as compared to core measurements. The dissimilarity in increment values calculations between the two methods

ranged from -5.2 to + 6.8 mm, -4.5 to + 7.8 mm and -3.8 to + 3.7 mm for *U. procera*, *P. x acerifolia* and *Q. robur*, respectively. The accuracy of RD readings for assessing tree increments varied according to species particular annual ring width. Regardless of species and drill axes, delineating a narrow annual increment (less than 1 mm width) seems to be problematic from RD profiles (Figure 3.4).

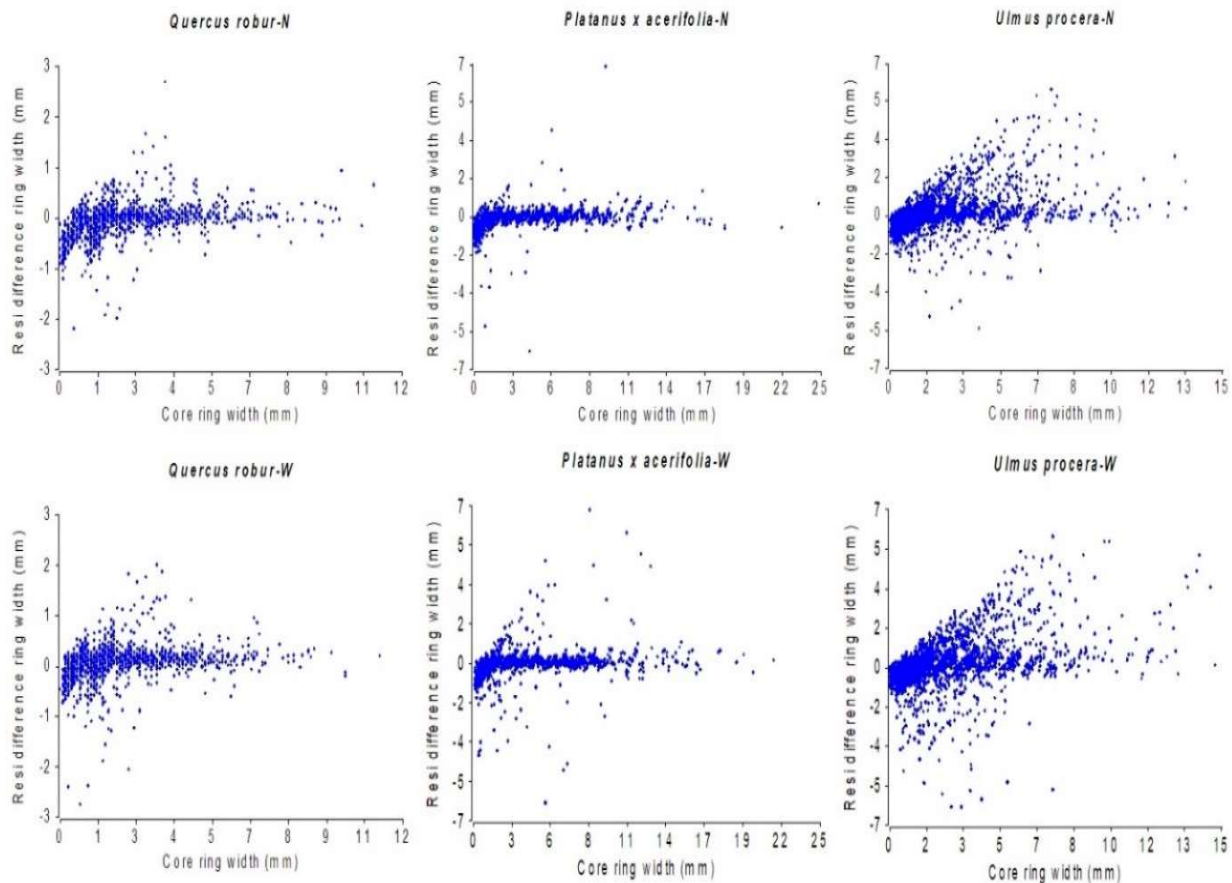


Figure 3.4. Differences of annual ring width (mm) calculations as measured by core-sampling (Core) and resistance drilling (Resi) for *Quercus robur* (n=25 trees, n=2555 rings), *Platanus x acerifolia* (n=29 trees, n= 1618 rings) and *Ulmus procera* (n=24 trees, n= 2845 rings). Annual ring width presented from North (N) and West (W) axes.

Annual tree increments of stem-cored *Q. robur* seem to be well marked and could be easily delimited onto the corresponding RD profiles. This situation was not the case for large *P. x acerifolia* trees in which small annual rings were less noticeable and tended to be more difficult

to mark onto paired RD profiles. The high incidence of decay in *U. procera* trees limited the quality of RD profiles for ring analysis. Decayed wood produces a wave-like drilling profile which affected the ability of the operator to delineate annual ring width along the sample. This condition lead to a less accurate ring width analysis for this species (underestimation of narrow rings and overestimation of the actual ring width values) as compared to core measurements for the same species.

3.4.3 Age calculation between methods and species

The accuracy of RD to estimate age of sampled trees was similar for all species and across drilling axes. Although not statistically significant, differences in tree age values estimated between core measurements and RD ranged from 3-5 years. Estimated average age for *U. procera* trees were 225 ± 25 years, 114 ± 60 years for *P. x acerifolia* trees and, 204 ± 56 years for *Q. robur* trees (see Appendix 1 for details). Species age-related growth trends also influenced the accuracy of RD to assess annual ring width across species. For all species, RD accurately captured annual ring width patterns of trees aged 50 - 60 years, however; for older trees the level of accuracy decreased (Figure 3.5). Mature and over mature trees (older than 60 years) tended to grow slower, therefore those trees showed narrower annual ring (≤ 2 mm) which were difficult to correctly delineate on to RD profiles.

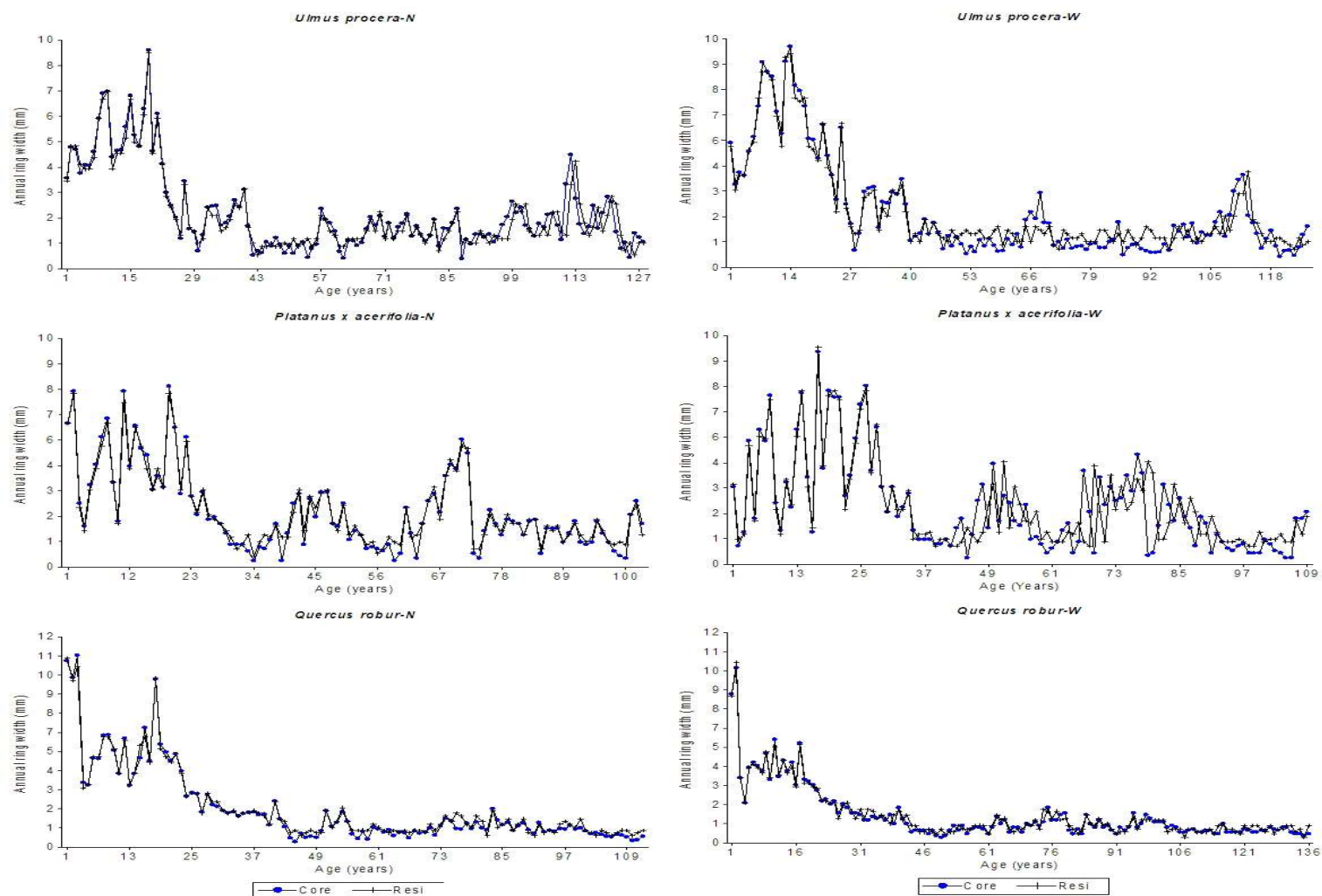


Figure 3.5. Annual ring width (mm) series of the oldest tree per species as measured by the core measurements (core) and the resistance drilling readings (Resi). Annual ring width series presented for two drill axes North (N) and West (W).

3.4.4 Identification of pointer years at population level

Regardless of drill axes, annual growth series from RD reading could accurately detect pointer years at population level for *Q. robur* only. For *P. x acerifolia*, although RD readings did capture similar trends in growth at population level as compared to core measurements, the analysis did not show either positive or negative pointer years from both methods and drill axes (Figure 3.6). For *U. procera*, identifying pointer years from RD profiles was irregular and exhibited a decreasing trend in growth as compared to core measurements. These findings confirmed that, at least at population level, RD can be used to retrospectively assess growth trends of standing *Q. robur* trees with statistical confidence but not for *P. x acerifolia* and *U. procera* trees.

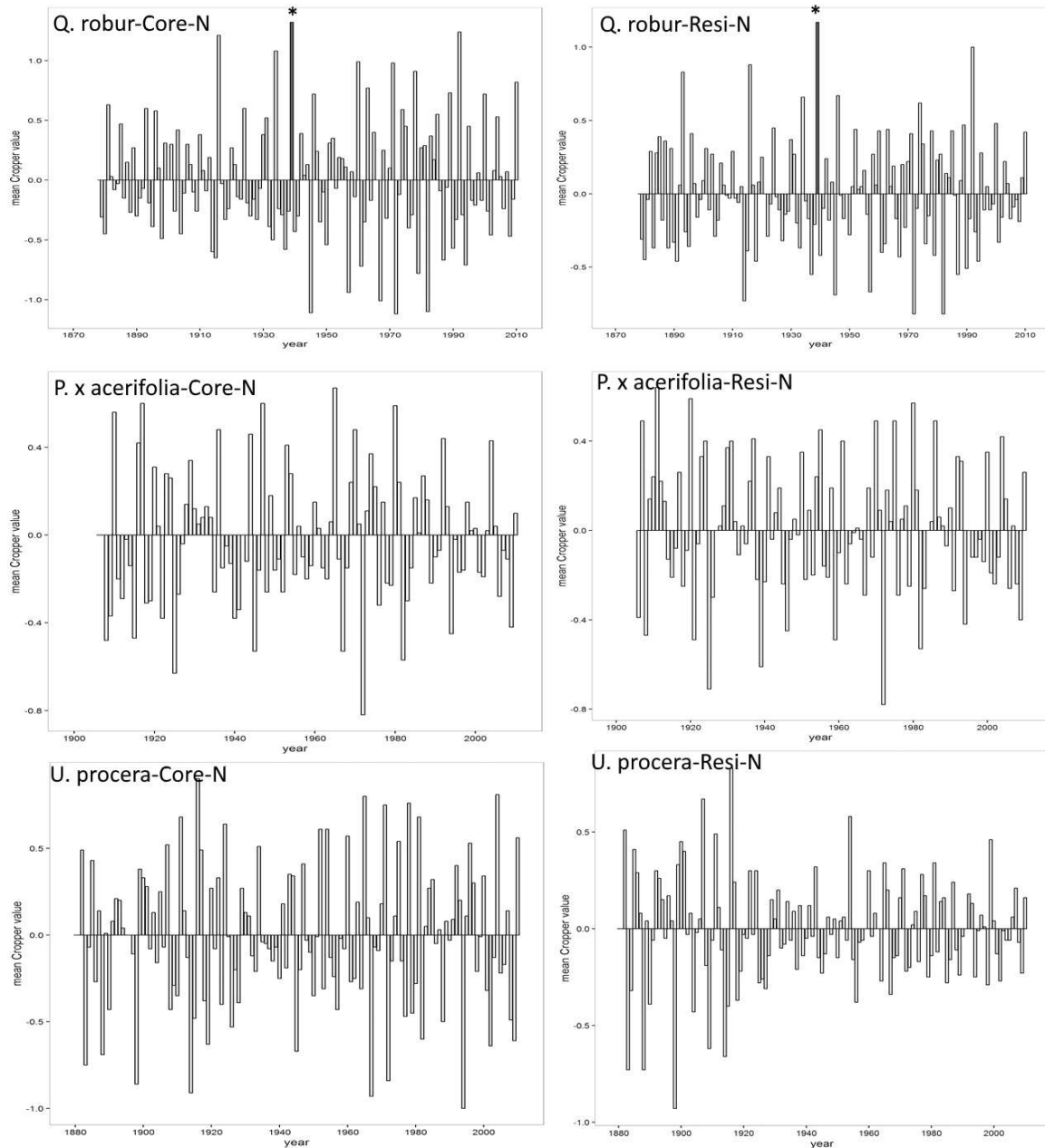


Figure 3.6. Bar plot of mean growth deviation in *Quercus robur* (n=25), *Ulmus procera* (n=25) and *Platanus x acerifolia* (n=29) calculated by pointer.rgc, and plotted for the period 1870–2010 with the rgc.plot function. Pointer years are highlighted in dark grey and an asterisk on the top. Applied Cropper value of > 0.75 SD for both axes.

3.4.5 Identification of event years at tree level

Annual increment series from RD allowed the identification of both extreme and strong positive and negative event years at tree level with varying degree of accuracy. Regardless of species, RD tended to over-detect the number of either positive or negative event years as

compared to core measurements. Hence, it was confirmed that over detection is a constant error throughout RD readings. RD is sensitive to reaction wood recorded as a false ‘peak’ within drilling profiles. Moreover, urban trees undergo regular arboricultural practices, such as pruning, lopping and wounding causing strong signals in tree-ring series, including missing, false and wedging rings which were difficult to identify on to RD profiles.

The identification of event years showed a negative association with tree age. In general terms, the older the tree the more event years were either over or miss-identified. For younger trees, RD tended to over-identify event years within sampled trees of the same species. RD also tended to miss-identify and incorrectly locate event years outside the evaluated time window as compared to core measurements. The Jacquard similarity index used to compare correctly identified and shared event years between methods (Core vs Resi) ranged from 0.42 to 0.50 across species, which in ecological terms indicate low similarity (Table 3.2). Across species, the level of similarity regarding the other two event year classes (namely weak negative and weak positive) was less than 0.40 (data not shown) which indicates very low similarity between methods. These findings confirmed a limited ability and lower accuracy of RD to correctly identify event years at tree level as compared to core measurements.

Table 3.2 Number of event year class shared by the core measurements (Core) and resistance drilling (Resi) for *Quercus robur*, *Platanus x acerifolia* and *Ulmus procera* and their corresponding Jaccard similarity index.

Species	Method/Event year classes	Negative extreme	Negative strong	Positive Strong	Positive extreme
<i>Q. robur</i> (n=25)	Core	16	135	179	58
	Resi	18	147	194	51
	Shared	9	65	84	28
	Similarity	0.50	0.48	0.47	0.48
<i>P. x. acerifolia</i> (n=29)	Core	7	56	108	12
	Resi	6	69	105	24
	Shared	3	26	52	5
	Similarity	0.43	0.46	0.48	0.42
<i>U. procera</i> (n=24)	Core	16	113	178	36
	Resi	18	125	174	44
	Shared	7	53	86	17
	Similarity*	0.44	0.47	0.48	0.47

*The Jaccard coefficient measures similarity between finite sample sets and is defined as the size of the intersection divided by the size of the union of the sample sets.

3.4.6 Series intercorrelation, mean sensitivity and cross dating index

Output from COFECHA for total-width measurement series showed marked differences in the accuracy of series intercorrelation and average mean sensitivity between methods and across species. The greatest differences between methods (Core s Resi) were seen in the number of “A” flagged segments. Regardless of species and drilling axes, ring width series derived from RD profiles yielded low mean series intercorrelation indices as compared to core-derived ring width series (Table 3.3). Ring width series for *Q. robur* achieved the best mean intercorrelation index followed by *U. procera* and least for *P. x acerifolia*, which indicates that RD can provide a chronology master series, but it may not be as robust as with a core ring width series. Moreover, RD ring width series did not correctly date 3-5 rings, 5-7 rings and 7-9 rings for *Q. robur*, *P. x acerofolia* and *U. procera*, respectively. COFECHA analysis indicated a low ability of RD-derived ring width series to identify either false or missing rings as per core-derived ring width series. These findings suggest that RD could not capture the annual pattern in growth

across sampled species, therefore RD is unlikely to provide a reliable assessment of the role of climate on tree growth.

Table 3.3 Dated ring width series, mean intercorrelation indices (MI), average mean sensitivity and flagged segments as yielded by COFECHA and per method (core sampling-Core- and resistance drilling-Resi-) and the specie's assigned cross dating index (CI).

	<i>Q. robur</i>	<i>P. x acerifolia</i>	<i>U. procera</i>
Sampled-trees (n)	25	29	24
Cross-dated trees (n)	16	15	15
Core method			
Dated series	22	57	48
Series dates	1880-2012	1904-2012	1877-2012
Series intercorrelation	0.572	0.523	0.532
Average mean sensitivity	0.466	0.459	0.472
Flagged segments	6	5	8
Mean length of series	97.8	54.5	118.7
Resi method			
Dated series	32	47	38
Series dates	1880-2012	1904-2012	1877-2012
Series intercorrelation	0.466	0.386	0.423
Average mean sensitivity	0.349	0.352	0.326
Flagged segments	43	47	88
Mean length of series	90.5	57.8	117.6
CDI*	2	0	1

*CDI: The cross dating index (CDI) was used by Grissino-Mayer (1993) to identify tree species suitable for tree ring research: 0= no or little importance to dendrochronology as species do not cross date or no information on cross dating has been published; 1= minor importance (good for local scale comparisons and interpretations); 2= major importance and suitable for macro-scale comparisons.

3.5 Discussion

3.5.1 Scope and limitation of resistance drilling (RD) for ring analysis

This study tested the suitability and reliability of resistance drilling (RD) to conduct ring analysis in urban trees. RD has been used to assess wood density and ring width values of standing forest grown and urban trees with varying degree of success (Guller et al., 2012; Isik et al., 2003; Kraler et al., 2012; Maxwell et al., 2011; Oliveira et al., 2017; Rinn, 2012;

Szewczyk et al., 2018; Wang et al., 2003). Nevertheless, none of the studies presented above contrasted their finding against core-derived growth series or explored the potential of RD-derived growth series for climate-growth studies of urban trees.

The availability of raw growth series data (Nitschke et al., 2017) allowed us to overcome limitations previously listed by Lukaszkiwicz et al. (2005). The first of them was a limiting length of the boring bit. The length of the needle used in this study was 40 cm and since we sampled trees with diameter between 40-90 cm, is highly likely that the length of a given RD profile reached the tree pith properly, so the most accurate tree age was estimated (Downes et al., 2009; Maxwell et al., 2011). Contrary to our results Oliveira et al. (2017) observed a clear trend of weakening correlation as the drill penetration depth increased, affecting the overall accuracy of RD readings on specific gravity values for *Eucalyptus urophylla* plantation trees.

In order to sample larger trees ($DBH \geq 90$ cm) a device with a 50 cm to 1 m needle in length is also available (IML-Norteamerica, 2016). The second limitation was drilling tangential to ring structure. As sampled trees were revisited, and resistance drilled two years after core-sampling took place, coring points along the stem were still detectable, therefore we were able to re-sampled trees slightly above or below that reference point. Moreover, the time interval between the two field work campaigns was two years, therefore we avoided the inclusion of two growing seasons into the comparative analysis performed.

The last limitation was wood decay within the trunk. This issue was not important when assessing ring width of *P. acerifolia* and *Q. robur* trees but significantly affected the delineation

of ring width values onto *U. procera* drilling profiles. Given that sampled trees were reported as having an useful life expectancy of less than 20 years (City of Melbourne, 2012), it is likely that wood decay deteriorates tree structure, thus affecting the ability of RD profiles to record meaningful data (Orozco-Aguilar et al., 2018). In this study, RD profiles showing segments of decay resulted in dissimilar ring width values from paired core data sets. Decayed wood has lower density values, which affects the ability of RD to record clear peaks for accurate ring width delineation (Johnstone et al., 2011). Likewise, Lombardi et al. (2008) reported a strong effect of decay classes on quality and lifespan of master chronologies built from core-sampled *Abies alba* and *Fagus sylvatica* trees. Guller et al. (2012) reported similar issues when assessing ring width values of *Pinus brutia*.

The fact that RD needle is more flexible than the core borer, it is likely that the needle moves sideways as it penetrates the tree, therefore not capturing the same ring pattern. Bartens et al. (2012) found that *Quercus virginiana* did not exhibit concentric annual rings along the stem even from the same coring axes. Recent research showed that the ability of the IML-Resi E400-profiles to assess tree ring width and age of *Quercus robur*, *Pinus sylvestris* and *Betula pendula* is influenced by species wood anatomy features and other deformations found along the device's needle, such as a small necrosis or covered bark pockets (Szewczyk et al., 2018). Other defects such as cracks, wounds, knots and pockets of resin affected the reliability of RD ring measurements (Guller et al., 2012).

As shown in Figure 3.4, the lack of ring parallelism may lead to variations in ring width analysis thus decreasing the overall accuracy of RD as compared to core measurements. Drill's position and drilling angle also affected the likelihood of capturing the same wood density and ring

width patterns of sampled trees (Sharapov et al., 2018). Clear and detectable tree-ring structures are provided by radial drillings so that the needle penetrates the tree-ring borders (Maxwell et al., 2011; Tardif et al., 2006). The more this penetration angle deviates from 90°, the less clear the tree rings appear on to RD profiles (Guller et al., 2012; Rinn, 2012; Ukrainetz et al., 2010). Finally, an inherent user error or rather potential variation among different users may arise when delimitating ring width values from RD profiles (Figure 3.4).

3.5.2 The strength of resistance drilling (RD) and the effect of ring width on ring analysis

The strength of RD is the time saving ability on data sampling and subsequent ring analysis. On average, core sampling 30 trees and then performing stem core assessments can be done in time intervals of 200-250 working hours¹. Based on author's working time records, RD and subsequent ring analysis of the same sample size can provide reliable data on tree growth in half that time. In addition, when tree planting records are not available, estimated average growth rates and age from RD combined with measurements of tree attributes (DBH, height, crown width, crown height, etc) can be used to develop allometric equations for individuals planted in different growing conditions (Stoffberg et al., 2008; Troxel et al., 2013). Szewczyk et al. (2018) demonstrated that the electrically recording resistance drill IML-Resi E400 enables a quick, although approximate, tree age assessment as compared core sampling. The overall accuracy of RD to assess tree growth rate and age achieved in this study is comparable to that reported by Wang et al. (2003), Guller et al. (2012), Kraler et al. (2012) and Maxwell et al. (2011).

¹ Carolyn Copenheaver, Dendrochronologist, Virginia Tech University, USA, personal communication, 2017.

The lowest previously reported value for ring width delineation from RD graphs was 0.5 mm depending on wood anatomy and tree ring density differentiation (Rinn et al., 1996). However, as shown in Figure 3.4 we demonstrated that regardless of species and drilling axes, annual rings narrower than 1 mm were difficult to delineate on to RD profiles.

Recently, Szewczyk et al. (2018) revealed that the most accurate tree age assessments of three different urban trees were obtained from tree rings wider than 2 mm. The difficulty in identifying small rings was also reported by Kraler et al. (2012) and Guller et al. (2012). Drought events of 2-5 years might produce segments of narrow false and intra-annual rings making ring identification of Mediterranean tree species a hard task (Cherubini et al., 2003; Smith et al., 2001). In practical terms, this finding suggests that when tree growth pattern decreases for whatever reason (age, climatic variations, management practices, competition, etc) the accuracy of RD to assess annual ring width diminished.

Age-related growth trend also affected the suitability and reliability of RD for ring analysis. Across species, RD provided more accurate tree increment values for young trees (<30 years) while for older trees (≥ 60 years) its accuracy declined significantly. Tree rings of *Quercus* spp. formed early in the life are more clear and discernible than rings formed later (Leal et al., 2015; Marion et al., 2007). Therefore, as shown in Figure 3.5, it seems that RD may yield more reliable growth rate estimates for younger and healthier specimens in open grown conditions (e.g., <50 years old) when growth appears to be more uniform around the circumference and tree rings are usually thicker (Bartens et al., 2012; Ise et al., 2008; Sharapov et al., 2018).

3.5.3 Mean intercorrelation values, wood anatomy and cross-dating index

Cross-dating is a standard procedure within dendrochronology to verify the accuracy of annual increments estimates from paired core-sampled trees to further perform climate-growth analyses (García-Suárez et al., 2009; Mbow et al., 2013). As shown in Table 3.3, core measurements yielded significant mean intercorrelation indices (MI) (0.53-0.57) for all species, whereas, regardless of species, RD readings did not yield acceptable MI to perform cross-dating analysis of sampled trees (MI: 0.38-0.46). Calculated MI values are congruent with the species capacity to yield accurate and robust chronologies, referred to as the cross dating index (CDI) (Grissino-Mayer, 1993).

For instance, *Quercus*. spp. with a CDI=2 is the most suitable and assessed species in dendrochronology studies in both natural and urban settings (Catton et al., 2007; Gillner et al., 2013; Goldblum, 2010). Growth pattern of *Ulmus*. spp. with a CDI=1 has also been successfully cross-dated in parks and street of Helsinki, Finland and Melbourne, Australia (Helama et al., 2012; Nitschke et al., 2017). Finally, *P. x acerifolia*, a species with a CDI=0 has been subject to less growth-climate studies, presumably because its difficulty in ring boundary identification. However, other researchers recently demonstrated the feasibility of applying cross dating analysis in this species (Cedro et al., 2006; Gillner et al., 2014; Nitschke et al., 2017).

This study sampled trees from three different genera with very distinct wood anatomy features which in turn effected the ability of RD to capture tree annual growth pattern within species (Figure 3.7). Firstly, ring-porous genera such as oak (*Quercus* spp.) and Ash (*Fraxinus* spp.)

both have a distinct row of vessels occurring at the beginning of the growth ring (known as the early wood zone), therefore trees within these genera produce annual increments with clear and consistent boundaries in a cross-sectional view. Secondly, semi-ring porous genera, such as *Carya* spp and *Ulmus* spp. have some vessels formed at the beginning of the ring but also have smaller vessels distributed throughout the ring, thus the early wood zone is not as distinctive and consistent as the ring-porous genera. Finally, diffuse-porous genera, such as *Acer* spp., *Betula* spp. and *Populus* spp. have small vessels distributed throughout the ring hence obscuring ring boundaries and making ring identification quite difficult. *Platanus* spp. is included in this latter category (Downes et al., 2002; Plomion et al., 2001). The use of wood decay fungi has been seen to enhance annual ring detection in diffuse-porous species such as *A. pseudoplatanus*, *P. tremula* and *B. pendula* (Deflorio et al., 2005).

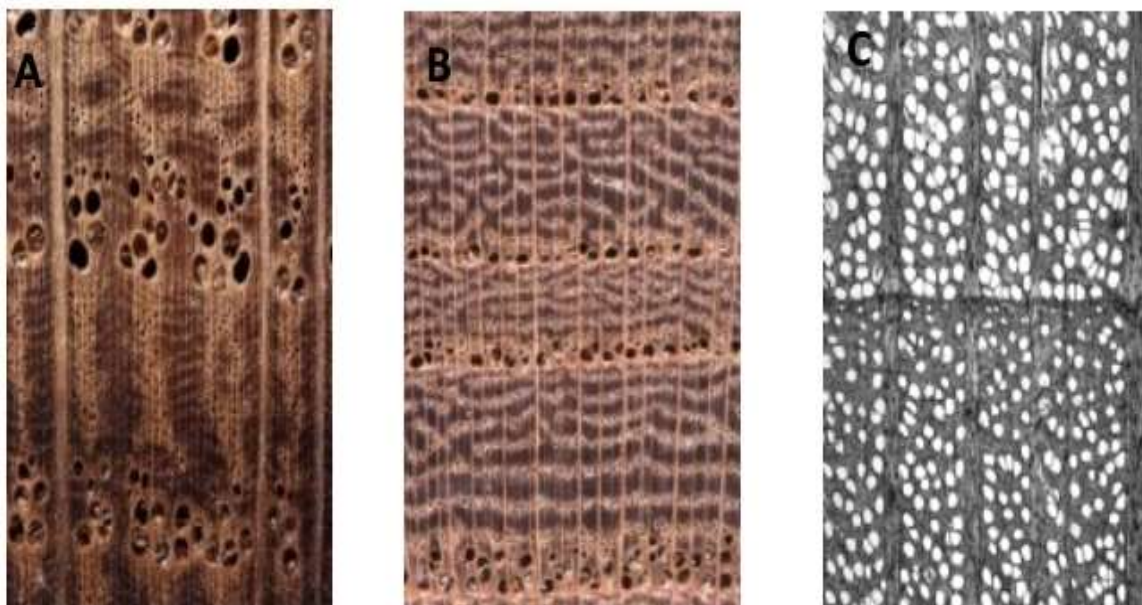


Figure 3.7. Ring-porous genera (A-*Quercus* spp.), semi-porous genera (B-*Ulmus* spp.) and diffuse-porous genera (C-*Platanus* spp) showing strong and no-association between the pores and the ring boundaries in a cross-section view. Sourced with permission from: *InsideWood-2017*. Published on the Internet. <http://insidewood.lib.ncsu.edu/search> [accessed on August-28, 2017]. The readers are advised to visit the website <http://insidewood.lib.ncsu.edu> for more details on the wood anatomy of sampled species.

3.5.4 Resistance drilling (RD) has limited use for climate-growth studies

In this study and as shown in Table 3.2, RD readings could not detect event years at individual tree level. Moreover, similarity indices of identified and shared event years between core measurements and RD were low. These findings framed the suitability and reliability of RD for assessing mean growth rates and age at population level only. Guller et al. (2012) reported significant differences between ring width values measured by a particular resistograph and those measured by core sampling at ring basis whereas mean ring width values of sampled populations were statistically similar.

In this study a tree increment within RD profiles was considered as the distance between the middle point of two consecutive peaks. This assumption means, however; that RD is sensitive to reaction wood and false rings which may cause a spike onto drilling profiles, leading to the recording of an incorrect annual ring (Downes et al., 2009; Oliva et al., 2012). A second issue limiting the application of RD for ring analysis is the presence of missing rings. During unusually poor growing years (due to drought, high competition or severe damage) a tree may not form xylem in all portions of the stem (Cherubini et al., 2003; Clark et al., 2007).

Dendrochronologists identify these missing rings by using visual aids and statistical matching of tree-ring widths, whereas the RD's user does not have visual or wood anatomy clues when marking ring width along RD profiles (Marion et al., 2007; Plomion et al., 2001; Szewczyk et al., 2018). In addition, urban trees undergo regular arboricultural practices, such as pruning, lopping and wounding causing strong signals in tree-ring series, including missing, false and wedging rings expressed as event years; which were difficult to identify on RD profiles (Clark et al., 2007; Downes et al., 2002). Although, RD has significant advantages over traditional increment borer methods in terms of lower tree damage and faster operation speed; available

‘ring analysis package’ of RD are unable to detect these features hence cannot yield reliable single tree growth patterns (Gao et al., 2017; Guller et al., 2012; Sharapov et al., 2018).

3.6 Conclusion

Resistance drilling (RD) is a fast, less-invasive and reliable way to assess the average growth rate and age of urban trees at population level but cannot reliably discern growth trends at individual tree level. Based on findings and statistical tests done, the research approach followed in this study provided a solid ground to use RD to rapidly assess growth trends and age of an urban tree population in a robust manner. However, since the RD device used in this study did not detect the inter-annual tree growth pattern to the same standard as stem core analysis, RD should not be used to replace dendrochronology when analysing climate-tree growth relationships, unless RD accuracy and precision can be improved and demonstrated.

This research, based on sound statistical tests and by sampling three different tree species, highlights the scope and limitations of RD for dendrochronology. The research approach applied here should be considered for testing the robustness of RD in other species and for future applications requiring tree level accuracy of growth ring measures. Overall RD appears to be the most suitable method for estimating the extent of wood decay in urban trees and as such will be the method used for comparison with tree vitality and internal decayed wood in the next experimental chapter.

Chapter 4. The overlooked carbon loss due to decayed wood in urban trees

4.1 Abstract

Decayed wood is a common issue in urban trees which deteriorates tree structure and vitality over time, yet its effect on biomass yield therefore stored carbon has been overlooked. The occurrence and extent of decayed wood in standing *Ulmus procera*, *Platanus x acerifolia* and *Corymbia maculata* trees was mapped in this study. The main stem of 43 trees was measured every meter from the ground to the top by two skilled arborists. All trees were micro-drilled in two to four axes at three fixed points along the stem (0.3 m, 1.3 m, 2.3 m), and at the tree's live crown. A total of 600 drilling profiles were assessed for decay. Descriptive statistics were used to summarize the occurrence and extend of decayed wood of sampled trees. Simple linear regression analysis tested the correlation of decayed wood (cm²) against a vitality index and stem DBH. Decay was more frequent and extensive in *U. procera*, than *P. acerifolia* and least in *C. maculata*. Decay was found to be distributed in three different ways in the three different genera. For *U. procera*, decay did appear to be distributed as a column from the base to the live crown; whereas, decay was distributed as a cone-shape in *P. acerifolia* and was less likely to be located beyond 2.3 m. In *C. maculata* decay was distributed as pockets of variable shape and size. The vitality index showed a significant but weak correlation with the proportion of decayed wood along the stem of *P. acerifolia* and *C. maculata* but not for *U. procera*. However, in *U. procera*, a strong and significant relationship was found between DBH and stem volume loss ($R^2 = 0.8006$, $p = 0.0046$, $n = 15$). The actual volume loss ranged from 0.17-0.75 m³, equivalent to 5 % to 25% of whole stem volume. Carbon loss due to decayed wood for all species ranged between 69 to 110 kg per tree. Based on model's calculation, tree stem volume of *U. procera* trees with DBH ≥ 40 cm needs to be discounted by a factor of 13% due to decayed wood regardless of tree vitality. Decayed wood significantly reduced stem volume of *U. procera* trees and needs to be considered to better assess its carbon storage potential citywide.

Key words: urban tree benefits, decay assessment, tree vitality, carbon storage, Melbourne.

4.2 Introduction

The investigations in this chapter focus on the quantitative measurement of the extent of wood decay in individual standing trees, so the amount of wood decay can be compared to tree vitality and further factored into carbon stock calculations. Instruments used for quantifying wood decay vary greatly in the principles on which they function, hence resistance drilling was chosen as a cost-effective, suitable and reliable method to quantify decay in this investigation. The aim of the present study was to detect the occurrence and calculate the extent of decayed wood along the stem of three common species (*Ulmus procera*, *Platanus x acerifolia*, *Corymbia maculata*) growing in the city of Melbourne.

Urban trees are valuable assets for modern cities and they deliver significant functions and benefits which enhance city liveability (Davies et al., 2011; McPherson et al., 2013; Nowak et al., 2008). The various function and benefits of urban forests have been well documented elsewhere (Baumgardner et al., 2012; Escobedo et al., 2008; Livesley et al., 2016; Nowak et al., 2002b). Numerous researchers and arborists agree that the urban landscape imposes several adverse environmental conditions impacting tree survival, growth, vitality and longevity of urban forests (May et al., 2013; Sjöman et al., 2012; Vogt et al., 2015). While many functions and benefits of urban forests are linked to tree size, height and appearance of the crown, stored carbon is mostly a function of tree bole (Peper et al., 2014; Troxel et al., 2013). In the broadest sense, the bigger and healthier the tree the greater the carbon storage potential of urban trees over time (Dwyer et al., 2003; McHale et al., 2007; McPherson et al., 2012).

During the last decade, there has been considerable research effort to quantify stored carbon of urban forests worldwide (FAO, 2013; Poudyal et al., 2011; Schnell et al., 2015). Urban trees are credited as suitable tools to reduce carbon emissions within cities, therefore accurate estimations of above-ground biomass which consider volume loss due to decayed wood is key in accounting for their carbon storage potential (Chave et al., 2009; Frank et al., 2018; Koeser et al., 2016). When a tree is decayed its standing biomass decreases and its carbon stock declines, therefore, decayed trees may become a source of carbon emissions if sequestration rate is slower than the C loss rate, hence affecting the net carbon balance of urban forests (Brazee et al., 2010; Cousins et al., 2015; Luley et al., 2009; Stephenson et al., 2014).

Although, stored carbon in urban forests is relatively small in scale compared to forest stands and plantation trees, the proximity of urban forests to emission sources mean that their carbon storage potential should not be neglected (Frank et al., 2006; Moore, 2009; Raciti et al., 2014). Researchers have attempted to calculate and value carbon stocks in urban trees ranging from single species, through to city-wide urban tree populations (Brack, 2002; Davies et al., 2011; Dobbs et al., 2011b; Kuittinen et al., 2016; McPhearson et al., 2013; Nowak et al., 2013; Russo et al., 2014; Stoffberg et al., 2010; Strohbach et al., 2012b).

Approaches and methodologies aimed at calculating standing biomass, therefore stored carbon, vary widely in their suitability, reliability and replicability (Fatemi et al., 2011; Lefsky et al., 2008). In addition, most stored carbon studies rely on forest-based allometric equations developed in the United States of America (USA), consequently, when applied outside their defined range of diameter, climatic region and scale of use, these equations yield less reliable estimates (McHale et al., 2009; McPherson et al., 2012).

The development of species-specific allometric equations based on destructive sampling provides accurate estimations of carbon pools in trees (Jenkins et al., 2004; McHale et al., 2009). Although feasible, destructive sampling is not always practical in an urban context and alternative techniques are needed. Non-destructive methods such as terrestrial LiDAR, Ariborne LiDAR, as well as partially-destructive (non-fatal) sampling methods; namely randomized branch sampling (RBS); are now available (Dobbs et al., 2011b; Jung et al., 2011; Shrestha et al., 2012). While the utilization of remotely sensed data to capture urban tree biomass is cost-effective, both early and recent research has shown lower accuracy than those calculations based on stem diameter measurements and allometric equations (Alonzo et al., 2016; Ardila et al., 2012; Hecht et al., 2008; Lee et al., 2016; Omasa et al., 2007; Raciti et al., 2014; Shrestha et al., 2012; Xu et al., 2013). Finally, Chirici et al. (2014) tested RBS against full tree measurements and argued that unless a minimum of three paths are followed, above-ground biomass estimations based on RBS can yield an estimation error of up to 300%.

Little is known about biomass loss due to decay wood in both natural and urban forests (Helama et al., 2008; Hutrya et al., 2011; Terho et al., 2008). Recently, Cousins et al. (2015) pointed out a reduction of up to 18 % the amount of stored carbon in natural forests as a result of decayed wood. Similarly, Brazee et al. (2010) estimated the actual carbon stock in a decayed portion of a tree as being only 57% compared to that calculated for a decay-free stem.

The study conducted by McPherson et al. (1997), which is the foundation of most published above-ground biomass and stored carbon calculations, sampled and assessed for decay only 30 trees out of 8000+ measured citywide. Decay was evident in 10 of those trees but was considered “not significant” to be included as a detrimental factor of biomass yield when

developing allometric equations. Instead; a “discount” factor of 0.8 was proposed to account for differences in biomass yield between forests and urban trees. As a result, currently used model to quantify stored carbon in urban trees do not take into account differences in biomass loss due to internal decay (Frank et al., 2018; Johnstone et al., 2010b; Koeser et al., 2016; Marra et al., 2018).

Decay, and the resulting hollows, are usually linked to ageing urban trees, yet previous research has documented a high occurrence of decay in trees of various size growing in a wide range of urban settings (Eisner et al., 2002; Koeser et al., 2016). For instance, Luley et al. (2009) reported high occurrence of wood decay in *Acer* spp. trees of different diameters (30-80 cm DBH) which damaged up to 25% of a tree’s cross-sectional area. The authors claimed that decay can take place early in tree’s life but is most severe in larger (and therefore older) trees ranked as poor compartmentalizers of decay.

Likewise, Terho et al. (2008) examined the stage and extent of wood decay in 181 park and street trees and found heavily decayed trees (between 70-80 % of the trunk’s cross-sectional area) specially those large individuals. Recently, Koeser et al. (2016) examined the amount of decay presented in +400 *Quercus* spp. (DBH: 25-157 cm) and reported a significant proportion (58 %) of sampled trees as being decayed or having trunk’s hollow of considerable size. Although most published studies were conducted on street trees already assessed as hazardous and they do not represent unbiased sample, reported findings are suggestive of a frequent and severe stem wood decay in urban trees.

The science of detecting and quantifying decay in trees has evolved considerably over time. Decay can be detected from field visual assessment and basic screening conducted by experienced arborists, and for those trees deemed ‘unsafe’ the level of decay within cross-sectional discs can be evaluated from harvested trees (Koeser et al., 2016; Pearce, 2000), however; this approach requires whole tree destructive harvesting (Johnstone et al., 2012; Wang et al., 2008). Visual inspections and basic screening can be reliable ways to predict the presence of internal decay and hollows, but are limited in calculating the extent of decayed wood in standing trees (Koeser et al., 2016; Lin et al., 2015; Terho et al., 2005).

New equipment and approaches may provide opportunities to more accurately assess the existence, distribution and extent of wood decay in urban forests without the need for destructive harvesting (Castello et al., 1999; Gilbert et al., 2016; Larsson et al., 2004; Leong et al., 2012; Lin et al., 2015). These new methods vary considerably in their invasiveness, easy to use, interpretation and reliability (Gao et al., 2017; Johnstone et al., 2010a; Wessels et al., 2011). Among those methods, stem core sampling is the most common non-destructive technique which allows a rapid assessment of decay in standing trees, yet coring holes left may play a role for decay infection (Helliwell, 2007; Kersten et al., 2005; Weber et al., 2006). Less-invasive portable drills have been widely applied in urban contexts with consistent results (Gao et al., 2017; Koeser et al., 2016; Leong et al., 2012; Luley et al., 2009; Wang et al., 2008).

Assessing wood decay is significant element in arboriculture aimed at maintaining tree stability and safety within public spaces (Gilbert et al., 2004; Larsson et al., 2004; Sterken, 2006). In this regard, an expert system which combines the “assessment” of drill outlines and the widely accepted model “Compartmentalization of Decay in Trees” (CODIT) was developed and

proposed as a reliable way to locate and calculate wood decay (Johnstone et al., 2007). Moreover, visual tree vitality coupled with decay assessment is a well established approach aimed at documenting decay incidence in urban trees (Dobbertin, 2005; Johnstone et al., 2013).

In this Chapter, the following research questions were addressed: 1) Does decayed wood occur in a similar pattern along the stem of tree species under study? 2) Does decayed wood affect only in large-mature trees within each species evaluated? and, 3) Does a vitality index may be used to explore the relationships between tree vitality and severity of wood decay among sampled species?

4.3 Materials and Methods

4.3.1 Study site

This research was carried out in the City of Melbourne, Australia (Latitude 37°48'S, Longitude 144°57'E). Citi's climate is "temperate" with uniform annual precipitation of 656 mm. Average annual temperature is 19.7°C with the highest value recorded in February (25.7°C) and the lowest in July (13.4°C) (www.bom.gov.au). The City of Melbourne has a population of +100000 residents over 3760 ha of highly urbanized land. The city centre contains 486 ha of parks, 286 ha built space and 1112 ha of roads (City of Melbourne, 2012). Melbourne's council maintains more than 70,000 trees in both parks and streets. The City of Melbourne's urban forest has an average tree density is 26.5 ha⁻¹ (±18 ha⁻¹) with a canopy cover of 12.3% (3-20%). The four most common species are *Eucalyptus camandulensis*, *Platanus x acerifolia*, *Ulmus* spp. and *Corymbia maculata* which together accounted for 29% of tree population (Dobbs et al., 2013). An assessment undertaken on 35 0000 street and park trees indicated a high

proportion (23%) reaching the end of their life expectancy within 10 years. Regular tree care of sampled trees includes lifting of canopies to remove low branches, pruning, topping and mulch application if needed (City of Melbourne, 2012; Moore, 2009).

4.3.2 The CODIT model for describing and assessing wood decay

A framework used in this study is the CODIT model (Compartmentalization of Decay in Trees) described by Shigo (1965) which states that decay spreads faster in a longitudinal direction (up or down the stem) rather than in a cross-sectional direction (the diameter). The CODIT's model defines that trees have four walls which isolate decay with variable rate of success. The CODIT model also describes that tree's "capacity" to isolate decay is dictated by its vigour and vitality over time. The CODIT models' theory and premises were then applied as part of an "expert system" devised by Johnstone et al. (2007) to assess wood decay in standing trees.

4.3.3 Tree measurements and vitality assessment

A total of 43 trees consisting of three dominant species (*Ulmus procera*, *Platanus x acerifolia* and *Corymbia maculata*) in the Melbourne's urban forest were measured and assessed for vitality in summer 2015 (January-April). These trees were situated in parks, and general had stems >40 cm in diameter and height between 15 and 20 m (Table 4.1). Trees were selected in conjunction with two skilled arborists and based on the following criteria: 1) species natural canopy structure, 2) located where a pedestrian risk was low, 3) trunk not obviously damaged due mechanical injury and, 4) safe tree climbing was possible. Age structure of sampled trees varied widely according to species. Most *U. procera* trees evaluated were over mature planted between 1900-1920 but a few juvenile trees were also sampled (2000-2010). *P x acerifolia* trees

measured in this study were planted during 1950-1960 and included both mature and juvenile trees (1990-2000). *C. x maculata* measured tree were juvenile and mature individuals planted during 1970-1980 (City of Melbourne, 2012). The range of age, tree diameter, wood properties, and vitality index of evaluated trees is shown in Table 4.1.

Table 4.1 Number of individuals, tree attributes and wood properties of three urban species (*Ulmus procera*, *Corymbia maculata*, *Platanus x acerifolia*) included in the study.

<i>Variables/Species</i>	<i>U. procera</i>	<i>C. maculata</i>	<i>P. x acerifolia</i>
No. of trees	15	15	13
DBH (cm)	80.6 ± 14.8	64.3 ± 24.7	70.2 ± 30.2
Tree height (m)	14.8 ± 3.2	17.3 ± 3.4	17.5 ± 6.5
Stem volume (m ³)	3.6 ± 1.8	5.8 ± 4.7	3.5 ± 2.5
Vitality Index*	20 (17-22)	22.5 (19-25)	23.5 (20-25)
Age class	Over mature	Mature/Juvenile	Mature/Juvenile
Specific density (g/cm ³)**	0.53	0.62	0.57
Carbon content (%)***	46.32	49.63	49.97

*Values in parenthesis represent the range of vitality index recorded for each species. ** Species-specific wood density values reported for natural stands in the USA (Miles et al., 2009). *** Average value for hardwood species (Lamlom et al., 2003).

Tree vitality was visually assessed (score 1 to 25) following a method devised by Johnstone et al. (2012). The method incorporates a score for crown position in relation to other trees, crown size, crown density, the number of dead branches and epicormic growth. Vitality index of sampled trees included individuals with medium vitality (15 points) to high vitality (up to 25 points). Tree vitality assessment was done during the 2014-2015 growing season when trees exhibited full canopy foliage (Figure 4.1).

4.3.4 Stem volume calculation

The main stem and branch taper diameter of each tree was measured (using a diameter tape) every metre from the ground to the top by two independent skilled arborists. All measurements were recorded in the field in cm. The top of the tree was defined as the stem/dominant branch reaching a diameter greater than 5 cm within the canopy. The main stem volume of each tree was then calculated using the Smalian equation (Dobbs et al., 2011b):

$$V = (Ga + Gb)/2 * L$$

Where g is the cross-sectional area of the lower (Ga) and the upper (Gb) section of the stem, L is the length of the stem in meters, and V is the volume of the stem expressed in m^3 . The Smalian's formula states that the volume of a log can be closely estimated by multiplying the average of the cross-sectional areas of the two log ends by the log's length.

4.3.5 Tree stem micro-drilling

Trees were micro-drilled using an IML PowerDrill® with the following specifications: diameter needle shaft: 1.5 mm, diameter needle tip: 3.0 mm and 40 cm in length. The drill feed speed (penetration) and needle speed (rotation) was adjusted according to species wood density (www.imlaustralia.com). Device defined settings were 25 cm/min and 5000 rpm for *C. maculata*, 100 cm/min and 3000 rpm for *U. procera* and 50 cm/min and 3500 rpm for *P. x acerifolia*. All trees were micro-drilled at three fixed points (base-0.3 m, DBH-1.3 m, trunk-2.3 m) and a fourth point at the tree's live crown position. Taper diameter was taken from each point to calculate its corresponding cross-sectional area. At each point trees were micro-drilled

at between two to four axes, depending upon stem diameter at that given point. Trees with diameter ≤ 80 cm were micro-drilled in two perpendicular axes (N, W); for those trees with diameter greater than 80 cm, three to four drilling axes were taken (N, E, S and W). The IML PowerDrill[®] was evenly positioned for tree drilling at each position along the stem.

4.3.6 Terms and definition used for decay assessment

- ***Decay:*** the process by which wood is broken down by microorganisms into simpler forms to provide nutrients for their survival (Harris et al. 2004). Decay result in wood strength loss (Kane et al., 2004; Larsson et al., 2004).
- ***Wood decay:*** defined as wood displaying clear changes in texture, structure, and color, that is, decay from intermediate stage through to advanced decay (Harris *et al.* 2004).
- ***Intermediate decay:*** is a stage of decay where wood shows a decreased density as a result of degradation by fungi; hence wood structure starts to deteriorate (Harris *et al.* 2004).
- ***Advanced decay:*** In the advanced stages of decay wood becomes fibrous or powdery and the wood structure is drastically altered or non-existent (Harris *et al.*, 2004).
- ***Decayed wood:*** defined as section within RD profiles showing significant “yield” on the graph in relation to the rest of the trace and/or lacking clear “peaks” associated with growth increments (Johnstone et al., 2007; Koeser et al., 2017).
- ***Absence of wood:*** defined as a section within RD profiles showing no wood resistance in relation to the rest the trace (Johnstone et al., 2010b). Absence of wood results in tree hollowness (Luley et al., 2009).

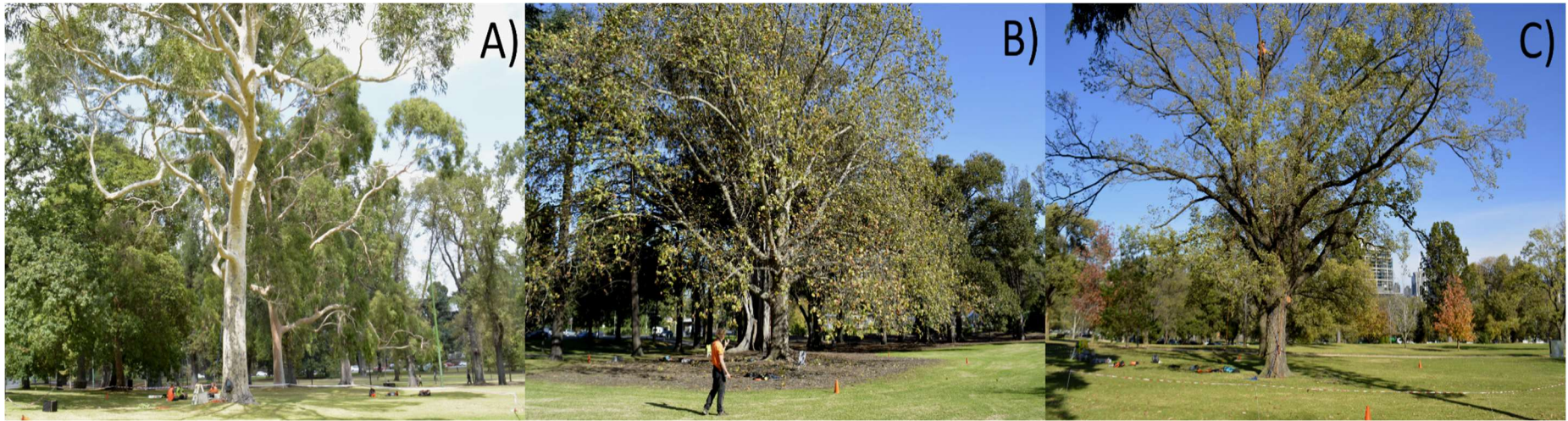


Figure 4.1. Overview of sampled trees of different size class and tree vitality index (VVI): A) *Corymbia maculata*, VVI= 25, B) *Platanus x acerifolia*, VVI=22 and C) *Ulmus procera*, VVI= 21.5. (Photos taken by Luis Orozco Aguilar).

4.3.7 Assessing wood decay

In this study, a total of ~600 drilling profiles were used to assess decay on 43 sampled trees. Decay assessment was done as follows 1) for each drilling profile, the “average curve” function of the IML PowerDrill® was activated to capture the overall trend in wood resistance, 2) segments with amplitude value of $\leq 5\%$ lower than the average curve were considered as decayed wood. A decline of 5% amplitude within RD profiles might signifies a decrease in wood density in the range of 100-150 kg/m³ (Cousins et al., 2015; Frank et al., 2018; Isik et al., 2003; Oliveira et al., 2017). Those segments with amplitude value of 0% were recorded as absence of wood, 3) only segments of decayed wood, segments of absence of wood and sections showing absence of “annual rings” greater than 1 cm were considered significant for decay assessment, 4) both “pockets” and larger areas of decay wood identified on each drilling profile were not considered linear but in fact circular or rounded. Thus, the area of decayed wood (expressed in cm²) for each drilling point was calculated using the formula of either a circle or ellipse using AutoCAD (2017), 5) to account for volume loss, both categories of decay (decayed wood + absence of wood) were added as decayed wood within a single tree. The protocol to assess decay followed in this study is in line with guidelines proposed by Mattheck et al. (1997) and in accord with the approach developed by Johnstone et al. (2007). A summary of the steps taken in the process is presented in Figure 4.2

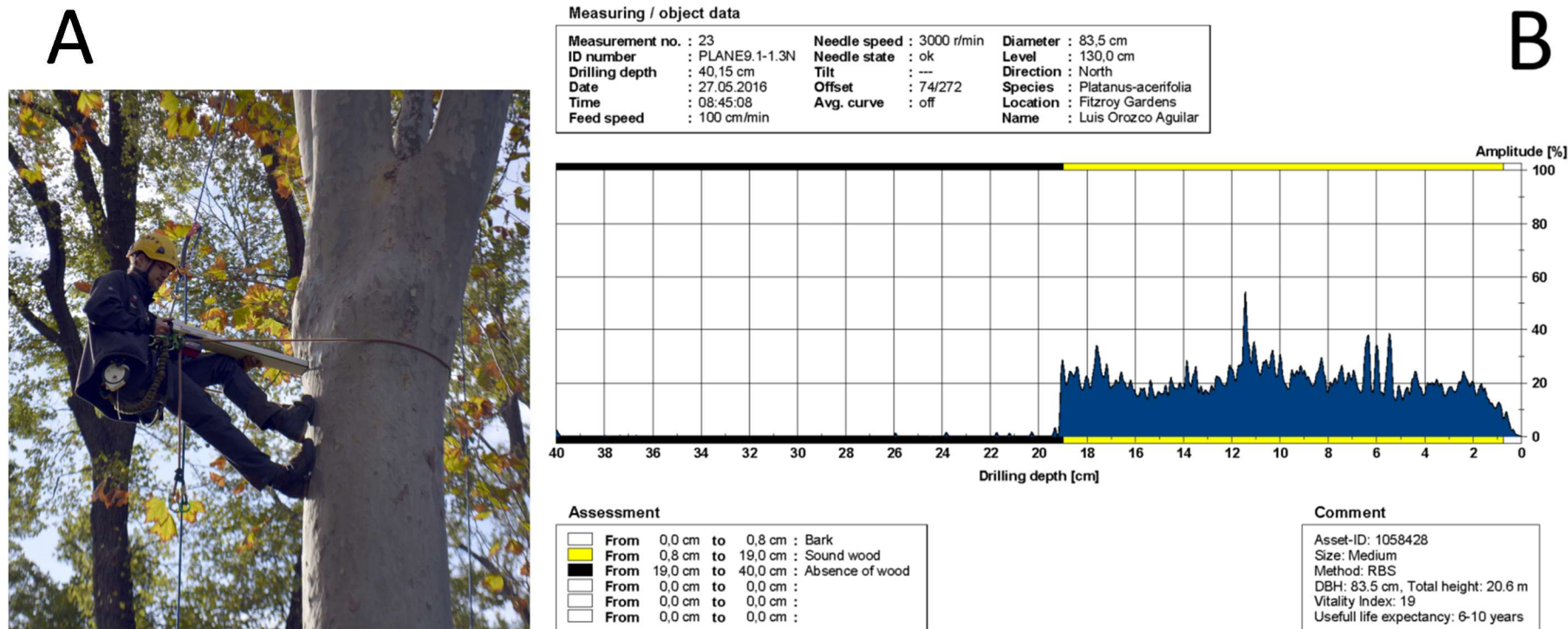


Figure 4.2 Overall methodology followed in this study to assess the occurrence and calculate the extent of decayed wood along the trunk of *Platanus x acerifolia*. The left picture (A) shows the arborists micro-drilling at the tree's live crown position. The right picture (B) displays the decay assessment done using IML PowerDrill® tools. The drilling profile shown here has 40 cm in length and corresponds to the live crown position (N axis). Drilling height and stem diameter at this position were 5.3 m and 83.5 cm, respectively. (Photo taken by Luis Orozco Aguilar).

4.3.8 Decayed wood area and volume loss calculation

Decayed area (cm²) was calculated for each drilling point (Base, DBH, Trunk, and live crown), then to convert from decay area to decay volume (m³) the equation below was applied:

$$VD_{TOTAL} = [(AD_{BASE} + AD_{DBH})/2 * 1.3 \text{ m}] + (AD_{DBH} + AD_{Trunk})/2 * 1 \text{ m} + (AD_{Trunk} + AD_{crown})/2 * L]$$

Where: VD_{TOTAL} is the total volume of decay (m³), AD_{BASE} is the cross-sectional area of decay at the base, AD_{DBH} is the cross-sectional area of decay at DBH point, AD_{TRUNK} is the cross-sectional area of decay at 2.3 m, AD_{CROWN} is the cross-sectional area of decay at the live crown position and L is the length (m) of the log between the trunk and the crown's point. Log's length varied from 1.3-3.3 m according to tree size and species' canopy structure.

Volume loss estimated for each species/tree was then subtracted from whole tree volume (m³) per tree previously calculated. Converting from volume (m³) to carbon mass was determined by multiplying wood volume (m³) x carbon factor. The carbon factor = Specific gravity x 1000 kg (weight of 1 m³ of water) x ratio of percent C of the species (Brazee et al., 2010). Published specific gravity and % C values were used in the calculation of carbon loss (Lamlom et al., 2003; Miles et al., 2009; Zhang et al., 2009).

4.3.9 Data management and statistical analysis

Descriptive statistics were generated to summarize the extent of decay along the stem of sampled trees. Simple linear regression analysis tested the correlation between decayed wood against a vitality index and stem DBH. Those trees severely decayed due to arboriculture treatments (heavy pruning) or branch loss due to strong winds or mechanical injury were

considered as outliers, therefore these individuals were not included in regression tests against vitality index but were taken in to account to calculate the extent of stem decay.

An explorative analysis was carried out seeking to identify variables which could predict decayed volume loss in *U. procera*. This species was selected since mapped wood decay was widespread along the stems of sampled trees. A linear model was fitted to predict actual volume loss in standing *U. procera* trees. In addition, a correlation matrix was devised to visually explore potential effects that tree and stand attributes may have on the predictability of volume loss in standing trees. Variables selected for correlation analysis were DBH (cm), total height (m), crown height (m), crown surface (m²), stem volume (m³), competition status (number of trees within 10 m radius) and vitality index. Simple linear regression tested the correlation between volume loss (m³), vitality index and stem DBH per species. All statistical analysis was performed in R (R Core Team, 2015).

4.4 Results

4.4.1 Occurrence of decay among species

In the whole sample of 43 trees, 37 trees (87%) showed some level of decay, 20 trees (47%) showed decayed wood and 12 trees (27%) showed absence of wood internally. Significant variation was found in the cross-sectional area affected by decay among sampled species. Decay was more frequent and extensive in *U. procera*, than *P. acerifolia* and least in *C. maculata*. Mean decayed cross-sectional area at the DBH point for *U. procera*, *P. x acerifolia* and *C. maculata* was 983 cm² ($\pm$ 625.2), 359.5 cm² ($\pm$ 545.2) and 255.6 cm² ($\pm$ 234.4),

respectively. In *U. procera*, cross-sectional areas of decay at the base, DBH and trunk (2.3 m) positions was statistically different from that recorded for the other two species. The cross-sectional area of decayed wood at the stem base was twice as large in *U. procera* than in the other two species. Decayed cross-sectional area at the DBH and trunk level was approximately 50% greater in *U. procera* than in the other two species (Figure 4.3).

The maximum proportion of cross-sectional decayed area recorded at the DBH point ranged from 15.6% to 29.2% for all species. The decayed cross-sectional area at the live crown position showed a decreasing trend according to sampled species. The extent of decayed at crown position was greater in *P. x. acerifolia*, followed by *U. procera* and least in *C. maculata*. In both, *C. maculata* and *P. x acerifolia* trees, the extent of decay wood at the stem and live crown position was lower than 10%. In these last two species, decay was only present at the crown of those individuals that had been severely pruned or had broken branches within their canopy. Appendix 1 provides a detailed summary of the extent of decay along the stem of sampled tree species.

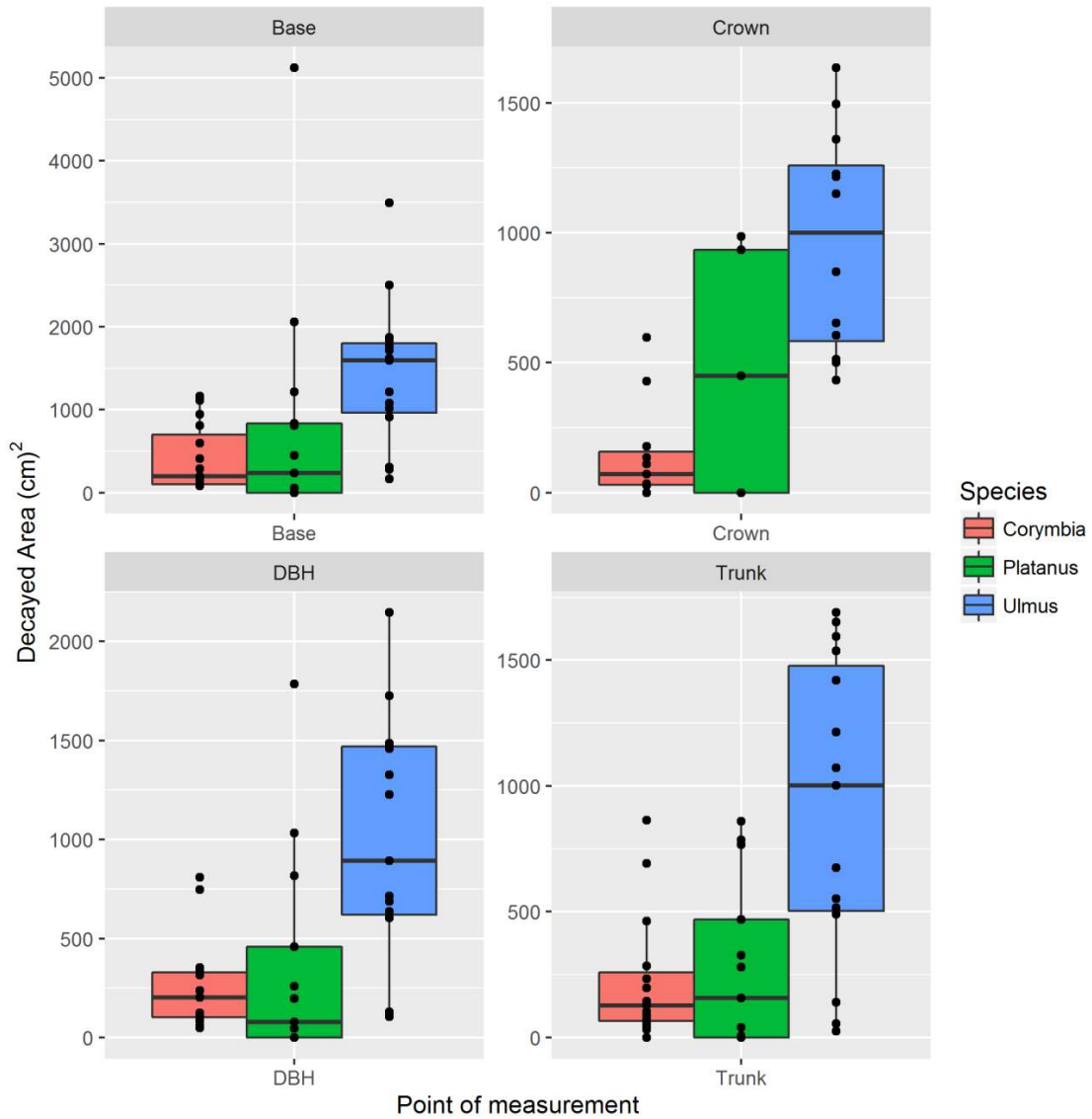


Figure 4.3. Box plots of the cross-sectional area of decayed wood in urban trees (*Ulmus procera*, *Platanus x acerifolia*, *Corymbia maculata*) growing in the city of Melbourne, Australia. Decayed wood was measured at four points up the stem: Base= 0.3 m above ground, DBH= 1.3 m, Trunk= 2.3 m and Crown+ variable mid-crown position (3.3-6.8 m).

4.4.2 Decay distribution within species

Decayed wood was found to be distributed in three different ways in the three-species evaluated. In *U. procera*, decay was distributed as a column from the base to the live crown point, affecting on average 17.5% ($\pm 6.2\%$) the stem cross-sectional area. In contrast, in *P. acerifolia*, decay wood was distributed in a cone-shape pattern affecting on average 7.5% ($\pm$

2.3%) the cross-sectional area from the base to the trunk position (2.3 m) (Figure 4.3). In *C. maculata*, pockets of decayed wood of variable shape and size were distributed throughout the stem affecting on average 6.7% ($\pm 1.3\%$) the stem cross-sectional area from the base to the trunk position. Although, the distribution pattern of decay of *C. maculata* and *P. x acerifolia* was different, average values of decayed wood along the trunk of both species were similar and ranged between 6% - 9%.

4.4.3 Relationship between vitality index and decayed wood

No significant relationships were found between a visual vitality index (VVI) and the proportion of decayed wood along the stem of *U. procera* sampled trees (Figure 4.4). This finding suggests that wood decay is not correlated with tree vitality in *U. procera* and may occur even in visually healthy standing trees within the genera. However, in *P. x acerifolia*, the VVI showed a significant and moderate relationship with the proportion of wood decay at the base (0.3 m), DBH (1.3 m) and trunk (2.3 m) positions (Figure 4.5). Finally, there was a significant but weak relationship between VVI and the proportion of decayed wood at DBH (1.3 m) position of *C. maculata* sampled trees (Figure 4.6). Overall, these findings suggest that a low to moderate VVI seems to be indicative of the presence of decay in standing *P. x acerifolia* and *C. maculata* trees.

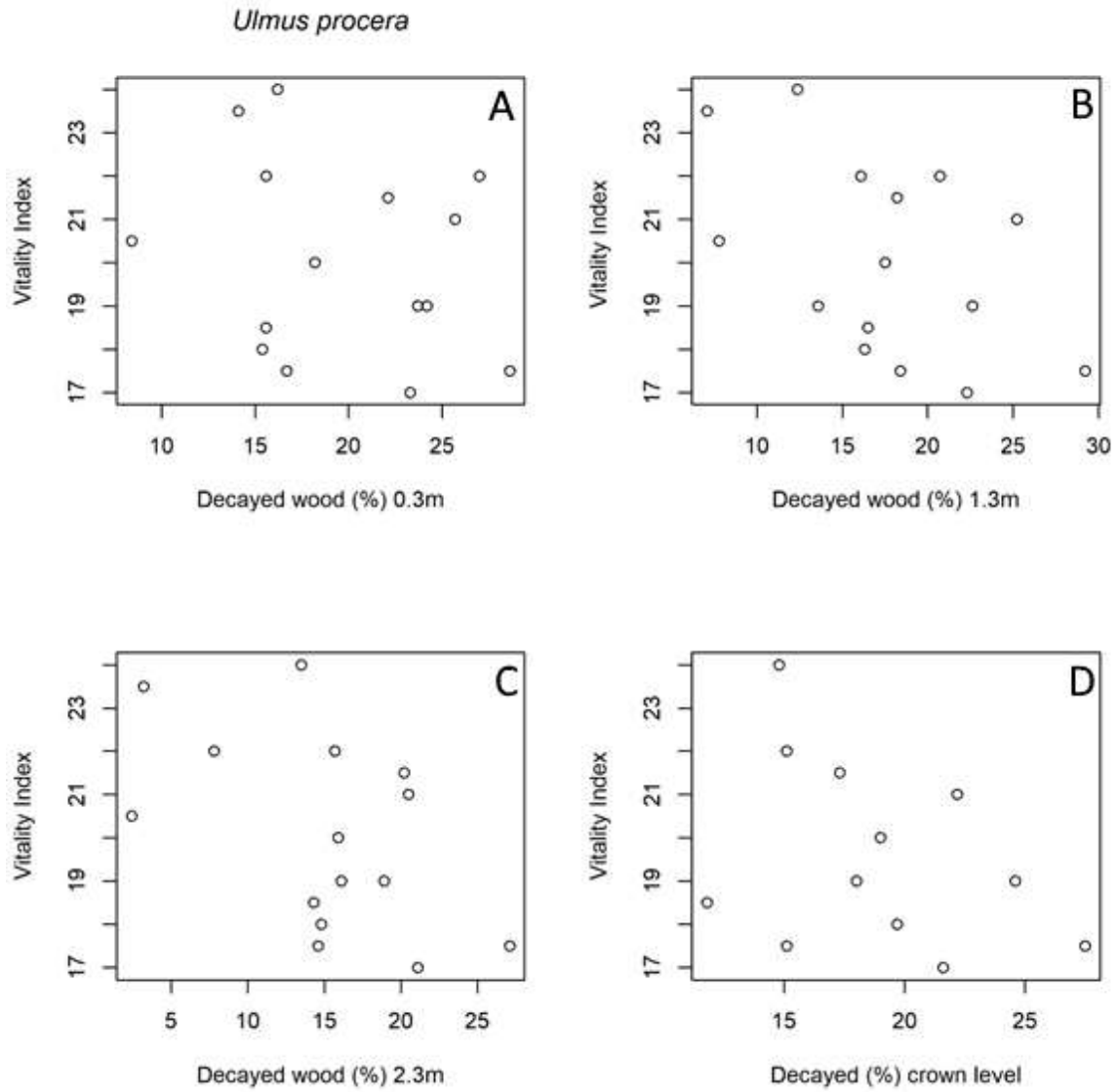


Figure 4.4. Tree vitality index versus the proportion of decayed wood (%) along the stem of *U. procera* trees in parks of the city of Melbourne, Australia. Regression values and related statistics were: (A)-Base: $R^2 = 0.0568$, $p = 0.3924$, $n = 15$. (B)-DBH: $R^2 = 0.2447$, $p = 0.0608$, $n = 15$. (C)-Trunk: $R^2 = 0.2571$, $p = 0.0536$, $n = 15$. (D)-Crown: $R^2 = 0.1329$, $p = 0.2441$, $n = 12$.

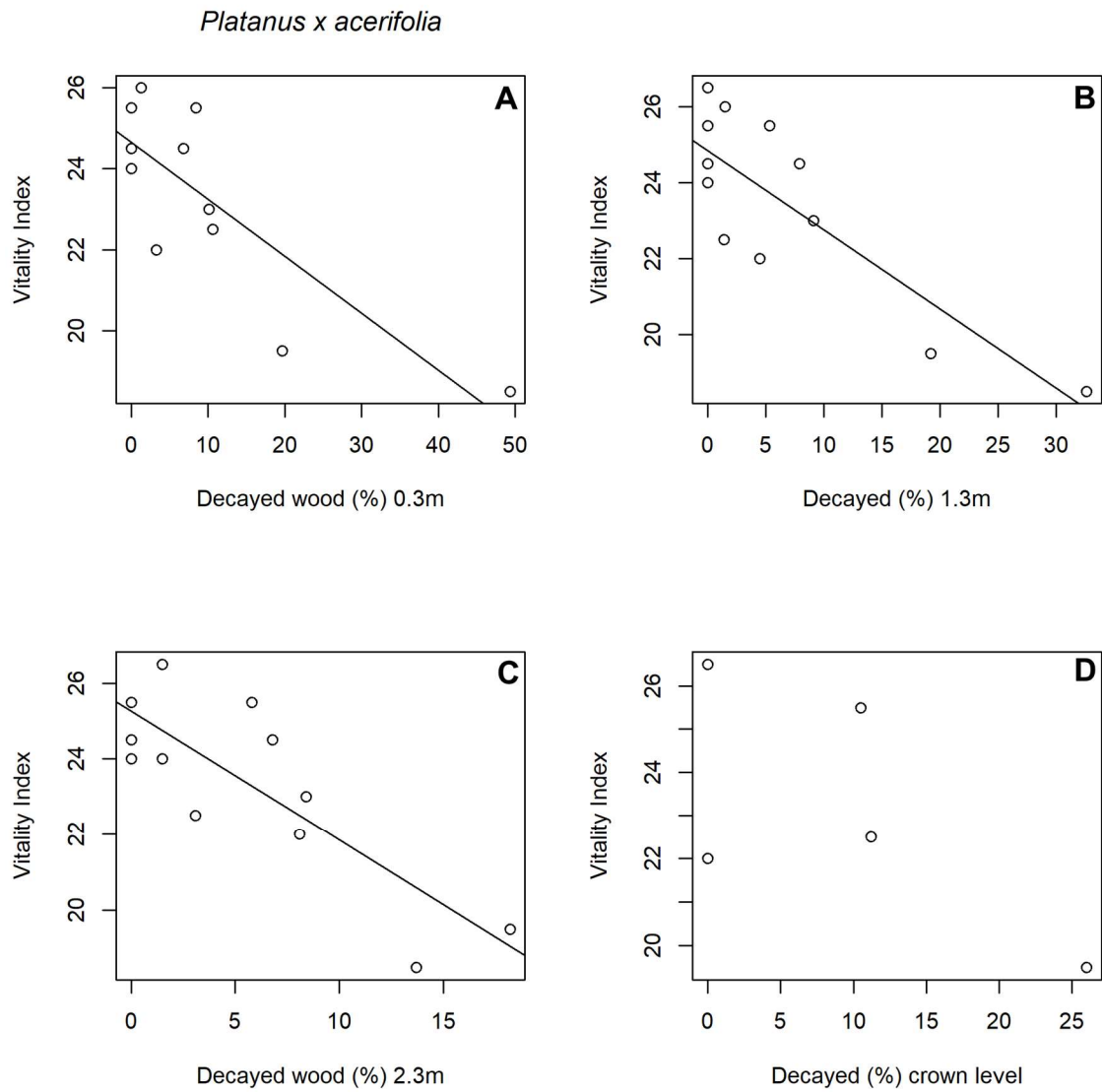


Figure 4.5 Tree vitality index versus the proportion of decayed wood along the stem of *P. x acerifolia* trees growing in parks of the city of Melbourne, Australia. Regression values and related statistics were: (A)-Base: $R^2 = 0.6628$, $p = 0.0010$, $RSE: 1.564$, $n=15$, (B)-DBH: $R^2 = 0.6422$, $p = 0.0007$, $RSE: 1.975$, $n=15$ (C)-Trunk: $R^2 = 0.6803$, $p = 0.0005$, $RSE: 2.201$, $n=15$, (D)-Crown: $R^2 = 0.4415$, $p = 0.2190$, $RSE: 2.0.73$, $n=7$.

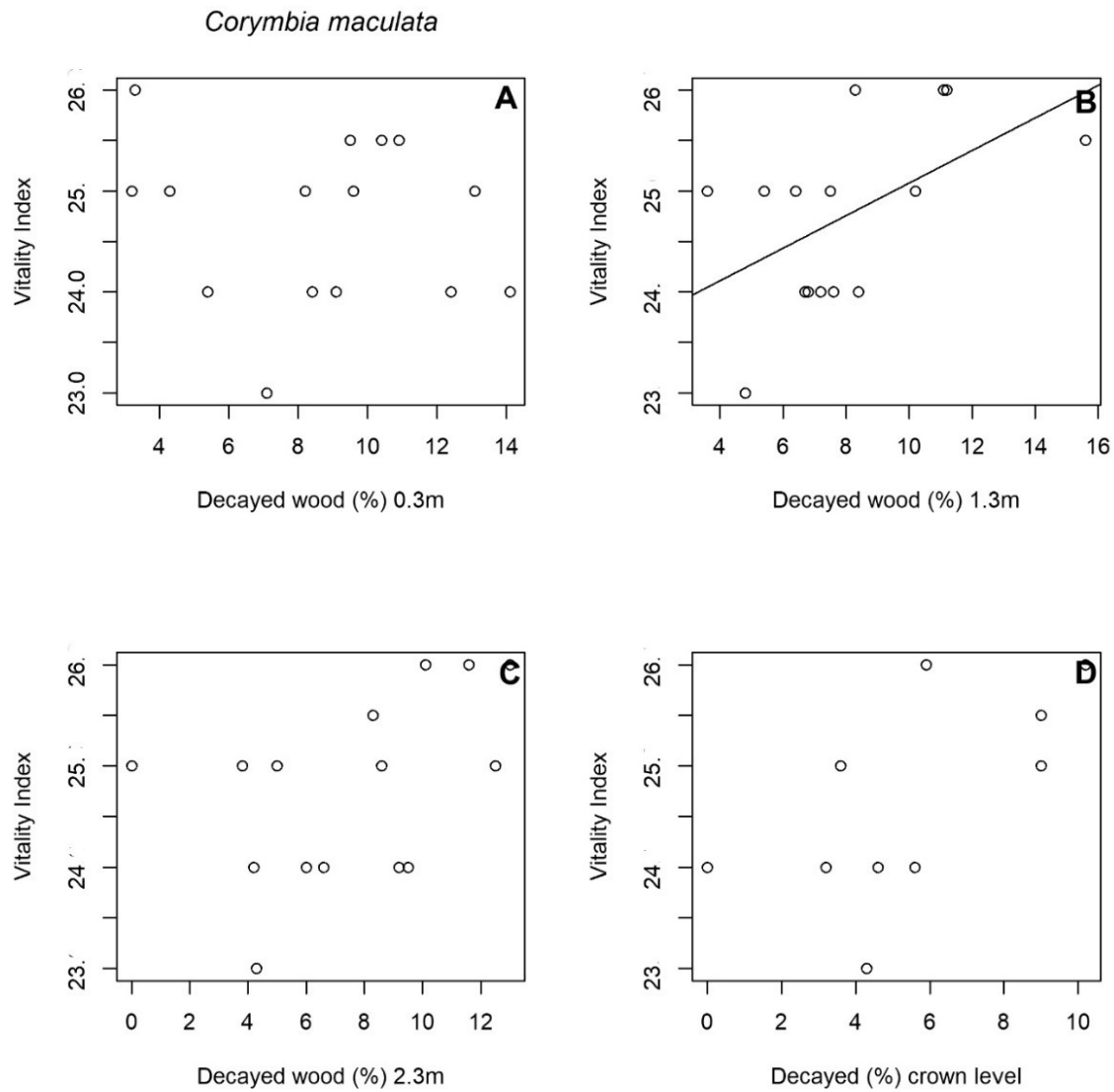


Figure 4.6. Tree vitality index versus the proportion of decayed wood along the stem of *C. maculata* trees growing in parks of the city of Melbourne, Australia. Regression values and related statistics were: (A)-Base: $R^2 = 0.07379$, $p = 0.1393$, $RSE: 1.158$, $n=15$, (B)-DBH: $R^2 = 0.3037$, $p = 0.0351$, $RSE: 1.086$, $n=15$, (C)-Trunk: $R^2 = 0.1741$, $p = 0.1303$, $RSE: 1.324$, $n=15$, (D)-Crown: $R^2 = 0.3531$, $p = 0.0538$, $RSE: 1.417$, $n=10$.

4.4.4 Stem volume loss

The absence of wood because of decay significantly reduced tree stem volume of all species examined. Mean decayed volume loss varied from 0.25 to 0.46 m³, equivalent to 5 % to 13.8% of the actual stem volume per tree. Volume loss was more frequent and extensive in *U. procera*, followed by *C. maculata* and least in *P. acerifolia*. In *U. procera* the proportion of volume loss along the stem (13%) was twice as large than the other two species whereas mean proportion of stem volume loss for *P. acerifolia* and *C. maculata* was less than 10%. Total volume loss calculated for all species ranged from 0.17-0.75 m³, equivalent to 5 % to 25% of the tree stem volume (Table 4.2). Summary statistics of internal decayed volume loss in urban trees (*U. procera*, *C. maculata* and *P. x acerifolia*) growing in parks in the city of Melbourne, Australia.). Carbon loss due to decayed wood was in the range of 69 to 110 kg per tree and was more severe in *U. procera*, followed by *C. maculata* and least in *P. x acerifolia*.

Table 4.2 Summary statistics of internal decayed volume loss in urban trees (*U. procera*, *C. maculata* and *P. x acerifolia*) growing in parks in the city of Melbourne, Australia.

Variables/Species	<i>U. procera</i> [n=15]	<i>C. maculata</i> [n=15]	<i>P x acerifolia</i> (n=13)
Total stem volume [m ³ tree ⁻¹]	3.5 (1.8)	6.0 (4.7)	3.52 (2.4)
Mean decayed volume loss [m ³ tree ⁻¹]	0.46 (0.2)	0.30 (0.2)	0.25 (0.15)
Proportion of internal volume loss [%]	13.8 (4.7)	6.60 (4.8)	5.63 (4.5)
Maximum proportion of internal volume loss [%]	23.9	18.2	12.4
Carbon loss [kg tree ⁻¹]*	111.8 (56.2)	94.0 (68.5)	69.2 (48.2)

Values in () represent the standard deviation of each calculation. * Based on the equation: kg of carbon = wood volume × carbon factor; where carbon factor = SG × 1 000 kg (weight of 1 m³ of water) × ratio of per cent C (Brazee et al., 2010).

4.4.5 Relationship between vitality index (VVI), diameter and stem volume loss

Decayed area (cm²) and volume loss (m³) were two different calculations made in this study. The former is the cross-sectional area affected by decay at a given point along the stem of sampled trees, and the latter is a calculation derived from added decayed area within a tree stem. No significant relationships were found between VVI and volume loss across species (data not shown). This finding suggests that internal volume loss is not correlated with tree vitality in *U. procera*, *P. acerifolia* and *C. maculata*. However, in *U. procera*, a strong and significant relationship was found between DBH and stem volume loss ($R^2 = 0.8006$, $P = 0.0046$), regardless of VVI (Figure 4.7). In the broadest sense, the larger the stem tree diameter (range of 35-110 cm), the greater the volume loss internally. Finally, the relationship between stem volume loss and DBH for *P. acerifolia* and *C. maculata* trees was weak but not significant ($R^2 = 0.32$, $p = 0.6864$, RSE: 0.6318 and $R^2 = 0.16$, $p = 0.7291$, RSE: 0.5756, respectively).

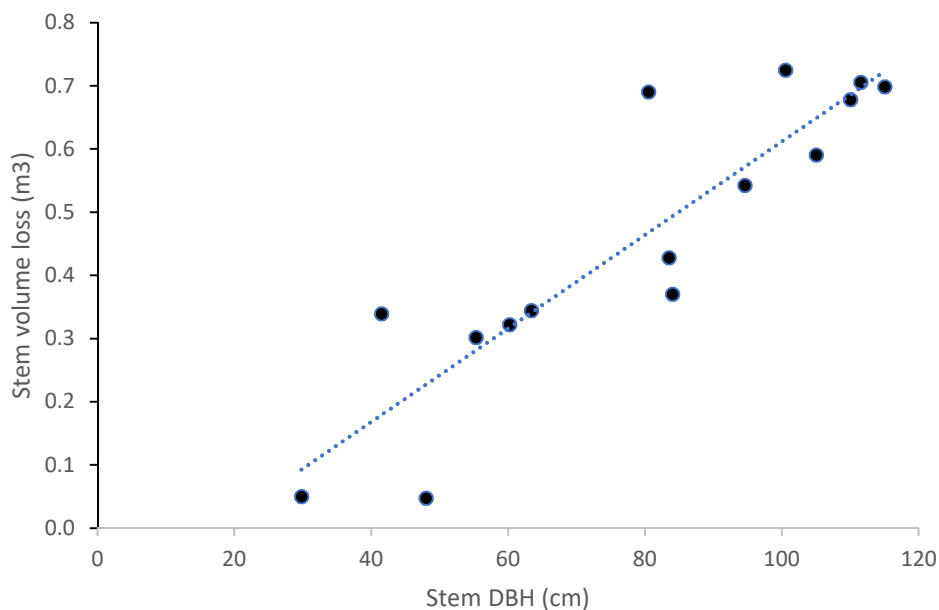


Figure 4.7. Diameter at breast height (stem DBH) versus stem volume loss (m³) for *U. procera* trees growing in parks in the city of Melbourne, Australia. Regression coefficients and related statistical values were as follow: $Y = 0.0074x - 0.1279$ ($R^2 = 0.8006$, $p = 0.0046$, Residual standard error-RSE: 0.1424) where: Y is volume loss (m³) and X is stem DBH (cm).

The linear model that better projected the actual volume loss in standing *U. procera* trees was $Y = 0.0074x - 0.1279$ ($R^2 = 0.8006$, $p = 0.0046$, $n = 15$). Based on model's calculation, *U. procera* tree stem volume of those individuals with $DBH \geq 40$ cm needs to be discounted by a factor of 13% due to the extent of internal decayed wood regardless of tree's vitality index. Moreover, in *U. procera*, DBH (cm), VVI (0-25 points) and competition status (number of trees within 10 m radius) showed a relative importance value of $R = 0.84$, $R = 0.61$ and $R = 0.35$; respectively (Figure 4.8). Individual categories within VVI scores such as crown density and presence of dead branches within tree canopy also showed a moderate and positive association with internal decayed volume loss ($R = 0.45$, $R = 0.56$, respectively).

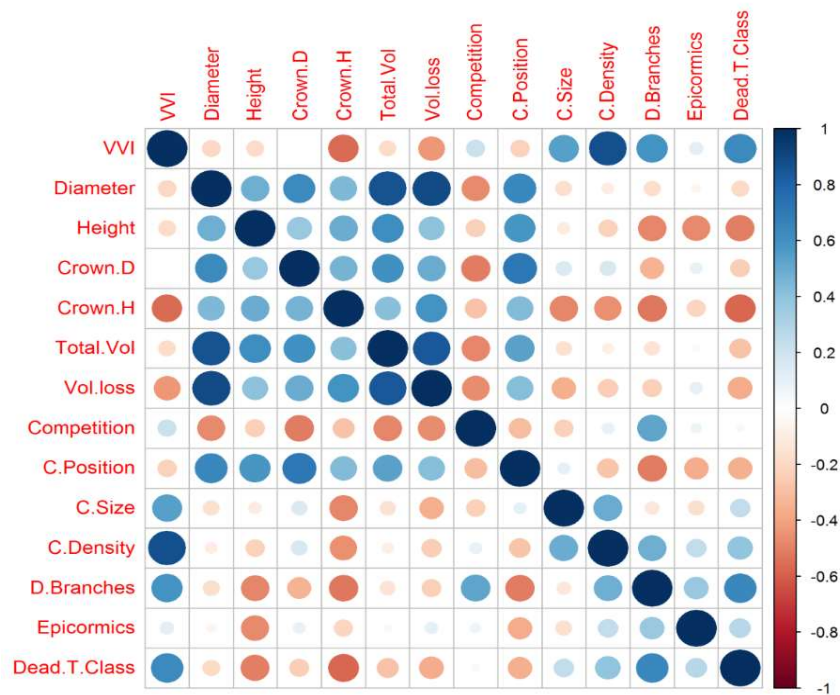


Figure 4.8 Correlation matrix of stand and tree attributes with potential effect on the predictability of volume loss (m^3) in standing *U. procera* park trees, Melbourne, Australia. Blue colour represents a positive correlation between paired variables and red colour denotes otherwise. The bigger and darker the colour of the circles, the stronger the correlation. Matrix's variables were: VVI (visual vitality index), C-Density (crown density), C-size (crown size), Crown-H (crown height), Total.Vol (total stem volume), Vol.loss (volume loss due to decay), C-position (crown position), Competition (number of trees within 10 m radius), D-Branches (dead branches retained within the canopy), Epicormics (presence of epicormics along the trunk and canopy), Dead-T-class (overall dead tree class).

4.5 Discussion

4.5.1 Decay distribution patterns along the stem

In this study, the assessment of drilling profiles coupled with advanced climbing techniques, both framed in the CODIT model, allowed to map and quantify the distribution of decay along the stem of standing trees. Based on findings it was demonstrated that decay reduces significantly (between 5-25%) tree stem volume of abundant species in the city of Melbourne. The presence and extent of decay differed according to tree species. As expressed in the CODIT model, the occurrence of decay among species found in this study is suggestive of the species-capacity to limit the longitudinal and radial spread of decay (Boddy, 1994; Shigo, 1965).

In this study, decay was found to be distributed in three different ways in the three-species evaluated. For *U. procera*, decay did appear to spread as a column from the base to the live crown; whereas, decay spread as a cone-shape and as pockets of decay in *P. acerifolia* and in *C. maculata*, respectively. Similar patterns of decay progression have been documented in several species using different equipment and approaches. Larsson et al. (2004) reported cone-shaped decayed regions extending up to 2 m along the stem of standing Norway spruce (*Picea abies*) trees. Pockets of decay at the trunk's base (0.3 m) of 36 *Eucalyptus saligna* trees were reported by Johnstone et al. (2010b). Although the sample size was quite small (five trees), Castello et al. (1999) reported central columns of decayed wood of considerable size in mature (> 75 years old) *Ulmus glabra* street trees.

4.5.2 Decay affects a wide range of stem tree diameter

Decayed wood is usually associated with ageing trees with poor vitality (Dobbertin, 2005; Luley et al., 2009; Terho et al., 2008). This research confirmed that decay occurs across a wide range of tree stem diameters in *U. procera* regardless of vitality index, however there was a significant relationship between wood decay and tree vitality in *P. x acerifolia* whereas a weaker relationship was observed in *C. maculata*. As show in Figure 4.5 and Figure 4.6 these correlations appear to be heavily influenced by two unusual data, therefore caution should be taken with the generalization of this research finding (Chave et al., 2014; Frank et al., 2018).

Based on findings, it seems that decay is a significant issue for both large mature trees as well as younger trees and can reduce the carbon storage potential of urban trees. Likewise, Koeser et al. (2016) found that the likelihood of detecting severe decay in *Quercus* spp. increased with tree diameter, however; as tree diameter surpass 75 cm, the probability of incidence of decay declines. In *U procera*, the maximum proportion of decayed cross-sectional area recorded at the DBH point ranged from 15% to 33%, which based on wood strength loss assessment, all sampled trees were ranked within the caution zone and must be evaluated with respect to other defects which could contribute to a potential hazard. The strength loss due to decayed wood of the other two species do not represent any hazard (Kane et al., 2004; Smiley et al., 1992).

Wood density also has a role to play in limiting the distribution of decay along the stem of evaluated trees. In this study, the lower density trees (*U. procera*, wood density value of 0.53-0.58 g/cm³) did not show correlations between tree vitality and wood decay whereas the higher density trees (*P. x acerifolia* and *C maculata*) did. In this study, *P. acerifolia*, classified as

hardwood with a higher wood density (0.62-0.67 g/cm³) did show a significant but moderate relationship with tree vitality which suggest that a single tree vitality index might be a good predictor of decay in stronger compartmentalizer tree species (Luley et al., 2009; Robles et al., 2015). Internal decay in *C. maculata*, a native species with high wood density values (0.57-0.63 g/cm³), showed a significant but weak relationships with tree vitality (Lamlom et al., 2003; Miles et al., 2009).

In natural stands, increasing decay rates were correlated with lower wood density in flowering, but not coniferous species across 816 species, worldwide (Chave et al., 2009). Other studies reported that relationships between decay and wood density within a species differed depending on the type of decay (Frank et al., 2018; Yu et al., 2003). Overall, findings from this study are suggestive of 1) low wood density trait appears to be a strong predictor of wood decay, 2) tree vitality in poor compartmentalizer species does not matter, the tree will decay anyway (Callow et al., 2018; Harper et al., 2005) and, 3) with medium to high density trees visual vitality does matter because trees will only decay if they have low vitality, in agreement with Johnstone et al. (2010b).

Arboricultural treatments aim to maintain the amenity and safety of trees in public places might play a role in preventing or spreading decay in standing trees (Boddy, 1994; Ellison, 2005; Pearce, 2000). In this study, decay was detected at the base, DBH, trunk and crown positions of *U. procera* but was less likely to be distributed beyond a height of 2.3 m in *P. aceriolia* and *C. maculata*. In these last two species, decay was only present at the crown position in those individuals that had been severely pruned or had broken branches within their canopy.

Recovery time and the ability of branches to limit wood decay is significantly influenced by the frequency and severity of pruning regimes in both natural and urban settings (Barry et al., 2000; Eisner et al., 2002; Frank et al., 2018; Grabosky et al., 2007). In natural stand, the extent of branch discoloration was positively correlated with branch diameter (green pruning) or the dead branch length (natural shedding), which was itself correlated to branch diameter in *Acer pseudoplatanus* and *Fraxinus excelsior*, respectively (Dănescu et al., 2015).

Branch morphology also impacts compartmentalization of pruned or broken branch wounds. For instance, Gilman et al. (2006) revealed that branch collar in *Acer rubrum* and *Quercus virginiana* was an indicator of strong compartmentalization potential. Branch size also seems to affect tree's capacity to compartmentalize pruning wounds, since the removal of large limbs and branches resulted in severe stem discoloration of juvenile *Q. virginiana* and *A. rubrum* (Eisner et al., 2002). *P. acerifolia* evaluated in this study appeared to lack a branch collar and therefore, this species may be unable to generate a branch protection zone (BPZ) when limbs and large branches are removed (Barry et al., 2000; Dănescu et al., 2015; Grabosky et al., 2007).

All *P. acerifolia* sampled trees were situated in parks, however; a large number of street *P. acerifolia* trees in the City of Melbourne are subject of major pruning and branch removal regimes to avoid conflicts with infrastructure and power lines, consequently they are more prone to be more affected by internal decayed wood (May et al., 2013; Ryder et al., 2013). *C. maculata* trees, however; appeared to have branch collar, hence, the species is capable of creating BPZ and more effectively limit decay originated from branch removal due to regular tree care. In a field study on natural *Eucalyptus nitens* stands (a close relative of *C. maculata*)

in Tasmania Wardlaw et al. (1999) reported a range of 13-16% of sampled trees as having columns of discoloration and decay spreading from pruned stubs into the main stems. The risk of a pruned branch being associated with spreading decay columns increased with increasing branch diameter and increasing height up the pruned stem. However, further research is needed to test this generalization across urban planting sites.

4.5.3 Vitality index as a reliable proxy for stem volume loss calculation

In this study, both decayed area (cm²) and volume loss (m³) do not shown any significant association with vitality index of *U. procera* trees. This finding suggests that, regardless of tree's vitality status, decay might occur, and can occur at any point along the stem. Nevertheless, in *U. procera* volume loss was strongly linked with stem DBH, which based on findings the species can be ranked as poor compartmentalizer of decay (Frank et al., 2018; Marra et al., 2018). For *P. x acerifolia* and *C. maculata* trees, relationships between VVI and stem volume loss were absent.

Studied trees were situated in parks under relatively favorable growing conditions such as regular irrigation, application of mulch and, formative pruning. As such, our 43 sampled trees were restricted to a low range of VVI with individuals scored between 15 to 25 points. Sampling several trees in different planting sites (streets, car parks, roads, boulevards, etc.), showing a wider VVI range (≤ 5 points ≥ 25 points) and including a broader age class (juvenile, mature, over mature trees) may allow to better test whether a VVI can be a good predictor of decayed volume loss in *C. maculata* and *P. x acerifolia* trees.

The VVI proposed by Johnstone et al. (2012) and used in this study to assess tree vitality does not take into account external signs of decay such as fungi fruiting bodies along the stem, cranks and wounds, therefore; no association between causal agents and the extent of decayed wood estimated among and within species can be drawn. In contrast, Koeser et al. (2016) found that a visual decay factor (VDF) which encompassed all the visual indicators of decay was effective (70% of predictability) in identifying the presence of decay in *Quercus* spp. with diameter range of 45-75 cm, yet the reliability of the VDF for larger tree diameter plateaued.

The exploratory correlation analysis performed for *U. procera* trees suggests that a set of stand and tree attributes (DBH, tree height, crown diameter, vitality index and competition status) can be used as predictors of volume loss calculation in standing trees. The linear model constructed in this study was quite strong ($R^2 = 0.8006$, $P = 0.0046$), however; since sample size was small ($n=15$), its predictive power and extrapolation potential are limited. Even though the VVI used in this study accounted for dead branches within the tree canopy, we did not tested the occurrence and extend of decay in large branches which may increase the whole tree volume loss (Eisner et al., 2002; Gilman et al., 2006; Heikura et al., 2008). A further assessment that includes a greater sample size and different planting sites may assist in the development of a more robust and reliable predictive model of decayed wood in urban trees.

4.5.4 Scope and limitations of internal decayed volume loss calculation

Although premises assumed in this study to derivate volume loss (m^3) from decay area (cm^2) were valid and framed in the CODIT model, errors in the calculation of internal volume loss is an entirely reasonable assumption. Our calculations of volume loss using the Smalian equation

added the segments of decayed wood at a given point and assumed that decay was distributed as either a cylinder or truncated cone from one drilling point to another, regardless of the species' particular pattern of decay registered. A constant drilling distance of 1 m along the stem until the crown position is reached might allowed a more accurate estimation of both the decayed area and the internal volume loss.

Another source of error of internal volume loss calculations made in this study is the fact that the base micro-drilling point was set at 0.3 m indicating that decay is extrapolated from the ground to the first 30 cm of the trunk. This assumed uniformity of decay might be valid for street trees which are more exposed to mechanical injury due to construction work or similar soil disturbances which can lead to decay at tree base (Shortle, 1979; Terho, 2009; Watson, 2008). Yet, this is not the case for our sampled park trees.

In this study we did not take into account changes of wood density along the trunk, limbs and branches which in turn may affect the distribution patter of internal decay in trees (Brazee et al., 2010; Henry et al., 2010; Luley et al., 2009). A subsequent study which includes the assessment of decay along scaffolds and branches may aid in a more accurate estimation of the extent of decay in urban forests (Frank et al., 2018; Koeser et al., 2016; Marra et al., 2018). In order to account for the cross-sectional distribution of decay, each tree's position was micro-drilled at between two to four axes according to stem diameter, however; since the length of the needle was only 40 cm and, for those trees with diameter ≥ 80 cm, drilling profiles evaluated for decay may not accurately detect the maximum extent of decay at each drilling point.

4.5.5 Decay classes, tree parts and C contents

A significant bias of carbon loss calculations made in this study is that both categories of decay (advanced decay + absence of wood) were added as decayed wood within a single tree regardless of C content at a given decay stage. However; tree size, species and present decay condition in standing trees are key determinants of wood decay rates (Bert et al., 2006; Zhang et al., 2009). Parts of the stem can also decay at different rates since contact with soil can increase moisture content and facilitate access for decay organisms, accelerating decomposition near ground level compared to upper portions of the stem (Stephenson et al., 2014). In addition, older trees could have been exposed to elements for longer periods of time, hence increasing the likelihood that the tree may have developed broken branches or other wounds which may serve as entry points for decay organisms (Frank et al., 2018; Giroud et al., 2008).

Gradients in wood density values from the originating live tree also shape patterns of decay (Harmon et al., 2013; Lamloom et al., 2003). In this regard, Cousins et al. (2015) found that as decay class advanced (1: intact – 5: advanced decay) standing dead trees (SD) showed a progressively lower density and a small increase in C concentration. Net carbon density of the most decayed SD trees was only 60% of that of sound trees. Overall, when using the decay adjusted factor, SD carbon stock estimates were 18% lower than estimates that do not incorporate change due to decay. Likewise, Brazee et al. (2010) estimated the actual carbon stock in a decayed portion of a tree as being only 57% as compared to that calculated for a decay-free stem. Recently, Marra et al. (2018) reported decay wood in 47 out of 72 sampled trees, with C% values ranging from 0.13% to 36.7%. This study did not consider variations in C contents, wood density gradient and decay rates along the stem of samples trees, hence the

chosen approach to assume all decayed wood, independent of the stage of decay, holds no C may lead to overestimating C loss in urban trees.

4.6 Conclusions

Decay is a significant issue in *U. procera* trees and may occur in a wide range of stem diameter and visual vitality index. The incidence and severity of wood decay in *P. x acerifolia* and *C. maculta* trees found in this study was not significant. The distribution patterns and extent of decayed wood documented in this study was species-dependent and it seems to be aggravated by arboticultural practices in those trees undergoing heavy pruning such as *P. x acerifolia*.

Based on our results, it appears that decay wood reduces the storage carbon potential of *U. procera* trees in the city of Melbourne. Calculations of stored carbon by *U. procera* trees need to be discounted by a species-decay factor rather than a standard factor traditionally use elsewhere. The research protocol described in this study may be useful in documenting and quantifying the occurrence and extent of decay in several urban trees. The detrimental effect of decayed wood on tree stem volume of urban trees cannot longer be overlooked and need to be considered to better assess urban tree benefits. Overall, the research approach followed in this study constitutes a important step in urban forestry science which advances our knowledge on the assessment of decay and stored carbon in urban trees.

The fact that wood decay patterns found in this study affected tree species differently, highlights the necessity to incorporate volume loss due decayed wood into above-ground

biomass calculations, thus stored carbon in urban trees. It has been suggested by some authors that wood decay significantly reduces biomass and carbon stocks of standing trees, hence the practice of applying a generalized discount factor of 0.8 (McPherson et al., 1997; Nowak et al., 2002a) which account only for differences in biomass yield between natural and urban trees needs to be revised (Brazee et al., 2010; Koeser et al., 2016; Luley et al., 2009; Terho, 2009) or replaced by a species-decay factor. Yet, no systematic studies have been done with objective measurements to confirm or refute this claim. The next experimental chapter (Chapter 5) will combine full tree measurements and decay calculations made in Chapter 4 to perform a practical assessment to 1) develop species-specific allometric equations and, 2) incorporate volume loss due to decayed wood into tree standing volume estimates.

Chapter 5. Standing volume yield, canopy structure and allometric relationships of urban trees.

5.1 Abstract

Most allometric equations currently used to quantify above-ground biomass of urban trees are derived from natural forest stands and can produce unreliable estimates of biomass for individual trees grown in open conditions. In addition, distribution of standing volume between stem, branch and foliage in solitary grown urban trees is poorly understood. In this study, a total of 45 trees of three species (*Ulmus procera*, $n=15$, *Corymbia maculata*, $n=15$ and, *Platanus x acerifolia*, $n=15$) of different size (small, medium and large) were measured. For six trees of each species (18 in total), the stem and all major branches were fully mapped so that an accurate wood volume was established, and various random branch samples (RBS) and composites could be used to estimate standing volume. For the remaining nine trees of each tree species standing volume was estimated by only measuring five RBS pathways. Allometric relationships between diameter and volume were explored using linear, quadratic, cubic, log and exponential models. Slenderness ratio (SR) and bifurcation ratio (BR) were derived to explore canopy structure among species. *U. procera* trees showed the greatest BR, followed by *P. x acerifolia* and lowest in *C. maculata*. In *U. procera*, SR displayed a decreasing trend from scaffolds to third order branches while the opposite was true for *C. maculata* and *P. x acerifolia*. Number and dimensions of scaffolds, first and second order branches of small and medium size trees were similar but differed from that of large trees. Overall, standing volume distribution among species was 40% to the main stem and 60% to the crown. Across species and tree size class, RBS systematically under- or over-estimated standing volume in the range of -30% to +42% as compared to full tree measurements. Regardless of tree size, allometric relationships were similar within species but varied among crown structural parts. Linear models better explained diameter-volume relationships of whole tree and main stem across species. Log-Log and polynomial models better described diameter-volume relationships of branches of all orders. These findings suggest that a set of allometric equations could be developed to more accurately predict standing volume yield of urban trees.

Key words: urban forest, allometry, tree attributes, biomass, allocation, branching pattern.

5.2 Introduction

The previous chapter (Chapter 4) was concerned with quantifying wood decay in standing trees. As the results from Chapter 4 suggest, wood decay is closely related to species' natural capacity to limit decay and it spreads differently across and along tree stems of urban trees. This chapter will focus on measuring volume yield and distribution, assess canopy structure and will develop a set of allometric equations to predict standing volume of urban trees. By combining full tree measurements and randomized branch sampling this investigation will also provide quantitative inputs on tree structure and dimensional relationships which can be used for tree growth modelling and the consequent assessment of urban tree benefits at city scale.

Significant progress has been made to explore relationships of tree dimensions and growing sites to further develop predictive equations for urban trees (Blood et al., 2016; Day et al., 2011; Moser et al., 2015; Stoffberg et al., 2008; Troxel et al., 2013; Vaz Monteiro et al., 2016). Yet, few published studies evaluated differences in allometric relationships and biomass distribution among urban tree species (Dahle et al., 2014; Grabosky et al., 2007; McFarlane, 2011; Urban et al., 2012). A well-established statement is that trees grown in 'closed' forest environments exhibit taller stems and thinner canopies while 'open' grown urban trees display shorter stems and broader canopies (Casella et al., 2003; Rautiainen et al., 2008; Schwets et al., 2000).

Tree form influences the amount of tree biomass distributed to each structural part (roots, stem, crown and foliage). Early research showed that biomass distribution pattern of a typical 'closed' forest tree is about 17% in roots, 50% in trunk, 30% in branches and, 3% in foliage

(Birdsey, 1992). Conversely, urban trees partition relatively more biomass to branches and foliage, and less biomass to the stem as compared to forest trees (Brack, 2002; Dobbs et al., 2011b; Xiao et al., 2000). Overall, whole tree biomass distribution and allometric relationships of canopy structural parts in urban trees remains poorly explored.

Developing species-specific allometric equations based on destructive sampling is the most accurate way of estimating tree biomass (Jenkins et al., 2004; Peper et al., 2003; Riikonen et al., 2011). Typically, above-ground woody biomass of urban trees is calculated from stem diameter at breast height (1.3 m), collected as part of periodic urban tree inventories and used then as an input into allometric equation models such as i-Tree, Urban Forest Effect (UFORE) and Centre for Tree Carbon Calculator (CTCC). This modelling approach provides unreliable estimates of above-ground biomass and stored carbon when used elsewhere (Chaojnacky et al., 2014; McHale et al., 2009; Russo et al., 2014).

Although feasible, destructive sampling is not always acceptable in an urban context and alternative techniques are needed. Non-destructive methods to quantify components and standing trees such as terrestrial LiDAR, Ariborne LiDAR, as well as partially-destructive (non-fatal) sampling methods; namely randomized branch sampling (RBS). Yet, none of these techniques are without drawback. While the utilization of remotely sensed data to capture urban trees biomass is cost-effective, recent research has shown that they are less accurate than those calculations based on stem diameter measurements and allometric equations (Kankare et al., 2013; Vonderach et al., 2012). RBS has been proposed as alternative way to estimate woody volume of open grown trees (Dobbs et al., 2011b; Jung et al., 2011; Shrestha et al., 2012). In summary, RBS is an unbiased sampling technique where, starting from the ground level and

based on a selection probability, some parts of the main trunk and branches are sampled and measured to estimate whole tree standing volume (or other tree attribute) (Gregoire et al., 1995; Jessen, 1955). Chirici et al. (2014) tested RBS against full tree measurements and reported biomass estimation errors at tree level up to 300% depending on the number of paths followed.

The accuracy of most commonly used allometric models for urban trees is largely questionable as they typically assume a uniform stem and branch taper such as the Pipe model (Makela et al., 2000; Valentine et al., 2005). The Pipe model states that the aggregation of a cross-sectional area of a tree stem at any point predicts leaf mass, however; a large body of research demonstrated that the Pipe model performs well for small branches but is less applicable for larger stems and complex tree canopies (Berninger et al., 2005; Lehnebach et al., 2018; Makela, 2002; Osunkoya et al., 2007; Suzuki et al., 2000; West et al., 1999). Since urban trees 1) grow in a diverse range of planting sites, 2) are subject to regular tree care and 3) span an artificially wide age-size distribution, it is likely that this heterogeneity will lead to non-uniform tree growth patterns. This in turn will complicate using generic allometric models to assess biomass distribution and above-ground biomass (Lehnebach et al., 2018; Moser et al., 2015; Pretzsch et al., 2015; Taneda et al., 2004).

Canopy structure is defined as the geometric arrangement of all above-ground structural parts of a tree (Fournier et al., 2003; Menalled et al., 2001; Rautiainen et al., 2008; Rouvinen et al., 1997). In physiological terms, canopy structure (shape, size, branch angles and canopy phenology) underpins tree vital processes such as sunlight transmittance, evapotranspiration, heat regulation, gas and water exchange, competition and mortality (Barthelemy et al., 2007; Bascietto et al., 2012; Pretzsch, 2014; Vermeulen, 2014). In terms of the provision of goods

and services, canopy structure regulates tree biomass yield, carbon stock and fluxes, shade provision and microclimate regulation (Eiserhardt et al., 2017; Fournier et al., 2003; Stephenson et al., 2014; Welles, 1990).

Canopy structure and allometry show some degree of “plasticity” within and among tree species and over time as a response to changes in local growth conditions, environment, and management (Barthelemy et al., 2007; Pretzsch, 2014; Weiner, 2004). Closed-canopy forest trees can modify crown shape, size and vertical distribution of leaves and branches to thrive within a dense stand, mixture of species and limited resources supply (Jucker et al., 2015; Purves et al., 2007). In natural forests, canopy structure also varies according to species, size, age, stand density and successional status (Cieslak et al., 2011; Fournier et al., 1997; Weiner, 2004; Xiao et al., 2003).

In the urban landscape, canopy plasticity or changes in canopy structure may be altered by 1) climatic or induced drought (i.e. turn off irrigation), 2) the urban heat island effect as a result of existing and new infrastructure being developed, 3) pests and diseases outbreaks which can affect tree vitality, 4) soil nutrient decline, soil compaction and restricted soil area and, 5) lifting of canopies to remove low branches, pruning, topping and mechanical damage (Day et al., 2011; Rautiainen et al., 2008; Tahvanainen et al., 2008; Templeton et al., 2003; Vaz Monteiro et al., 2016). The list of possible factors influencing allometry of urban trees presented above is unlikely to be exhaustive, rather this set of site and management conditions leads to the need for species tailored allometric equations for open-grown trees. A satisfactory assessment of crown structure is essential to estimate tree biomass distribution, shade provision and explore

allometric relationships of urban trees (Godin et al., 2005; Paletto et al., 2009; Peper et al., 2014; Poorter et al., 2015; Trichon, 2001).

This research is aimed at investigating the distribution of standing volume, canopy structure and allometric relationships for three common urban tree species: *Ulmus procera* (English Elm), *Platanus x acerifolia* (London Plane) and *Corymbia maculata* (Spotted gum). To this end, the following research questions were addressed: 1) Does biomass distribution of urban trees change by species and tree size? 2) Does tree canopy structure affect the reliability of randomized branch sampling (RBS) to assess standing volume and, 3) Does allometric relationships among canopy structural parts change within and among tree species? This research is structured as follows: section 1 describes canopy structure, branching patterns and standing volume distribution among sampled species; section 2 offers a comparative analysis between volume estimates given by full tree measurements and those derived from RBS; section 3 reports a set of species-specific allometric equations to predict standing volume of all tree structural parts and, section 4 presents a practical assessment which factors in a species-decay factor into standing volume calculations by incorporating previously calculated decay estimation data from Chapter 4 on the same sampled trees.

5.3 Methodology

5.3.1 Study site

This research was carried out in the City of Melbourne, Australia (Latitude 37°48'S, Longitude 144°57'E). The city council maintains more than 70,000 trees located in both parks and streets with an average tree density of 26.5 ha⁻¹ ($\pm$ 18 ha⁻¹) and canopy cover of 12.3% (3%-20%). The

four most common species are *Eucalyptus camandulensis*, *Platanus x acerifolia*, *Ulmus* spp. and *Corymbia maculata* which together accounted for 29% of total tree population (Dobbs et al., 2013). Most *Ulmus* spp. and *Platanus* spp. are approaching the end of their useful life expectancy due to a combination of factors including age, drought events and water restrictions which deteriorates tree vitality overtime (May et al., 2013). The climate of Melbourne city is “temperate” with uniform annual precipitation of 656 mm, mean annual temperature is 19.7°C (ranging from a mean monthly temperature of 13.4°C in July and 25.7°C in February) (VLSAC, 2011). The City of Melbourne has a population of +200000 residents over 3,760 ha of highly urbanized land and contains 486 ha of parks, 286 ha of built space and 1,112 ha of road space (City of Melbourne, 2012) (www.abs.gov.au).

5.3.2 Tree measurements and vitality assessment

A total of 45 trees consisting of three species (*Ulmus procera*, *Platanus x acerifolia* and *Corymbia maculata*) were measured in summer 2015 (January-April). These trees were situated in parks with stems >40 cm in DBH and height between 15 and 20 m (Table 5.1). Trees were selected in conjunction with two skilled arborists and based on the following criteria: 1) no evidence of heavily pruned canopy structure, 2) pedestrian risk was low and, 3) safe tree climbing was possible.

Age structure of the sampled trees varied according to species. Most *U. procera* trees were planted between 1900-1920 but a few juvenile individuals were also included. *P x acerifolia* trees were planted during 1950-1960 and 1990-2000. *C x maculata* trees were planted during 1970-1980 (City of Melbourne, 2012; Frank et al., 2006). Tree vitality was assessed during

summer 2015 when trees exhibited the full canopy foliage following Johnstone et al. (2012).

Table 5.1 shows the range of age, diameter and vitality index of species evaluated.

Table 5.1 Number of individuals, tree attributes and vitality index of three urban species included in the study.

	<i>Ulmus procera</i>	<i>Corymbia maculata</i>	<i>Platanus x acerifolia</i>
No. of trees [# fully measured]	15 [6]	15 [6]	15 [6]
DBH [cm]*	80.6 ± 14.8	64.3 ± 24.7	70.2 ± 30.2
Tree height [m]	14.8 ± 3.2	17.3 ± 3.4	17.5 ± 6.5
Vitality Index**	20 (17-24)	25 (19-25)	23.5 (20-26)
Age class	Juvenile/Mature/Over mature	Juvenile/Mature	Juvenile/Mature

*Measured at 1.3 m above the ground. **Values in () represent the range of vitality index recorded for each species and tree size. The ± symbol denotes standard deviation of each value.

5.3.3 Full tree measurement and stem volume calculation

A total of 18 trees (six per species) were measured in full (by two independent skilled arborists using advanced climbing techniques and a diameter tape), recording diameters of every branch at every meter along their path from the stem to their tip (diameter of > 5 cm). Trees were classified into three “size classes”: small (S), medium (M) and large (L). Tree size class was defined based on tree diameter (cm) and total height (m) as follows: S (diameter 20-30 cm and < 10 m tall), M (diameter 30-40 cm and 10-20 m tall) and L (diameter > 40 cm and > 20 m tall). For each species, two trees of each size class (n = 6) were fully measured to determine standing volume distribution and canopy structure. Tree canopy structure was summarized into a hierarchical classification to ensure consistency and simplicity when describing different canopy structural components. The hierarchical classification used was: a) main stem, b)

scaffold branches, c) first order branch (1st), d) second order branch (2nd), e) third order branch (3rd) and f) terminal branches (Figure 1). The tree top was defined as the stem/dominant branch reaching a diameter of ≥ 5 cm within the canopy. All terminal branches ≤ 5 cm in diameter were assumed to be cone-shaped and their length (m) was recorded and their volume was calculated using the geometric formula of a cone. The volume of each 1 m section of stem and branches was then calculated using the Smalian equation (1):

Equation 1:
$$V = (Ga + Gb)/2 * L$$

Where G is the cross-sectional area of the lower (Ga) and the upper (Gb) section of the stem in m^2 , L is the length of the stem in meters, and V is the volume of the measured stem or branch expressed in m^3 (Dobbs et al., 2011b). The Smalian's formula states that the volume of a log can be closely estimated by multiplying the average of the cross-sectional areas of the two log ends by the log's length.

5.3.4 Application of randomized branch sampling

On the remaining nine non-fully measured trees of each species (27 in total) and regardless of tree size, five branches were measured using randomized branch sampling (RBS) originally proposed by Jessen (1955) and improved by Valentine et al. (1984) and Gregoire et al. (1995). In summary, RBS selects a data collection path from the base or the point where the branch attaches to the stem to a randomly selected terminal branch. Sampling begins at the base of the tree. The segment running from the base to the first ramification (branching point) is sampled

with probability equal to 1. At each ramification point, the user must choose which segment to follow. In this study, a segment with probability proportional to the basal branch diameter raised to the 2.5 power was used as a suitable path selection probability (Good et al., 2001; Gregoire et al., 1996). This procedure is repeated until a terminal branch is reached. The conditional probability (q_k) was determined using a random number generator to define the sampling path. Within RBS, the unconditional probability (Q) of selecting the r^{th} section of a branch sample was determined by equation (2):

Equation 2:

$$Q = \prod_{K=1}^r q_k$$

The resulting sum of the probability of the entire tree or branch is then used to estimate biomass/volume of a single tree (stem biomass + crown biomass + the sum of branches biomass). Woody biomass/volume ($B^{\wedge}$) amount was determined using (Gregoire et al., 1995) method based on equation (3), where br is the amount of biomass/volume measured on the r^{th} branch and $B^{\wedge}$ represents the estimated amount of woody biomass/volume of a tree component (i.e. stem, limbs, branches). Biomass was then calculated as the sum of the biomass of each section divided by a cumulative probability.

Equation 3:

$$B^{\wedge} = \sum br / Qr$$

As a final step, a random selection of three to five paths was simulated to compare RBS-wood volume estimates against full tree measurement of the same trees (six trees per species/two trees per size class). Figure 5.1 shows a medium size *P. x acerifolia* tree fully measured and the corresponding network of paths as drawn by RBS method. A total of 20 segments and 29 paths could be potentially followed based on RBS. On this sampled tree, simulated and measured RBS-3 paths were 10, 23 and 29 and; simulated and measured RBS-5 paths were 1, 10, 14, 23 and 29.

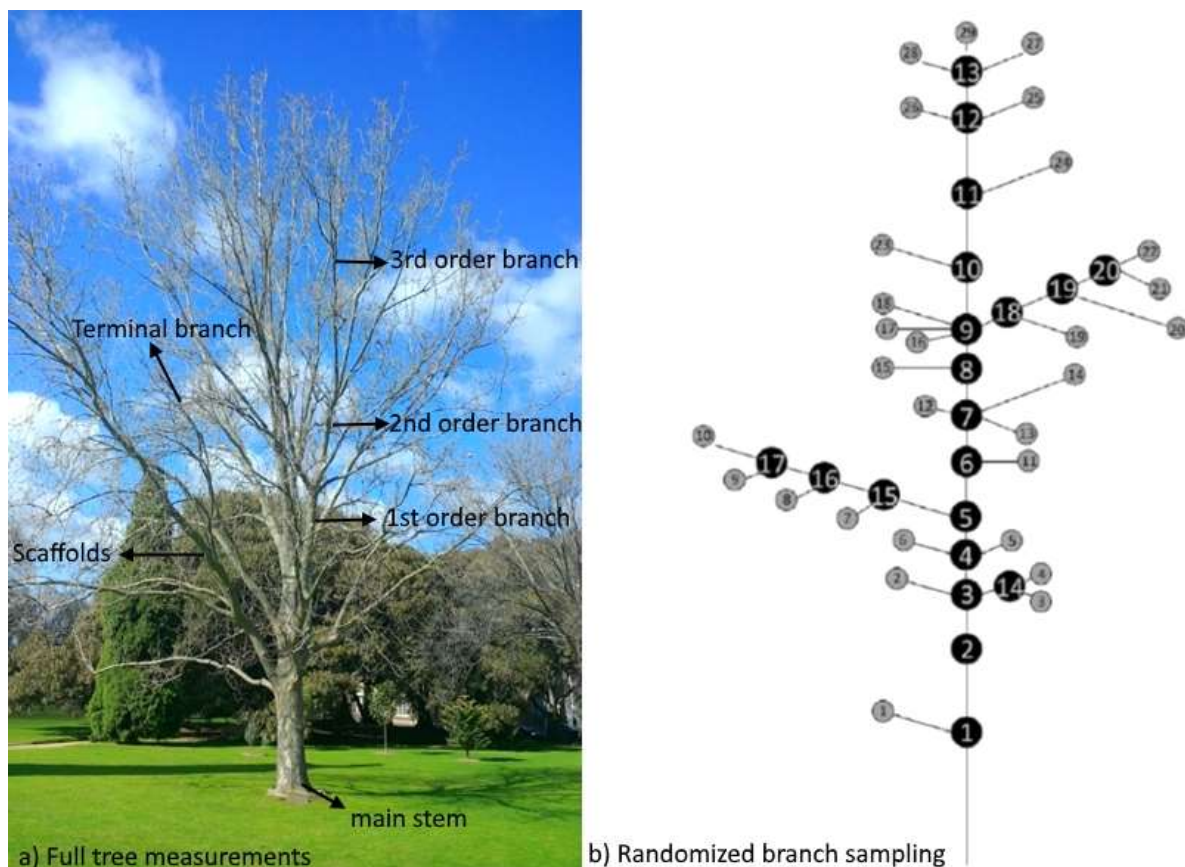


Figure 5.1 a) Hierarchical classification of canopy structural parts of a fully measured *P. x acerifolia* tree, b) Randomized branch sampling (RBS) with 20 segments and 29 possible paths to be followed in this study (Photos taken by Luis Orozco Aguilar).

5.3.5 Data analysis

Data gathered from the 18 fully measured trees (six trees per species, two trees per size class) were used to calculate descriptive statistics and summarize standing tree volume distribution and canopy structure/dimensions for all species and tree size. Volume distribution of sampled trees was described as per the hierarchical classification within the canopy. Slenderness ratio (length/radius) was calculated for all canopy structural parts (scaffold, 1st order branch, 2nd order branch and 3rd order branch) following Dahle et al. (2014). Slenderness ratio (SR) has been used as a threshold value to assess stability of stems and branches (Dahle et al., 2009; Mattheck et al., 2005; Rust, 2014). Values greater than 0.5 indicates structural strength against mechanical load or wind; values below 0.5 indicates otherwise.

Several approaches have been proposed to describe tree canopy structure. The foundation of those approaches is the stream network theory developed by geologists and hydrologists during the 50's and 60's (Barrera et al., 1989). The stream network theory was then applied to forestry sciences to improve our understanding of canopy structure and branching pattern of tropical trees (Pickett et al., 1980; Shukla et al., 1986; Zeide, 1998). Currently, fractal branching is a robust approach used to characterize the arrangement pattern of roots and tree canopy structure (Berntson, 1997; Fitter et al., 1992; Fleurant et al., 2004; López-López et al., 2017; Lynch, 1995; van Noordwijk et al., 2002). In this study, a bifurcation ratio per species was derived on the basis of Motomura's formula modified by Shukla et al. (1986):

$$BR = N - N_{max} / N - N1$$

where *BR* is bifurcation ratio, *N* is the total number of branches of all orders, *N_{max}* is the number of branches of the highest order, and *N1* is the number of branches of the first order.

5.3.6 Terms and definitions

- **Allometric equation:** is a formula that quantitatively formalizes the relationship between plant dimensions (Gayon, 2000; Mascaro et al., 2014).
- **Biomass allocation:** refers to how the biomass of one plant organ relates to that of another or of the whole plant. Biomass distribution within tree result from resources allocation overtime (Poorter et al., 2015; Poorter et al., 2012; Weiner, 2004).
- **Allometric relationships:** is defined as the relationship between tree dimensions. An allomeric equations represents the statistical relation between two size characteristics of individuals within a population (Gayon, 2000; Picard et al., 2015).
- **Decurrent tree:** refers to an individual with no single dominant stem, branches tend to curve upward so their tips are at the canopy surface. Good examples are mature *Quercus* spp. with wide spreading crowns (Kane et al., 2013; Wilson, 1990).
- **Excurrent tree:** refers to an individual with a dominant central stem and major branches at wide angles to the stem, upper branches shade lower branches, conifers form alike. Good example in this study is *Corymbia maculata* sampled trees (Wilson, 1990).
- **Stem volume:** refers to woody volume (m^3) calculated for a given tree main stem.
- **Standing volume:** refers to above-ground woody volume (m^3) calculated for whole tree canopy structure including main stem, scaffolds and branches of all orders.

5.3.7 Allometric relationships

Diameter-volume allometric relationships of tree canopy structure (all structural parts) were explored using published models as proposed by Dahle et al. (2014), Peper et al. (2014) and Troxel et al. (2013). All branches were accounted and measured to evaluate tree canopy structure but only those visually healthy were used for allometric analysis (Grabosky et al.,

2007; James et al., 2014). An exploratory analysis of untransformed data was conducted to confirm both normality (Shapiro-Wilks test and histogram) and heteroscedasticity (plot of residuals and leverage test) of the data. In addition, student deleted residuals (SDR) and D-Cook tests were used to identify outliers. The largest *U. procera* and *C. maculata* trees were identified as outliers so data from those trees were left out of allometry construction. The final data set was logarithmically (log) transformed to explore allometric relationships of all structural parts which substantially improved the fit for some relationships, especially for branches of all orders (Mascaro et al., 2014; Picard et al., 2015).

By combining volume data from the 18 fully measured trees and data collected from the 27 trees assessed via RBS-5 paths, a set of five allometric models (linear, quadratic, cubic, Loglog and exponential) were used to predict total standing volume as a function of DBH (Dobbs et al., 2011b; Peper et al., 2014; Timilsina et al., 2014). The Aikake's information criterion (AIC) and the Bayesian information criteria (BIC) were used to compare and rank the models since these combined statistical criteria significantly improve the robustness of biomass functions (Hounzandji et al., 2014). Models with the "best" fit as indicated by having the smallest AIC and BIC were selected.

Finally, using fully measured tree volume estimates and simulating the application of RBS-3 paths and RBS-5 paths, the relative estimation errors (REE-expressed in percent) as a function of the number of paths (RBS replications) carried out on the same tree was calculated and further used to test the suitability and reliability of RBS to predict whole tree standing volume. All statistical analysis was done in InfoStat (2016).

5.3.8 Factor in the overlooked decayed wood loss

Based on a recent publication by Orozco-Aguilar et al. (2018) a practical assessment to incorporate the effect of decayed wood into standing volume calculations of *U. procera* trees was devised. The authors discounted tree stem volume of those trees with a DBH ≥ 40 cm by 13% to account for internal decayed wood. In order to consider this species-decay factor five further steps were taken:

- 1) standing volume data of six sampled *U. procera* trees was calculated using a published allometric equation for *U. americana*, called it the urban USA model (McHale et al., 2009). Model and values of the published allometric equations used in this study are: $V = a \cdot (\text{DBH})^b$, where V: standing volume (m^3), a: $1.8 \text{ E-}03$ and b: 1.869, $R^2 = 0.92$, RSE: 0.268.
- 2) resulting standing volume estimates were contrasted with standing volume calculations obtained from data of fully measured *U. procera* trees (presented below in section 5.4.2).
- 3) tree stem volume of each fully measured tree was then discounted by a decay factor (13%).
- 4) differences between volumes estimates resulted from the use of a species-decay factor and that of standing volume estimates given by the USA-model was graphically demonstrated.
- 5) resulting standing volume yield is given by tree size class (small, medium and large).

5.4 Results

5.4.1 Section 1: Canopy structure and branching pattern among species

A total of 3538 structural parts were measured from 18 trees, including 247 scaffolds, 507 first order branches, 435 second order branches and 2297 third order branches. Since small and medium size sampled trees were still in an excurrent stage and large trees, especially *U. procera*, displayed a decurrent form, the number of scaffolds and branches 1st and 2nd order

were different among species and within trees size class (Table 5.2). Regardless of tree size, *U. procera* trees showed the greatest BR calculated, followed by *P. x acerifolia* and the lowest was recorded in *C. maculata*. Overall, branching ratio (BR) values increased as trees became large decurrent individuals.

Although all measured structural parts exhibited slenderness values (SR) above the safety threshold of 0.5, a clear trend of SR values across species was detected. For instance, in *U. procera* SR values showed a decreasing trend from scaffolds towards 3rd order branches. In *C. maculata* SR values displayed an increasing trend from scaffolds to 3rd order branches while all structural parts of *P.x acerifolia* trees recorded the greatest SR values (Table 5.2). The number and dimensions of all structural parts for each fully measured tree per size class are presented in the corresponding Appendix.

Table 5.2 Mean values of canopy structural parts of sampled trees in parks, Melbourne, Australia. Data derived from 18 fully measured trees.

	Small (n=2 trees)				Medium (n=2 trees)				Large (n=2 trees)				
Species/size class	D (cm)	L (m)	V (m³)	SD	D (cm)	L (m)	V (m³)	SD	D (cm)	L (m)	V (m³)	SD	BR
<i>U. procera</i>													
Scaffolds (76)	11.4a	4.3a	0.04a	0.78a	17.1b	4.4a	0.5a	0.55	34.9c	8.5b	0.34b	0.52b	3.8±0.6
1 st order branch (164)	6.9a	2.4a	0.02a	0.77a	9.5a	2.5ab	0.03a	0.55b	12.8b	3.4b	0.04a	0.53b	
2 nd order branch (116)	4.8a	2.2a	0.01a	0.98a	7.2b	2.3a	0.01ab	0.65b	10.6c	2.7a	0.02b	0.45c	
3 rd order branch (807)	4.3a	1.9a	0.01a	0.99a	5.0b	2.5ab	0.02a	0.98ab	5.6c	2.6b	0.02a	0.89b	
<i>P. x acerifolia</i>													
Scaffolds (83)	12.9a	4.1a	0.02a	0.67a	26.2b	8.6b	0.1b	0.65a	38.5c	11.6c	0.6c	0.62a	3.1±0.5
1 st order branch (215)	5.7a	2.1a	0.01a	0.79a	9.5b	4.0b	0.02a	0.86ab	12.2c	4.1b	0.07b	0.69b	
2 nd order branch (126)	4.8a	1.0a	0.01a	0.40a	7.2ab	2.6b	0.02a	0.72ab	8.7b	2.7b	0.04b	0.63b	
3 rd order branch (897)	4.0a	1.6a	0.01a	0.80a	4.9b	2.6b	0.02ab	0.94b	6.3c	2.7b	0.03b	0.73c	
<i>C. maculata</i>													
Scaffolds (88)	13.9a	3.7a	0.04a	0.53a	17.6a	5.1ab	0.08a	0.60a	32.3b	7.1b	0.34b	0.48a	2.3±1.3
1 st order branch (128)	8.5a	2.2a	0.01a	0.56a	8.05a	2.7a	0.01a	0.73b	13.9b	3.6b	0.07b	0.56a	
2 nd order branch (182)	5.9a	1.8a	0.01a	0.62a	5.4a	2.0a	0.01a	0.76ab	10.3b	2.8b	0.03b	0.58b	
3 rd order branch (594)	4.8a	1.7a	0.001a	0.72a	5.2ab	1.8ab	0.001a	0.75a	5.5b	2.0b	0.001a	0.76a	

Notes: D: diameter, L: Length, V: volume, SD: Slenderness. Mean values with a common letter in the same row are not significantly different ($p > 0.05$).

5.4.2 Section 2: Standing volume distribution among species

Standing volume distribution varied among species but was similar for similar sized trees within species. Overall volume distribution ratio (tree stem/canopy) of sampled trees was 40%:60% (Figure 5.2). *C. maculata* trees tended to distribute more volume to the main stem, followed by *P. acerifolia* and least in *U. procera* (Table 5.3). Regardless of tree size, *C. maculata* trees distributed between 50-60% of the above ground volume to the main stem and between 40-50% to the canopy (includes branches of all orders). *U. procera* trees tended to distribute less volume (35-40%) to the main stem and 60-65% to the canopy. Above-ground volume distribution in *P. x acerifolia* trees was 35-45% to the main stem and between 55-65% to the canopy. Terminal branches accounted for less than 2% of whole tree standing volume.

Table 5.3 Whole tree standing volume distribution (stem, scaffolds and branches) of sampled urban trees. Data from 18 fully measured trees. Six trees per species, two trees per size class.

Species/Structural part	Whole tree (m ³)	Main stem (m ³)	Scaffolds (m ³)	1 st order branch (m ³)	2 nd order branch (m ³)	3 rd order branch (m ³)
<i>U. procera</i>						
S	1.40	0.63	0.58	0.14	0.11	0.06
M	2.10	0.68	0.61	0.37	0.21	0.20
L	12.45	5.42	6.11	0.07	0.31	0.58
<i>P. x acerifolia</i>						
S	0.92	0.43	0.36	0.12	0.10	0.04
M	4.81	1.82	2.10	0.54	0.06	0.28
L	25.5	9.70	11.8	2.67	0.40	0.61
<i>C. maculata</i>						
S	1.7	0.94	0.54	0.03	0.12	0.09
M	3.0	1.8	0.83	0.18	0.10	0.07
L	25.35	13.0	6.60	3.67	0.84	1.26

Notes: Tree size class includes S-small, M-medium and L-large. No statistical comparisons were made among species, structural part and tree size.

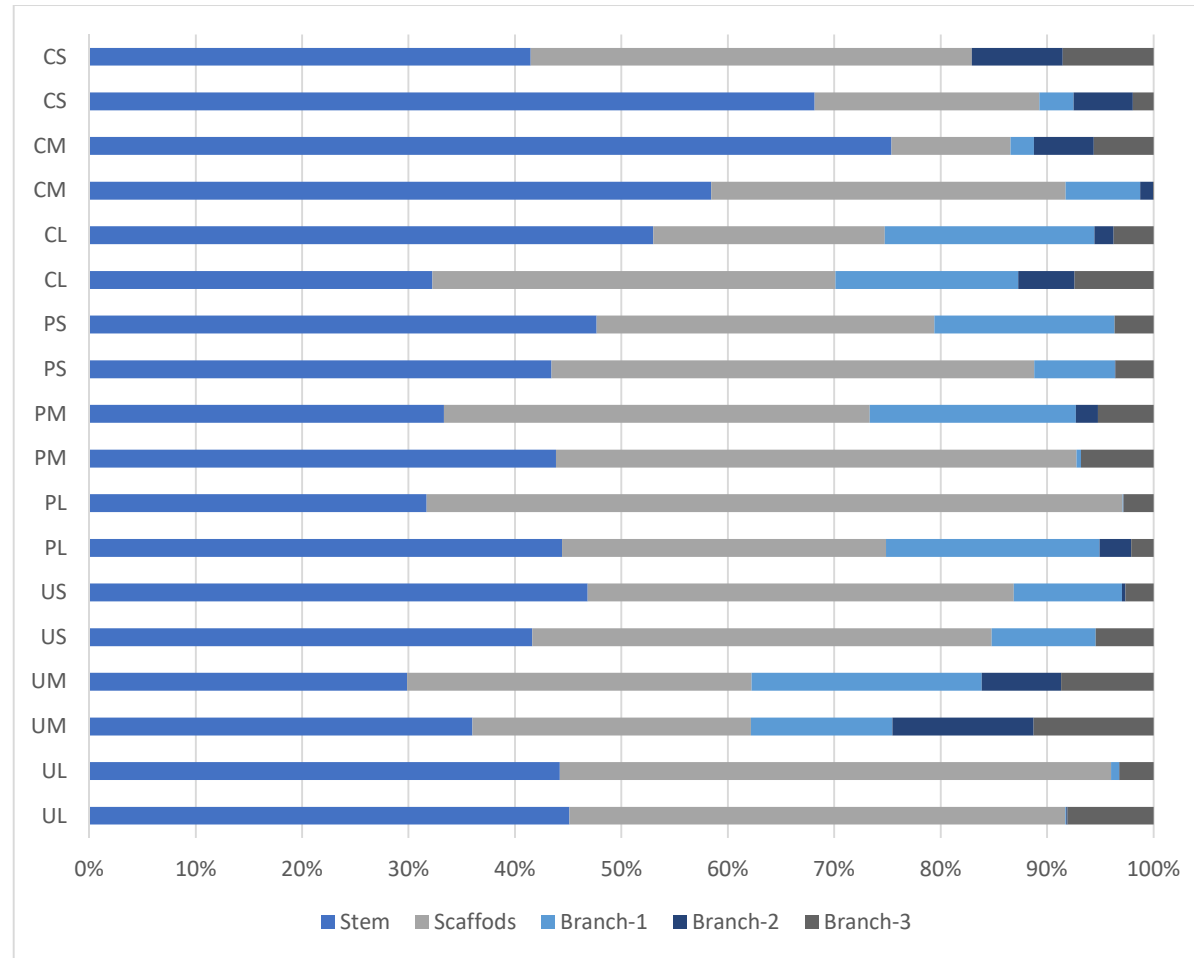


Figure 5.2 Standing volume distribution (%) as per structural part of 18 fully measured trees. Stem: tree main stem, Scaffolds: scaffolds branches, Branch-1: 1st order branches, Branch-2: 2nd order branches, Branch-3: 3rd order branches. Notes: Species and Tree size class: CS, CM and CS: *C. maculata* large, medium and small trees, respectively. UL, UM and US: *U. procera* large, medium and small trees, respectively. PL, PM and PS: *P. x acerifolia* large, medium and small trees, respectively.

5.4.3 Section 2.1 Volume estimations using full tree measurements and branch sampling

Species and number of paths differences in RBS volume estimation errors

Overall, the accuracy of RBS standing volume estimates did not appear biased across sampled species. Yet, RBS estimations introduced a sample error which is affected by species canopy structure and maturity of sampled trees (Table 5.4). As a general trend, the larger the tree the greater the REE recorded by species. For instance, RBS volume estimates were more similar for *P. acerifolia*, followed by *C. maculata* and less similar for *U. procera*. The number of paths followed on a given sampled tree also affected RBS volume estimates precision. Across species, volume estimations based on RBS-3 paths produced REE ranging from -11% to +42% as compared to full tree measurements data (Figure 5.3). The amplitude of the REE was further reduced to a range of -7% to +29% when RBS-5 paths were followed on sampled trees.

Tree size and branching ratio differences in RBS volume estimation errors

Species canopy structure, as expressed by branching ratio (BR), also affected RBS standing volume estimates precision (Figure 5.4). As a general trend, greater the BR the greater the imprecision of RBS estimations. For *U. procera*, a species with an average BR of 3.8, RBS-3 paths produced greater over and under estimates with relative estimation error (REE) between -30% to + 42%, respectively. REE were further reduced to a range of -15% to +29 when RBS-5 paths were chosen. In *C. maculata*, a species with a mean BR = 2.3, RBS-3 paths nor RBS-5 paths volume estimates were affected by BR values but yielded REE ranging from -13% to +18% as compared to full tree measurements (Figure 5.4). Finally, for *P. x acerifolia*, which recorded a mean BR of 3.1, RBS-derived volume estimates were slightly influenced by RB and generated REE in the range of -7% to +19% as compared to fully tree measurements.

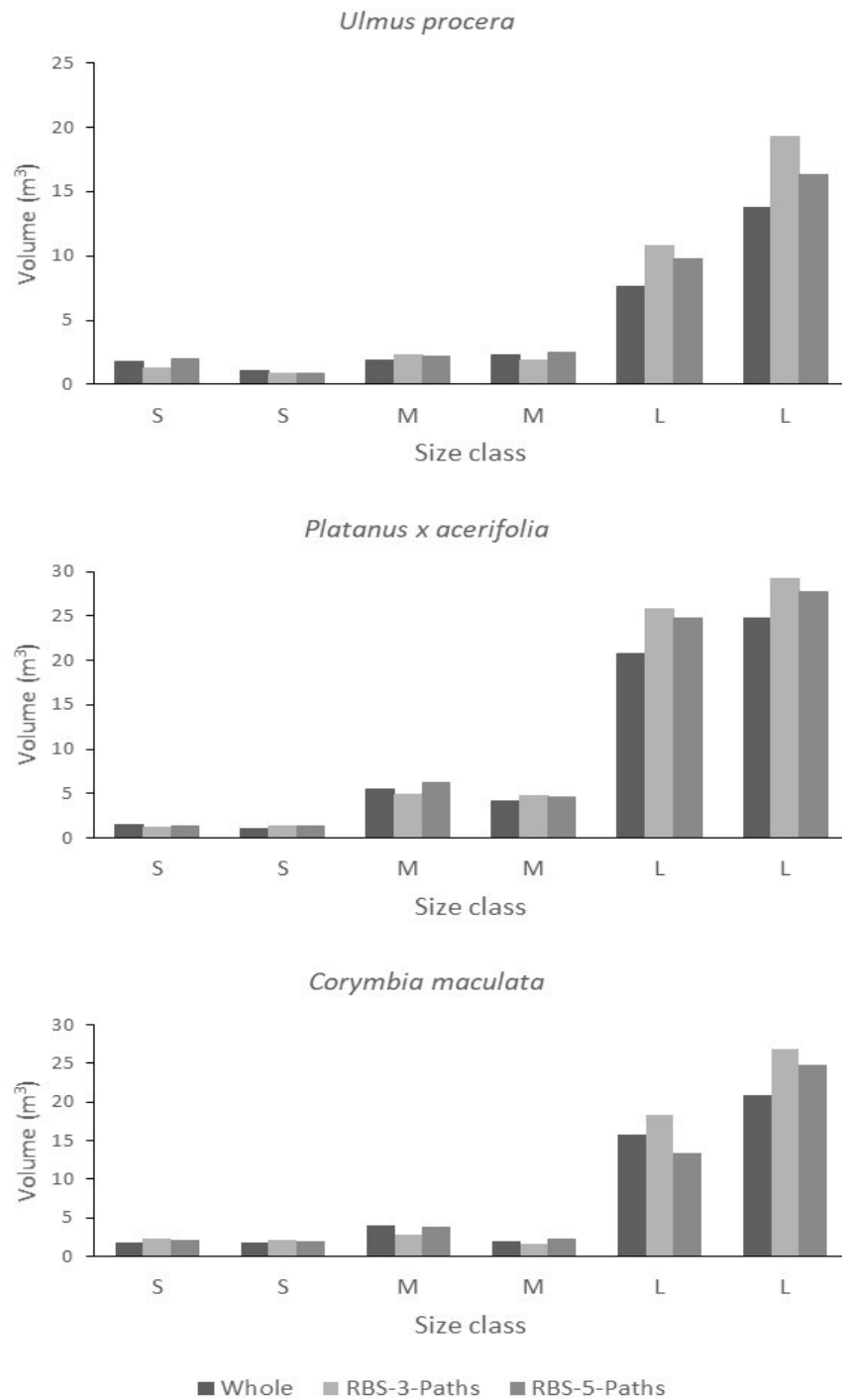


Figure 5.3 Effect of species and tree size class (S: small, M: medium, L: Large) on volume calculations using randomized branch sampling RBS-3-parths and RBS-5-paths as compared to full tree measurements (Full tree).

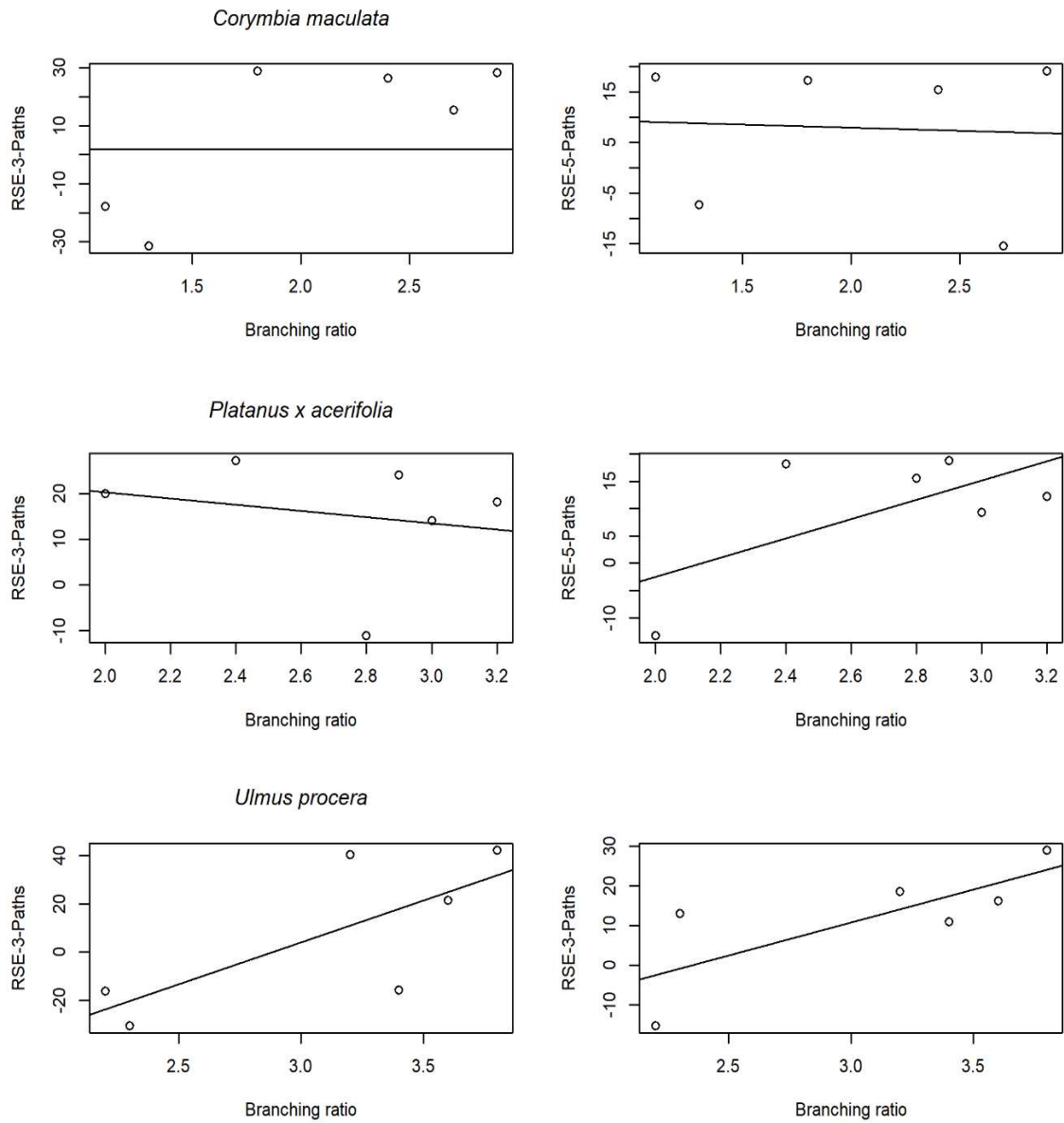


Figure 5.4 Relationships between branching ratio and relative estimation error (RSE) of volume estimates derived from the application of randomized branch sampling on fully measured trees (R^2 values for RBS-3 paths on *C. maculata*, *P. x acerifolia* and *U. procera* were 0.05, 0.55, 0.62, respectively. R^2 values for RBS-5 paths on *C. maculata*, *P. x acerifolia* and *U. procera*, were 0.03, 0.42 and 0.47, respectively). All relationships were not significant $p \geq 0.05$.

Table 5.4 Relative estimation errors (REE-expressed in %) of randomized branch sampling (RBS) volume estimates for 18 trees as a function of the number of paths carried out on the same tree. Volume for full tree (Full), RBS-3-Paths and RBS-5-Paths are expressed in m³.

Species	Tree size	Tree	D (cm)	H (m)	Full	RBS-3-Paths	REE	RBS-5-Paths	REE
<i>U. procera</i>	L	1	112.6	20.8	7.6	10.8	+42.2	9.8	+29.0
		2	84.2	19.3	13.7	19.3	+40.4	16.3	+18.6
	M	3	110.0	17.5	1.9	2.3	+21.5	2.2	+16.2
		4	42.5	9.7	2.3	1.9	-15.6	2.5	+11.0
	S	5	41.0	9.5	1.0	0.87	-16.2	0.9	-15.3
		6	33.6	10.3	1.8	1.2	-30.4	2.0	+13.1
<i>C. maculata</i>	L	1	105.8	23.7	24.7	29.2	+18.3	27.7	+12.2
		2	88.4	19.8	20.8	25.8	+24.1	24.7	+18.8
	M	3	49.2	17.2	4.2	4.8	+14.1	4.6	+9.3
		4	48.3	18.4	5.4	4.9	-11.1	6.3	+15.6
	S	5	43.4	15.0	1.1	1.4	+27.3	1.3	+18.2
		6	44.4	15.8	1.5	1.2	+20.0	1.3	-13.3
<i>P. x acerifolia</i>	L	1	115.6	20.8	20.9	26.8	+28.3	24.9	+19.2
		2	125.6	21.8	15.8	18.3	+15.5	13.4	-15.4
	M	3	63.2	14.3	4.1	2.8	-30.5	3.8	-7.2
		4	65.3	13.3	1.9	1.6	-17.8	2.3	+18.0
	S	5	32.5	8.9	1.7	2.2	+29.0	2.0	+17.3
		6	33.7	9.8	1.8	2.3	+26.5	2.1	+15.5

Notes: Tree size class: S: small, M: medium and L: large. D: Diameter. H: Height. The symbol $\pm$ denotes either under/over estimates as compared to full tree measurements data. REE is not the standard error of a given measurements. REE was calculated as the difference between volume estimates from full tree measurements and that derived from both RBS (3-5 paths) on the same tree. For further references see: (Chirici et al., 2014).

5.4.4 Section 3: Allometric relationships among species and canopy structure

Allometric relationships of sampled trees were similar within species but varied among tree structural parts. DBH-whole tree volume and DBH-tree stem volume allometry showed significant and strong linear relationship with R^2 values ranging from 0.89 to 0.95 (Figure 5.5, Figure 5.6, Figure 5.7). Across species, scaffold, 1st and 2nd order branches displayed strong and significant logarithmic relationships ($R^2 = 0.66-0.94$). While 3rd order branches of all species were better explained by a moderate and significant polynomial fitting ($R^2 = 0.45-0.86$). These findings suggest that a set of allometric equations could be developed to more accurately predict standing volume of urban trees.

Related statistics of better fitted models by structural parts are presented in Table 5.5. Although developed linear models have relatively normal precision, model's bias was significant for two sampled species. For instance, whole tree and main stem predictive models for *P. x acerifolia* had Root mean squared errors (RMSE) ranging from 4.20 to 17.73. In *C. maculata* RMSE varied between 2.15 to 7.11. For *U. procera*, RMSE values were less than 1. Finally, regression values of logarithmic models developed for all canopy structural parts (scaffolds, 1st, 2nd and 3rd order branches) produced RMSE closer to zero because of a greater sample size (the amount of data used to construct the model).

Table 5.5 Statistics of the best fitted models (based on AIC/BIC) to predict diameter-volume relationships for all measured tree structural parts.

Species/Structural parts	Diameter range (cm)	Model values	R ²	RMSE	AIC	BIC
<i>Ulmus procera</i>						
Whole tree (n=14)	23.5–110.5	$y = 0.1517x - 4.0035$ (Linear)	0.95	0.57	48.43	50.55
Main stem (n=14)	23.5–110.5	$y = 0.0545x - 1.3569$ (Linear)	0.94	0.22	17.68	19.81
Scaffolds (n=76)	19.5–70.0	$y = -0.8988 + 1.8424 \log_{10}(x)$ (Log-Log)	0.86	0.06	-3.24	6.08
1 st order branches (n=164)	9.5–44.5	$y = -0.895 + 1.8332 \log_{10}(x)$ (Log-Log)	0.75	0.06	-7.35	5.05
2 nd order branches (n=126)	5.5–21.5	$y = -0.7258 + 0.5497 \log_{10}(x)$ (Log-Log)	0.66	0.05	-26.23	-15.22
3 rd order branches (n=807)	5.5–9.5	$y = -0.0501x^2 + 0.7345x - 5.2182$ (Polynomial)	0.45	0.06	-53.03	-34.25
<i>Platanus x acerifolia</i>						
Whole tree (n=15)	24.5–125.5	$y = 0.2667x - 7.9631$ (Linear)	0.89	17.73	86.09	88.21
Main stem (n=15)	24.5–125.5	$y = 0.0509x - 1.1889$ (Linear)	0.95	4.20	63.00	65.12
Scaffolds (n=84)	7.5–69.7	$y = -1.0761 + 1.3342 \log_{10}(x)$ (Log-Log)	0.94	0.03	-61.36	-51.69
1 st order branches (n=215)	6.5–32.5	$y = -1.2173 + 1.4056 \log_{10}(x)$ (Log-Log)	0.81	0.06	14.48	27.96
2 nd order branches (n=128)	5.5–18.5	$y = -0.2875 + 0.2545 \log_{10}(x)$ (Log-Log)	0.80	0.02	-119.52	-108.17
3 rd order branches (n=896)	5.5–10.5	$y = -0.0204x^2 + 0.4346x - 4.5428$ (Polynomial)	0.86	0.01	-1479.68	-1460.48
<i>Corymbia maculata</i>						
Whole tree (n=14)	36.6–107.8	$y = 0.1617x - 4.7363$ (Linear)	0.92	7.11	70.26	72.39
Main stem (n=14)	36.6–107.8	$y = 0.0725x - 1.7772$ (Linear)	0.91	2.15	51.83	53.95
Scaffolds (n=88)	40.3–70.4	$y = -1.1252 + 1.2448 \log_{10}(x)$ (Log-Log)	0.92	0.04	-40.71	-30.80
1 st order branches (n=128)	5.0–35.5	$y = -1.0987 + 1.3089 \log_{10}(x)$ (Log-Log)	0.87	0.05	-32.39	-20.99
2 nd order branches (n=181)	5.0–27.2	$Y = -1.0957 + 1.6377 \log_{10}(x)$ (Log-Log)	0.88	0.04	-42.41	-31.01
3 rd order branches (n=594)	5.0–15.8	$Y = 0.0019x^2 + 0.2824x - 4.1773$ (Polynomial)	0.74	0.07	114.59	132.14

Notes: y = volume (m³), x = diameter (cm) RMSE: Root mean squared error, AIC: Akaike's Information Criterion, BIC: Bayesian Information Criterion. All allometric relationships/models were statistically significant at 95% of confidence. Values in () refers to the number of single measurements (samples) used for allometry construction. Diameter values refers to the range of the fitted data.

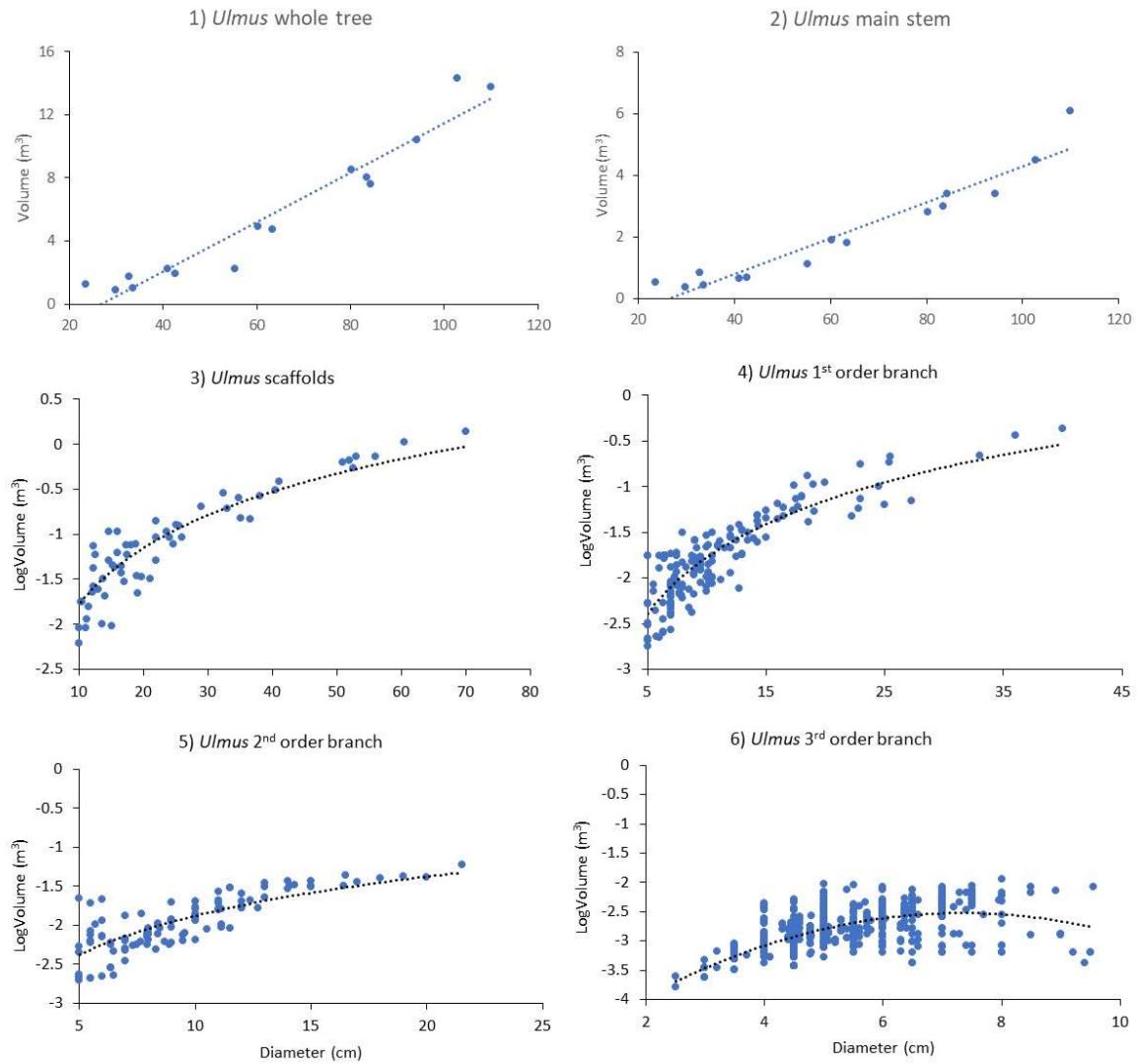


Figure 5.5 Allometric relationships of whole tree, main stem and canopy structure of *Ulmus procera* trees. Graphs display allometric relationships following the hierarchical order of canopy measurements: 1) diameter-whole tree volume, 2) diameter-tree stem volume, 3) diameter-scaffolds volume, 4) diameter-1st order branch volume, 5) diameter-2nd order branch -volume and 6) diameter-3rd order branches-volume.

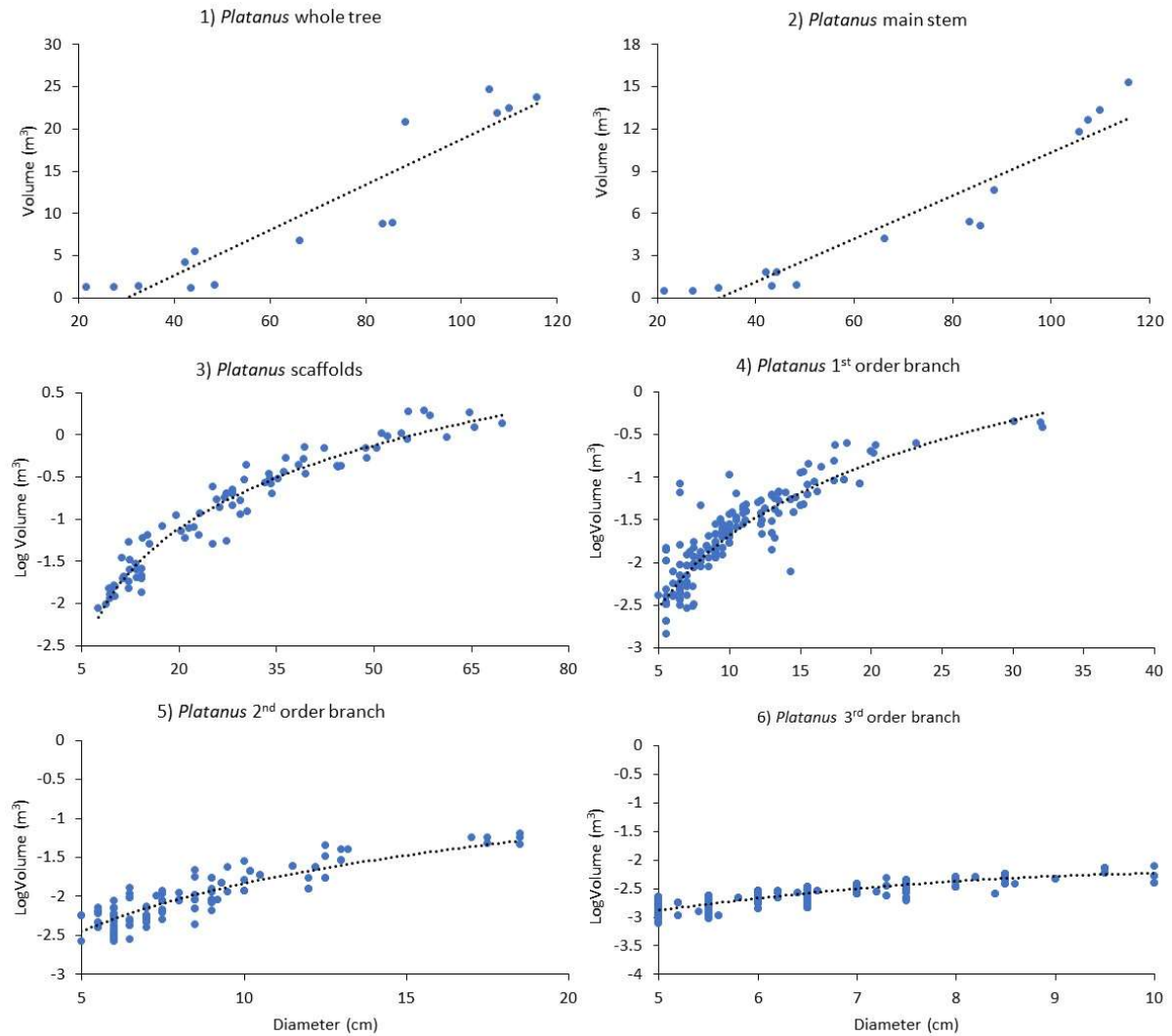


Figure 5.6 Allometric relationships of whole tree, main stem and canopy structure of *Platanus x acerifolia* trees. Graphs display allometric relationships following the hierarchical order of canopy measurements: 1) diameter-whole tree volume, 2) diameter-tree stem volume, 3) diameter-scaffolds volume, 4) diameter-1st order branch-volume, 5) diameter-2nd order branch -volume and 6) diameter-3rd order branches-volume.

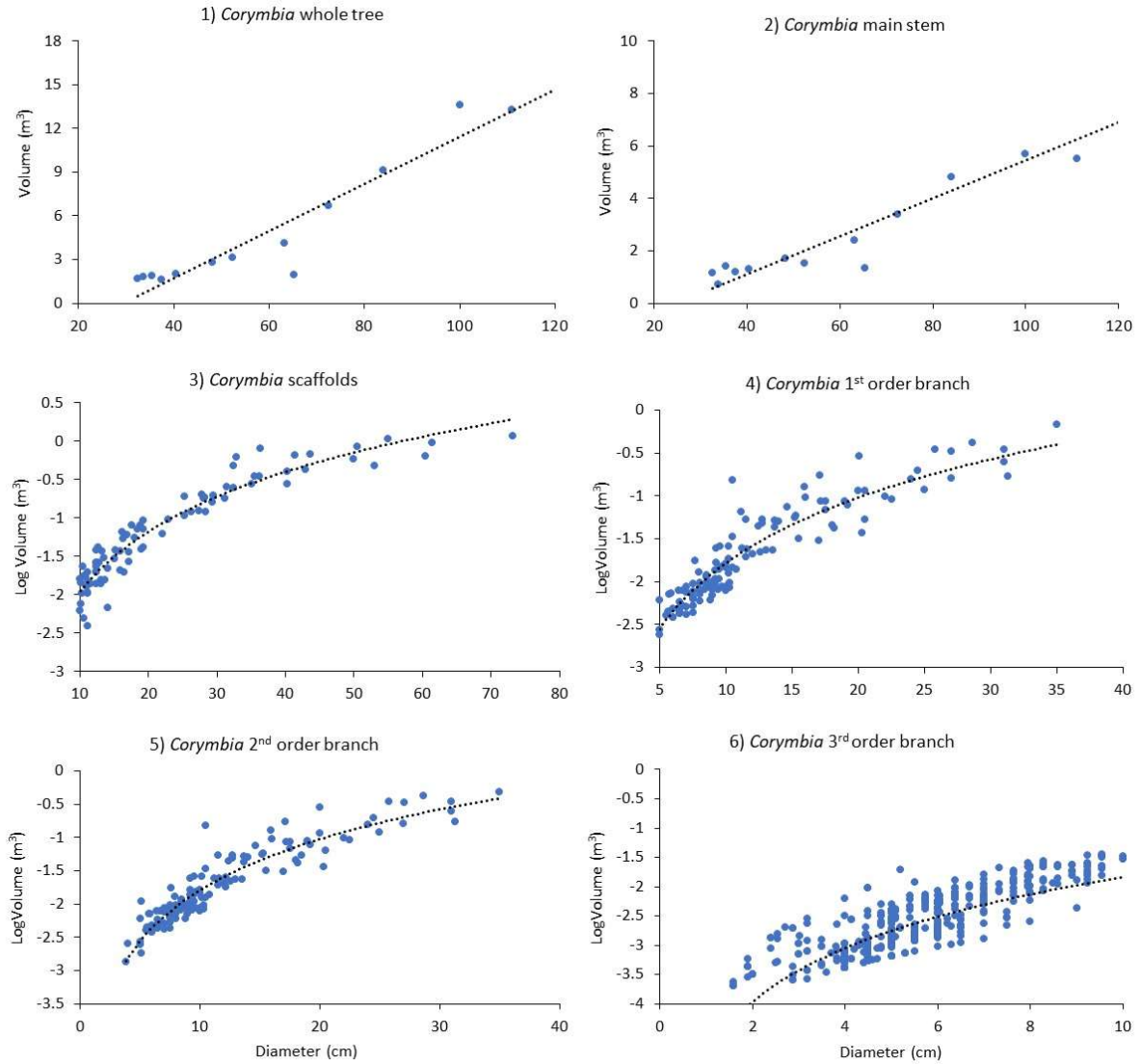


Figure 5.7 Allometric relationships of whole tree, main stem and canopy structure of *Corymbia maculata* trees. Graphs display allometric relationships following the hierarchical order of canopy measurements: 1) diameter-whole tree volume, 2) diameter-tree stem volume, 3) scaffolds diameter-volume, 4) 1st order branch diameter-volume, 5) 2nd order branch diameter-volume and 6) 3rd order branches diameter-volume.

5.4.5 Section 4. Factor in volume loss due to decay in standing trees

As shown in Figure 5.8, although the USA-model for *U. americana* was developed from trees growing in urban settings, when applied to our sampled *U. procera* trees, this model clearly underestimates the projected standing volume. The magnitude of the difference between these two estimates was greatest for large and medium size class trees. On average, the USA-model

estimated between 18% to 35% less standing volume as compare to full tree measurements. Yet, when a species-decay factor is applied to the main stem of six fully measured *U. procera* trees, a more accurate estimation of standing volume is given across tree size classes. This practical assessment highlights the necessity for developing species-specific allometric equations to more accurately assess above-ground biomass and stored carbon in urban trees.

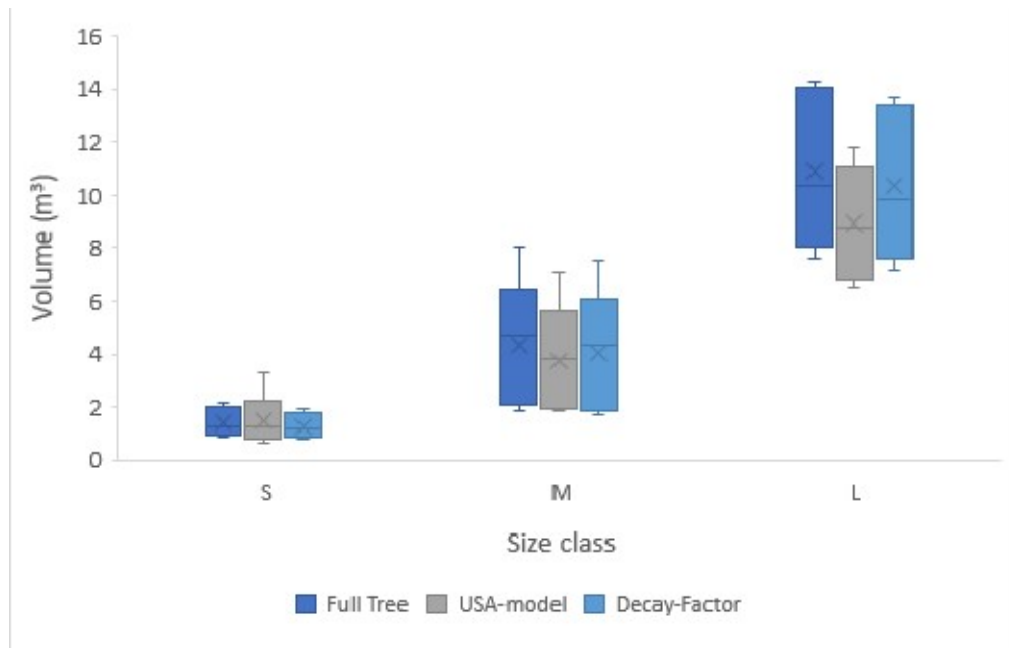


Figure 5.8 Standing volume of six fully measured *U. procera* trees (Full tree) by tree size class (S: small, M: Medium and L: Large) from this study. Full tree volume estimates which included tree stem volume loss due to internal decay wood (Decay factor of 13%) and standing volume yield as predicted by the published urban equation (USA-model) for *U. americana*. Model and values of the allometric equation used was: $V = a * (DBH)^b$, where V: standing volume (m^3), a: 1.8×10^{-3} and b: 1.869, $R^2 = 0.92$, RSE: 0.268 (McHale et al., 2009).

5.5 Discussion

5.5.1 Canopy structure and branching ratio among species

Most studies on crown structure of urban trees are focused on mechanical strength, stiffness and the effect of wind or imposed load on tree stability (Duryea et al., 2007; James et al., 2014; Kane et al., 2013; Miesbauer et al., 2014; Sanders et al., 2013; Sellier et al., 2009). Full tree measurements done in this study allowed not only to provide solid data on the number and dimensions (diameter, length and volume) of crown structural parts but also to assess both slenderness ratio (SR) and branching ratio of urban trees.

In this regard, all measured structural parts exhibited slenderness values (SR) well above the safety threshold of 0.5 but clear trends across species and structural parts was observed. For instance, in *U. procera* SR values decreased from scaffolds towards 3rd order branches while the opposite was true for *C. maculata*. The highest SR value was registered in *P.x acerifolia* trees across size class. A similar shift in SR among branches within species and across a wide range of species was observed by Dahle et al. (2014) and Rust (2014), respectively. Changes in SR resulted when branches modify their function transitioning from flexible to stiffer structural branches (Dahle et al., 2009; Grabosky et al., 2007). Data of SR provided in this study along with information on species wood density, may inform arborists and urban foresters whether a branch may pose a risk of injury to the public or to justify either pruning or branch removal (Ellison, 2005; Mattheck et al., 2005; Velázquez-Martí et al., 2013).

Branching ratio (BR) values recorded in this study varied among species and tree size class. *U. procera* trees registered the greatest (BR= 3.8), followed by *P.x acerifolia* (BR=3.1) and the

lowest value was recorded in *C. maculata* (BR=2.8). Across species, BR values increased as tree size enlarged. This increasing pattern of BR values is closely related with the current “stage of life” of each sampled tree. Small and medium size trees were excurrent in form, with faster growth rate and, therefore branched less than those mature individuals. Older trees, thus large decurrent trees, tend to have less internodal growth and branched more as result of less competition in open grown conditions (Dahle et al., 2009; Gebuek et al., 2008; Ryder et al., 2013).

BR is one of the most conspicuous features of woody plants, yet little investigated in urban settings. For instance, Pickett et al. (1980) examined *Acer saccharum*, *Quercus rubra* and *Fraxinus americana* in natural stands and found significant differences in BR between habitats. More exposed individuals had higher branching ratio and longer terminal branches than those beneath the canopy. In our study all individuals were in the “exposed” category belonging to urban parks. We did not measure individuals in street canyons or clustered trees which would mimic trees beneath a tree canopy in a natural forest. Nevertheless, measuring less sun exposed trees in urban sites would be a natural extension of this study.

The role of tree crown shape and size has been overlooked in theoretical biomass work. For instance, Goodman et al. (2014) found that tropical trees with a monopodial architectural type are estimated to have 21–44% less biomass than trees with other growth patterns such as urban trees. Trees in natural stands cope with space limitations and vertical light stratification by changing their crown architecture, therefore, diameter-crown size, diameter-crown shape and volume relationships changes over time (Alvez et al., 2002; Diaz et al., 2016; Manuri et al., 2017; Osada, 2012; Osunkoya et al., 2007). This natural crown allometry pattern is altered

because of challenging growing conditions and tree management in urban settings (Day et al., 2011; Pretzsch et al., 2017; Riikonen et al., 2011; Vaz Monteiro et al., 2016).

For instance, Pretzsch et al. (2015) reported varying crown allometric relationships among 22 urban tree species across planting sites. The authors claimed that changes in dimensional relationships need to be taken into account when selecting growing space requirements. Likewise, Blood et al. (2016) using a large regional dataset with 12 locations in southeastern USA, developed stronger diameter-based equations for 97 urban tree species to reliably predict tree crown features when site factors such as crown light exposure, land cover and locations were included. The authors concluded that man-influenced variation among cities can lead to significant differences in both tree form and structure thus affecting allometric relationships over time. Crown plasticity was not evaluated in this research but including trees growing in a wider range of planting sites (i.e. streets, median, roads, parking lots) could offer the opportunity to further test this theory in urban trees.

5.5.2 Volume distribution among species

Woody plant biomass distribution in natural habitats is modified by size, stage of life and competition level (Carbone et al., 2013; Diaz et al., 2016; Poorter et al., 2015; Poorter et al., 2012; Reich et al., 2014; Urban et al., 2014). In our study, whether a tree displayed either an excurrent or decurrent canopy affected volume distribution patterns registered. Overall volume distribution among sampled trees was 40% to the main stem and 60% to the crown, yet, as tree size increased, trees tended to proportionally allocate more volume to crowns in these exposed urban sites. In this study, volume distribution of sampled trees differed from that reported for

trees growing in forests (Birdsey, 1992; Good et al., 2001; Montagu et al., 2005) and from other species growing in peri-urban and urban settings elsewhere (Banks et al., 1999; Brack, 2006; Ossola et al., 2017; Tahvanainen et al., 2008).

Dobbs et al. (2011) sampled younger (DBH 10-80 cm, height 5-25 m), thus excurrent urban trees in Santiago, Chile and reported a distribution pattern of whole tree biomass as follows: approximately 7 % for leaf biomass, 24 % for branches, and 69 % for stem. This reported biomass distribution pattern resulted presumably due to the young age of sampled trees. This may explain to some extent the reason why DBH-based allometric equations developed for forest-grown trees tend to under or overestimate biomass for urban open-grown trees (Lefsky et al., 2008; McHale et al., 2009; McPherson et al., 2012; Peper et al., 2014).

5.5.3 Allometric relationships of tree structural parts

Current knowledge on canopy structure and allometric relationships of urban trees is limited. Geometric shapes and basic measurements such as crown width, crown height, crown volume and crown projected area have been used to assess canopy structure, tree dimensional relationships and shade patterns of urban trees (McPherson, 1988; Moser et al., 2015; Simpson et al., 1998; Stoffberg et al., 2008; Troxel et al., 2013; Vaz Monteiro et al., 2016; Wilkinson, 1995; Xiao et al., 2003). Although sample size of fully measured trees was small (six trees/species, two trees/size class), this study agreed with Peper et al. (2014) that canopy volume distribution of urban trees is relevant for allometric construction.

As shown in Table 5.5 allometric relationships of sampled trees were similar within species but varied among tree structural parts evaluated. DBH-whole tree and DBH-main stem showed significant linear relationships whereas diameter-scaffolds and diameter-branches of all order displayed both logarithmic and polynomial associations. Numerous studies confirmed that urban trees do exhibit different allometric relationships within the canopy.

Dahle et al. (2010) reported a shift in allometry from flexible sun branches to stiffer structural branches of *Acer platanoides* grown in a peri-urban forest. Later, Dahle et al. (2014) reported, although overall trends in DBH-biomass relationships were consistent across urban sites, several allometric relationships in *Betula populifolia* populations. Riikonen et al. (2011) found a strong influence of soil water content and time after transplanting on crown allometry of *Alnus glutinosa* and *Tilia x vulgaris* street trees. Relationships between medium branch leaf area and branch basal area were close to linear in *Tilia* trees whereas small branches exhibited more exponential relationships. Likewise, Suzuki et al. (2000) reported different allometric relationships among 1st order branches (called scaffolds in this study) and 2nd and 3rd order branches of 10 tree species in peri-urban forests.

Although linear models developed in this study have relatively normal precision, models' bias were significant for two sampled species (*P. x acerifolia* and *C. maculata*). This issue can be partially explained by a small sample size (15 trees per species) used for developing all equations. Similar issues in regards to allometry construction of urban and peri-urban trees were reported by Urban et al. (2012) and Dahle et al. (2014). Models constructed from a small number of samples and limited tree diameter range have the potential risk to be biased,

especially when applied beyond their sample framework (Day et al., 2011; Jara et al., 2015; McHale et al., 2009; Peper et al., 2014).

In addition, linear models developed for whole tree and main stem in this study should be applied cautiously outside the studied population since it was tested that volume predictions for small tree diameter (≤ 20 cm) yielded negative values. Therefore, for a sound standing volume estimation, it seems reasonable to limit their application to the fitted DBH range data (40 -100 cm) (Hounzandji et al., 2014; Jara et al., 2015). Regression values of logarithmic models constructed for all crown structural parts (scaffolds, 1st, 2nd and 3rd order branches) produced Root mean squared error (RMSE) closer to zero because of a greater sample size, so generated allometric equations have a stronger predictive power.

5.5.4 Suitability and reliability of RBS to estimate standing volume

RBS has been recently applied as an alternative method to estimate above-ground biomass of both natural and urban trees (Bascietto et al., 2012; Dobbs et al., 2011b; Ducey et al., 2009; Evans et al., 2007; Good et al., 2001; Gove et al., 2002; Schlecht et al., 2014). However, none of these investigations made any comparison against either destructive sampling or full tree measurements. In this study and across species, RBS systematically under- or over-estimated standing volume in the range of -31% to +42% as compared to full tree measurements. RBS estimations introduced a sample error which was affected by species canopy structure and maturity of sampled tree. In the broadest sense, the larger and higher the branching ratio (BR) the greater the relative estimation error of RBS-derived standing volume calculations.

In this study which RBS-sampling path should be followed on each tree was defined as the probability proportional to basal branch diameter raised to the 2.5 power, RBS-derived estimates can be considered biased since this sampling strategy constantly avoided measuring small diameter branches (<5 cm) within tree canopy. As per full tree measurements data shown in Table 5.3 and Figure 5.2, branches of 3rd order had diameter ≤ 5 cm and they accounted for 5% of whole tree volume, which seems to be a constant error within RBS-derived estimates. These results are consistent with Good et al. (2001) who found that RBS consistently underestimated leaf biomass and small diameter branches (<3 cm) of *Eucalyptus populnea* plantation trees thus producing weak predictive equations for whole tree volume. Yet, the study recommended RBS as a viable alternative to current methods available to calculate above-ground biomass of open-grown trees.

Results from this study suggest that RBS-5 paths are an adequate sampling effort to estimate standing volume of urban trees with simple canopy structure (low branching ratio) such as the one exhibited by *P. x acerifolia* and *C. maculata*. However, RBS-5 paths seem to be unsatisfactory to reliably estimate standing volume of species resembling *U. procera* canopy structure. For the latter species, it seems that at least RBS-7 paths would be required for a sound estimation of standing volume (Chirici et al., 2014; Ducey et al., 2009; López-López et al., 2017).

The fact that data collected from both six fully measured trees and nine RBS-sampled trees were combined for allometry construction and, as proven, RBS estimates produced over/under estimations in the range of -31% to +42% as compared to full tree measurements, predictive models for whole tree volume developed in this study factored in this RBS sampling error. A

suitable way to test and improve RBS precision to estimate standing volume and further develop allometric equation for urban trees could be 1) increase RBS paths, from five to seven or greater to be carried on sampled trees, 2) contrast the accuracy of developed equations against other equations developed via destructive sampling and 3) test the resulting volume predictions of constructed models against published models (Dobbs et al., 2011b; McHale et al., 2009; McPherson et al., 2012; Peper et al., 2014). Nevertheless, the set of allometric models for scaffolds and branches of all orders derived from this study could be useful to calculate the amount of merchantable wood or residual wood removed by pruning (Grabosky et al., 2007; López-López et al., 2017; Sajdak et al., 2012; Velázquez-Martí et al., 2013).

Given that the RBS-5 paths itself resulted in a large range of errors (-11 to +29%) as compared to full tree volume estimates, caution should be taken when using RBS-derived equations generated in this study. There is no doubt that the reliability of whole tree predictive models generated in this study would be improved by following RBS-7 paths on sampled trees before scaling up their application. These results are partially in line with Chirici et al. (2014) who tested RBS against full tree measurements and recommended five to seven paths (for trees with regular and irregular shape, respectively) to maintain RBS above-ground biomass estimation errors in the range of 10%-15%.

Finally, given the time-consuming effort required to measure five random selected paths on medium and large *U. procera* trees (based on field working records took approximately six hours/tree) and because of the large range of estimation error (-32 to + 42%) registered, tree climbing, or alternative practices should be used to fully measure trees and construct more reliable equations for this and possibly other species.

5.5.5 Factor in decayed wood loss into stored carbon calculations

By combining allometric models developed in this study and applying a species decay factor proposed by Orozco-Aguilar et al. (2018) it was demonstrate that the application of a standard factor (0.8) proposed by Nowak et al. (2002a) to calculate volume yield of urban trees is not valid for trees in this study. A significant reduction of standing volume (up to 57%) due to decayed wood in both natural and urban trees is reported elsewhere (Brazee et al., 2010; Cousins et al., 2015; Koeser et al., 2016; Luley et al., 2009; Terho et al., 2008), hence a species-decay factor suggested here (13%) might vary widely among species and across urban settings.

5.6 Conclusions

This study provided solid data on canopy structure, standing volume distribution and allometric relationships of urban trees. Crown's hierarchical classification adopted in this study allowed to 1) measure the number and dimensions of tree structural parts of sampled trees, 2) explore, to some extent, woody volume distribution of three different species, 3) assess dimensional relationships of all crown's structural parts and; 4) test the suitability and reliability of RBS to estimate and predict whole tree standing volume. Overall, sampled trees distributed 40% of whole tree volume to stems and 60% to crowns which differed from that described for other urban trees elsewhere. RBS constantly under-or over-estimated standing volume in the range of -31% to +42% as compared to full tree measurements, therefore RBS should be used only when there are no other accurate methods available to estimate woody volume and develop allometric equations. The set of allometric equations developed in this study may be potentially used for 1) tree growth modelling, 2) to more accurately estimate standing volume and merchantable wood of *Ulmus*, *Platanus* and *Corymbia* tree populations city-wide and, 3) to

assess branch biomass and C loss or movement off-site in pruning residues, to improve the accuracy of life cycle assessment of urban trees.

Chapter 6. General Discussion and Synthesis

6.1 Introduction

Tree growth rate and allometry underpin tree growth modelling and consequently the assessment of urban tree benefits. Nevertheless, currently models used to quantify tree carbon stocks and growth rate do not consider many of the unique issues inherent in urban tree growth and management. Urban trees undergo regular maintenance practices such as pruning and lopping which can cause strong signals in tree-ring series and, wounding and other mechanical injuries that may function as an entry point for decay infection (Koeser et al., 2016; Luley et al., 2009; Schwarze et al., 2006). Moreover, drought; whether induced by turning off irrigation or climatic due to low rainfall; may alter biomass yield and allometric relationships within canopy structural parts (Blood et al., 2016; Moser et al., 2015; Peper et al., 2014; Pretzsch et al., 2015). The urban heat island effect, pests and diseases outbreaks, and soil nutrient decline, soil compaction and restricted growing space can affect tree vitality over time (Dobbertin, 2005; Martinez-Trinidad et al., 2010). Finally, urban trees grow in a diverse range of planting sites and span an artificially wide age-size distribution, hence it is likely that this heterogeneity will lead to non-uniform tree growth patterns and will complicate using generic allometric models to assess above-ground biomass. This set of site and management conditions lead to the need for the development of species-specific allometric equations for open-grown trees (Lee et al., 2016; McHale et al., 2009; McPherson et al., 2012).

The aims of this PhD research were: 1) to evaluate a quick, reliable and semi-invasive method for estimating tree growth rate, 2) to factor in the overlooked volume loss due to decayed wood in stored carbon calculations and, 3) to develop allometric equations for several urban tree species. To achieve these research aims, a combination of approaches was applied to study

three key aspects of urban forests. Firstly, the reliability of resistance drilling (RD) was tested to assess trends in the growth of several urban trees and explore RD's potential to link tree-growth with past climatic conditions. Secondly, advanced climbing techniques and RD was used to map the occurrence and extent of decay along the stem of standing trees; and a model was constructed to predict internal decay in one sampled species. Lastly, complete tree measurements were combined with randomized branch sampling to explore urban tree canopy structure and assess biomass distribution in three different tree species and hence, develop species-specific allometric equations.

The research approaches and outcomes of this PhD study will aid urban foresters to make informed decision on tree selection, the assessment of growth trends, improve tree management and conduct more realistic valuation of urban tree benefits, particularly in the City of Melbourne (May et al., 2013; Moore, 2009; Nitschke et al., 2017). This synthesis chapter will draw together all studies presented in Chapters 3, 4 and 5 and will summarize their main findings, significance, limitations and further research opportunities. Overall, this PhD constitutes a significant step in urban forestry science which advances our knowledge on 1) measuring urban tree growth, 2) assessing decay and stored carbon and, 3) exploring allometric relationships of open grown trees. In addition, each experimental chapter of this PhD study delivers important outcomes with important implications for tree management and research (Table 6.1).

Table 6.1 Knowledge gaps addressed in each experimental chapter and main findings and research/management implications.

Experimental chapter	Knowledge gaps	Key findings and research/management implications
1. <i>Testing the accuracy of resistance drilling to assess growth rate and the relationship with past climatic conditions.</i>	Usefulness and reliability of resistance drilling (RD) to perform rig analysis of urban trees was unknown/untested.	A novel method (less-invasive, faster and reliable) to assess trends in growth is now available. This method could aid urban forest management where tree growth rates of a tree population need to be rapidly assessed in a robust manner. RD should not replace dendrochronology for tree-climate-growth research.
2. <i>The overlooked carbon loss due to decayed wood in urban trees.</i>	The distribution pattern and detrimental effect of decayed wood in biomass yield/stored carbon calculations of urban trees was overlooked.	The distribution pattern and extent of decay is species-dependant and can be aggravated by arboricultural practices. A species-decay factor is proposed to more accurately estimate above-ground biomass. The detrimental effect of decayed wood on stored carbon can no longer be overlooked.
3. <i>Standing volume distribution, canopy structure and allometric relationships of urban trees.</i>	Species-specific allometric equations are lacking. Biomass distribution and canopy allometric relationships of urban trees was poorly understood.	Understanding volume distribution and yield of several tree structural parts and developing allometric equations may aid in reducing the error in whole tree volume estimations. A set of allometric equations to predict standing volume of three abundant species in the city of Melbourne is now available.

Source: Based on findings reported in each experimental chapter.

6.2 A novel way to assess growth rate of urban trees

The development of a less-invasive method for assessing tree growth rate faster that provides reliable results is clearly beneficial for researchers and urban foresters. The investigation done in Chapter 3 constitutes the first impartial research which tested the scope and limitations of resistance drilling (RD) to conduct ring analysis in *Quercus robur*, *Platanus x acerifolia* and *Ulmus procera* urban trees. Regression analysis indicated that RD annual ring width datasets were significantly correlated with paired cored annual ring width dataset ($R^2 = 0.78 - 0.96$, $P \leq 0.05$) across species. Based on the identification of pointer years (years with remarkable growth) RD was confirmed as suitable and reliable in assessing the growth trends of these three species, but only to some extent.

For instance, it is argued in Chapter 3 that RD may provide consistent estimates of average growth rate at population level but is limited in the detection of the inter-annual variation of diameter growth at tree level. In terms of urban tree management, this finding supports the argument that RD can be used, instead of core sampling, to evaluate growth trends of a population of urban trees with statistical confidence. Moreover, in agreement with Lukaszkiwicz et al. (2005) who successfully used RD to develop a tree-age predictive model based on DBH of 50+ *Tilia cordata* trees of known age, it was established that the accuracy of RD to assess tree age of sampled *Q. robur*, *U. procera* and *P. x acerofilia* trees decreases as individuals get older (≥ 60 years), therefore, it seems that RD may yield more reliable age estimates for younger individuals (e.g., < 50 years old) when tree rings are usually thicker (Bartens et al., 2012; Ise et al., 2008). From the research point of view and in the absence of city's planting records, RD can be used to estimate the age of urban trees across planting sites

and combine this input with tree attributes to develop predictive equations of tree dimensions (Blood et al., 2016; Peper et al., 2014; Stoffberg et al., 2008; Troxel et al., 2013).

Furthermore, Chapter 3 documented that the accuracy of RD to assess growth rate declined when annual ring width was < 1 mm. This result challenges the findings of two previous studies: 1) Wang et al. (2003) who, regardless of ring width values; reported that RD reliably assessed growth rates of *Taiwania cryptomerioides* plantation trees and, 2) Rinn et al. (1996) who claimed that the lowest value for ring width identification from RD profiles is 0.5 mm. Chapter 3 provided solid comparative analysis to question these two assumptions. Recent research which used a similar approach of this study reported high reliability of RD to assess tree age but low accuracy in measuring ring width narrower than 2 mm (Szewczyk et al., 2018). RD's reliability can be improved by following a sound sampling strategy, hence potential users of RD should target young-mature trees, visually healthy and avoid those individual heavily affected by decay to ensure meaningful data for urban forestry research is collected.

Another significant outcome from Chapter 3 is the provision of a sound analysis to clarify the debate about the usefulness of RD to perform ring analysis. In this regard and based on the application of both the Jaccard similarity and mean intercorrelation tests (a standard procedure within dendrochronology) it was concluded that, since the RD growth series did not yield cross-dating index greater than 0.5 across species, RD should not be used to replace dendrochronology in climate-tree growth studies.

Finally, in Chapter 3 also highlighted that the accuracy of RD for ring analysis varied according to species wood anatomy and the incidence of internal decay. These two conditions affected the ability of RD profiles to correctly identify and delineate annual rings. When selecting appropriate field less-invasive tools for determining growth rate of standing trees (Core sampling or RD), it is important to note that the solution must meet the needs of practicing urban foresters, and reasonable estimates of mean growth values with measurable errors will be more useful than expensive, complicated procedures of greater accuracy required for traditional dendrochronology (Gao et al., 2017; Heinrich et al., 2013).

This research is limited by the fact that only tree species for which cored-growth series were available could be sampled, thus narrowing the number of urban tree species that could be studied elsewhere. Nevertheless, these tree species are widely planted in urban landscapes globally, thus maximizing the relevance of the chapter. Further research is required on other urban tree species (native and exotics) to confirm the usefulness of the novel RD method for estimating the growth rate of urban trees in different locations and climatic growing zones.

6.3 Assessing the occurrence and extent of decay in urban trees

Understanding the distribution pattern and detrimental effect of internal decayed wood on above-ground biomass estimates, therefore stored carbon, advances our knowledge pertaining to the valuation of urban tree benefits. It was demonstrated in Chapter 4 that decay is a significant issue in *Ulmus procera* trees and may occur in a wide range of tree stem diameters and vitality indices. Chapter 4 also confirmed that wood decay is less frequent and severe in visually healthy *Platanus × acerfolia* and *Corymbia maculata* sampled individuals.

Decay assessments followed in Chapter 4 were framed in the CODIT model (Compartmentalization of Decay in Trees) proposed by Shigo (1965) and in accord with an expert system devised by Johnstone et al. (2007). As a generalized theory, the CODIT model states that decay spreads faster along the stem than in a cross-sectional direction. Nevertheless, a throughout understanding of the CODIT model is essential to comprehend the distribution patterns of decayed wood found in this study. Within the CODIT model, walls 1, 2 and 3 are movable and, wall 4 is stationary. Wall 1 resists vertical spread, wall 2 resists inward spread and wall 4 resists lateral spread of microorganisms. Wall 4 (known also as barrier zone) separates the xylem present at the time of injury and infection from the xylem that forms later. Once formed, wall 4 remains in place, but walls 1, 2 and 3 may recede or give way to the pressure of the spreading microorganisms (Shigo, 1965). Thus, discolored and decayed wood may longitudinally increase in volume within the boundaries set by wall 4.

In this regard, the premise of the CODIT model was confirmed, but also the incidence, severity and distribution pattern of decay is strongly species dependent; and based on recorded data, it seems that indiscriminate pruning of large limbs or branches of species such as *P. x acerifolia* and *C. maculata* might result in wood decay (Eisner et al., 2002; Gilman et al., 2006; Orozco-Aguilar et al., 2018). Frequent and sometimes inappropriate pruning weaken *P. x acerifolia* trees and increase their susceptibility to the attack of wood decay fungi (Heredia et al., 2014; Vinciguerra et al., 2007). A field study on natural *Eucalyptus nitens* stands (a close *C. maculata* relative) in Tasmania Wardlaw et al. (1999) reported a range of 13-16% of sampled trees as having columns of discoloration and decay spreading from pruned stubs into the main stems. The risk of a pruned branch being associated with spreading decay columns increased with

increasing branch diameter. However, further research is needed to test this generalization across urban planting sites and a set of species.

Correctly assessing the stability and safety of trees in public places can be achieved through several means of assessment (Ellison, 2005; Fink, 2009; Koeser et al., 2017; Mattheck et al., 1994). In Chapter 4, it was established that decay occurs at the base, but also along the stem and crown position of visually healthy *U. procera* trees but was less likely to be distributed beyond a height of 2.3 m in healthy *P. x acerifolia* and *C. maculata* trees. In these last two species, decay was only present in the crown of those trees that had been severely pruned or had broken branches within their canopy. Reported findings in Chapter 4 and those from a few published studies (Frank et al., 2018; Marra et al., 2018; Oliva et al., 2011) confirmed the need for effective tree risk assessment of both stem and branches in order to fully document the severity and extent of decayed wood and improve regular tree care guidelines.

For instance, core-sampling or resistance drilling an *U. procera* tree at the standard DBH point seems to be enough to detect the presence/absence of decay but does not provide sound information to estimate the extent (severity) of decay along the stem. If an arborist commissioned to conduct a decay assessment tested a pruned *P. x acerifolia* tree at the standard DBH point it is likely that the risk assessment will deem the subject tree as having an acceptable level of decay when the opposite may be true if additional tests are not done near the crown (Ellison, 2005; Mattheck et al., 2005). In *C. maculata*, decay was distributed as pockets of variable shape and size along the stem, making decay assessment a challenging task.

The visual vitality index (VVI) proposed by Johnstone et al. (2012) and used in Chapter 4 was unsuccessful in predicting the occurrence of internal decay of *U. procera* sampled trees, a low wood density species classified as poor compartmentalizer of decay (Luley et al., 2009). In practical terms, this finding indicates that visual vitality inspections of trees within low density genera must be combined with the examination of decay along the stem to provide a comprehensive tree risk assessment in public places. On the other hand, the VVI did show a significant but weak correlation with internal decay along the stem of *P. x acerofolia* and *C. macualta* sampled trees. Both species have higher wood density values than *U. procera*, and thus are capable of limiting decay more successfully (Mucciardi et al., 2011).

Overall, these findings suggest that the general health of a tree is more significant for the development of decay in trees that compartmentalize more strongly than in ‘weak’ compartmentalizers. However, further research is needed to test this generalization across urban planting sites and tree species. Even though, the VVI index used in this study accounted for dead branches within tree canopy, this study did not test the occurrence and extent of decay in large branches or changes of wood density along the stem, limbs and branches which may increase the whole tree volume loss in standing trees (Cousins et al., 2015; Frank et al., 2018; Heikura et al., 2008; Marra et al., 2018). A subsequent study which assesses decay along scaffolds may aid in a more accurate estimation of the extent of decay in urban trees.

A correlation matrix devised to explore the relationship of tree attributes and stand features suggested that VVI and competition status (number of trees within 10 m radius) will potentially explain the occurrence and severity of decay in standing *U. procera*. Although the linear model constructed in Chapter 4 was quite strong ($R^2 = 0.80$, $P = 0.0046$), sample size was small

($n = 15$), therefore its predictive power and extrapolation potential are considered limited. A further assessment which includes a greater tree sample size across planting sites may assist in developing a more robust predictive model for sampled species in general and, for *U. procera* in particular. The research protocol for assessing internal decay described in Chapter 4 may be useful in documenting and quantifying the occurrence and extent of decay in many urban trees worldwide. Further investigations on other tree species commonly planted in urban landscapes and assessing decay on a greater sample size are required to develop new species-decay factors which may assist in a more realistic valuation of internal decayed wood in standing urban trees.

6.4 Improving standing volume estimates and allometry of urban trees

Understanding how different urban tree species partition biomass to their different structural components and developing species-specific allometric equations is important for more accurate estimations of above-ground biomass and carbon stocks (MacFarlane et al., 2017; McHale et al., 2009). Using advanced climbing techniques to fully measure standing trees, Chapter 5 provided unique data on canopy structure, above-ground woody volume distribution and allometric relationships for three common trees growing in the city of Melbourne. The set allometric models developed in Chapter 5 may be used for tree growth modeling of *U. procera*, *P. x acerifolia* and *C. maculata* populations in cities with similar climates to Melbourne. In addition, predictive equations for branches of all orders developed in Chapter 5 could be useful to calculate the amount of merchantable wood or residual wood removed when pruning urban trees (Grabosky et al., 2007; Sajdak et al., 2012; Sajdak et al., 2014; Velázquez-Martí et al., 2013). More importantly, allometric equations built in Chapter 5 may perhaps be used to assess branch biomass and C loss or movement off-site in pruning residues, to improve the reliability

of life cycle assessment of urban trees (McPherson et al., 2015; Strohbach et al., 2012a; Weissert et al., 2014).

Although sample size of fully measured trees in Chapter 5 was small (six trees for each of the three-tree species), this study demonstrated that biomass distribution patterns of sampled trees differed from that described for other urban trees elsewhere (Dobbs et al., 2011b; Good et al., 2001; Poorter et al., 2015). In agreement with Peper et al. (2014) it was demonstrated that canopy volume distribution of urban trees is relevant for allometric construction. Since destructive sampling to estimate above-ground biomass is not always practical in urban settings, alternative methods are needed. Among these methods, randomized branch sampling (RBS) is a promising one which has been widely used elsewhere (Bascietto et al., 2012; Cancino et al., 2005; Dobbs et al., 2011b; Ducey et al., 2009). In this regard, Chapter 5 constitutes the first reported investigation comparing the accuracy of RBS against full tree measurements for allometry construction of trees grown in urban contexts. In Chapter 5, it was documented that, regardless of species and tree size, RBS systematically under- or over-estimated the standing volume in the range of -31% to +42% as compared to full tree measurements, in line with Chirici et al. (2014).

Based on findings, Chapter 5 concluded that RBS is not as adequate as previously stated and should not be used in isolation to calculate allometric models for urban trees. Chapter 5 confirms that RBS-5 paths may be a sufficient sampling effort to estimate standing volume of urban trees that exhibit a canopy structure similar to *P. x acerifolia* and *C. maculata* but is not recommended for those species resembling *U. procera* canopy structure. Given the amount on

time (4-6 hours per tree) needed to measure the five randomly selected branches on medium and large trees, it is recommended that skilled arborists be used to climb and measure trees entirely and develop reliable allometric equations of urban trees using whole tree measurements.

Crown stratification has been proposed as a mean to increase the reliability of RBS when sampling trees with complex architecture, especially for those individuals with decurrent canopies such as *Picea abies*, *Sorbus aucuparia* and *Pseudotsuga menziesii* (Cancino et al., 2005, 2007; Schlecht et al., 2014). However, due to time and financial constraints crown stratification was not applied on sampled trees. In the field, I was challenged to make a practical decision between attaining a sufficient sample size (number of measured trees) and/or to apply the most accurate sampling strategy for RBS on non-fully measured trees. In addition, due to a small sample size (15 trees per each evaluated species) linear developed for whole tree and main stem in Chapter 5 have the potential risk to be biased (Jara et al., 2015; Manuri et al., 2017), hence they should be applied cautiously outside the studied population.

Finally, Chapter 5 confirmed that the woody volume of *U. procera* trees can be more accurately estimated by using a species-decay factor rather than using a generalized standard factor of 0.8 as proposed by Nowak et al. (2002a) widely applied by many authors (Liu et al., 2012; Nowak et al., 2002a; Stoffberg et al., 2010; Timilsina et al., 2014; Vaccari et al., 2013; Zhao et al., 2016) which account for differences in biomass yield between natural and open-ground trees. Based on the practical assessment done in Chapter 5 it was highlighted that species-specific equations are needed to better assess urban tree biomass and stored carbon. Further

investigations on other tree species commonly planted in urban landscapes including a greater sample size (more individual per size class) are required to explore key concepts related to allometry such as crown plasticity and biomass allocation in standing urban trees.

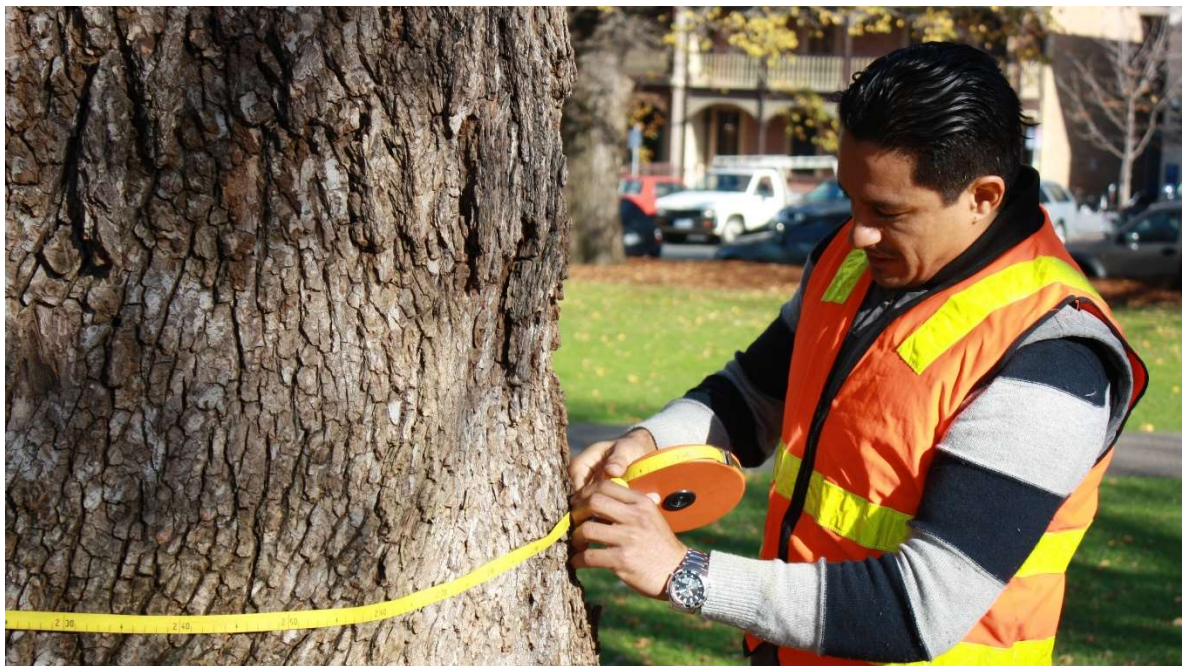
6.5 Research outcomes

This PhD study generated several research outcomes to improve the assessment of urban trees:

- A novel method (faster and reliable) to assess trends in the growth of urban trees was developed and is now available to benefit the work of arborists and urban foresters.
- This study established that resistance drilling (RD) cannot detect the inter-annual pattern of tree growth to the same standard as stem core analysis, so RD should not be used to replace dendrochronology in climate-tree growth studies.
- This study suggests that wood decay, in trees which are poor compartmentalizers-or lower wood density trees such as *U. procera*, did not show correlation with low visual vitality. However, this study does suggest that low visual vitality might be correlated to wood decay in ‘good’ compartmentalizers-or higher wood density trees- such as *P. x acerifolia* and *C. maculata*.
- This study proposed a species-decay factor of 13% to more accurately assess above-ground biomass yield and stored carbon of *U. procera* trees in the City of Melbourne.
- This study provided new insights on canopy structure, tree above-ground biomass distribution and the allometric relationships of urban trees.
- This study demonstrated that the accuracy of randomized branch sampling (RBS) to estimate standing volume of urban trees varied according to species’ canopy structure and the number of paths followed on sampled trees.

- This study established that, given the large range of estimation errors, RBS may only be used in combination with other methods to reliably assess standing volume and develop species-specific allometric equations of urban trees.

It is hoped that this PhD study will provide the methodological foundation to broaden the scope of research on wood decay and growth rate within urban forestry science and will also contribute to more accurately assess urban tree benefits.



The author measuring stem DBH of a mature *Ulmus procera* tree at University Square, Melbourne, 2016.

References

- Aiba, M., & Nakashizuka, T. (2009). Architectural differences associated with adult stature and wood density in 30 temperate tree species. *Functional Ecology*, 23(2), 265-273. doi:10.1111/j.1365-2435.2008.01500.x
- Alonzo, M., Bookhagen, B., McFadden, J. P., Sun, A., & Roberts, D. A. (2015). Mapping urban forest leaf area index with airborne lidar using penetration metrics and allometry. *Remote Sensing of Environment*, 162, 141-153. doi:10.1016/j.rse.2015.02.025
- Alonzo, M., McFadden, J. P., Nowak, D. J., & Roberts, D. A. (2016). Mapping urban forest structure and function using hyperspectral imagery and lidar data. *Urban Forestry & Urban Greening*, 17, 135-147. doi:10.1016/j.ufug.2016.04.003
- Alvez, L. F., & Santos, F. A. (2002). Tree allometry and crown shape of four tree species in Atlantic rain forest, south-east Brazil. *Journal of Tropical Ecology*, 18, 245-260.
- Ardila, J. P., Bijker, W., Tolpekin, V. A., & Stein, A. (2012). Quantification of crown changes and change uncertainty of trees in an urban environment. *ISPRS Journal of Photogrammetry and Remote Sensing*, 74, 41-55. doi:10.1016/j.isprsjprs.2012.08.007
- Axmon, J., Hansson, M., & Sornmo, L. (2004). Experimental study on the possibility of detecting internal decay in standing *Picea abies* by blind impact response analysis. *Forestry*, 77(3), 179-192.
- Baietto, M., Wilson, A. D., Bassi, D., & Ferrini, F. (2010). Evaluation of three electronic noses for detecting incipient wood decay. *Sensors (Basel)*, 10(2), 1062-1092. doi:10.3390/s100201062
- Banks, J. C., & Brack, C. L. (2003). Canberra's Urban Forest: Evolution and planning for future landscapes. *Urban Forestry & Urban Greening*, 1, 151-160. doi:10.1078/1618-8667-00015
- Banks, J. C., Brack, C. L., & James, R. N. (1999). Modelling changes in dimensions, health status, and arboricultural implications for urban trees. *Urban Ecosystems*, 3, 35-43.
- Barrera, P., & Rosso, R. (1989). On fractal dimensions of stream networks. *Water resources research*, 25(4), 735-741.
- Barrett, D. K., Seaby, D. A., & Gourlay, I. D. (1987). Portable 'Compression Strength Meter'; a Tool for the Detection and Quantification of Decay in Trees. *Arboricultural Journal*, 11(4), 313-322. doi:10.1080/03071375.1987.9756363
- Barry, K. M., Pearce, L. M., & Mohammed, A. M. (2000). Properties of reaction zones associated with decay from pruning wounds in plantation-grown *Eucalyptus nitens*. *Forest Pathology*, 30, 233-245.
- Bartens, J., Grissino-Mayer, H. D., Day, S. D., & Eric Wiseman, P. (2012). Evaluating the potential for dendrochronological analysis of live oak (*Quercus virginiana* Mill.) from the urban and rural environment—An explorative study. *Dendrochronologia*, 30(1), 15-21. doi:10.1016/j.dendro.2011.04.002
- Barthelemy, D., & Caraglio, Y. (2007). Plant architecture: a dynamic, multilevel and comprehensive approach to plant form, structure and ontogeny. *Ann Bot*, 99(3), 375-407. doi:10.1093/aob/mcl260
- Bascietto, M., De Cinti, B., Matteucci, G., & Cescatti, A. (2012). Biometric assessment of aboveground carbon pools and fluxes in three European forests by Randomized Branch Sampling. *Forest Ecology and Management*, 267, 172-181. doi:10.1016/j.foreco.2011.12.007
- Baum, S., & Schwarze, F. W. M. R. (2007). Large-leaved lime (*Tilia platyphyllos*) has a low ability to compartmentalize decay fungi via reaction zone formation. *New Phytologist*, 154, 481-490.

- Baumgardner, D., Varela, S., Escobedo, F. J., Chacalo, A., & Ochoa, C. (2012). The role of a peri-urban forest on air quality improvement in the Mexico City megalopolis. *Environ Pollut*, 163, 174-183. doi:10.1016/j.envpol.2011.12.016
- Berninger, F., Coll, L., Vanninen, P., Mäkelä, A., Palmroth, S., & Nikinmaa, E. (2005). Effects of tree size and position on pipe model ratios in Scots pine. *Canadian Journal of Forest Research*, 35(6), 1294-1304. doi:10.1139/x05-055
- Berntson, G. (1997). Topological scaling and plant root system architecture: developmental and functional hierarchies. *New Phytologist*, 135, 621-634.
- Bert, D., & Danjon, F. (2006). Carbon concentration variations in the roots, stem and crown of mature *Pinus pinaster* (Ait.). *Forest Ecology and Management*, 222(1-3), 279-295. doi:10.1016/j.foreco.2005.10.030
- Birdsey, R. A. (1992). Carbon storage and accumulation in United States forest ecosystems. *General Technical Report WO-GTR-59, Northeastern Forest Experiment Station, Forest Service, U.S. (Department of Agriculture)*, 52.
- Blood, A., Starr, G., Escobedo, F. J., Chappelka, A., Wiseman, P. E., Sivakumar, R., & Staudhammer, C. L. (2016). Resolving uncertainties in predictive equations for urban tree crown characteristics of the southeastern United States: Local and general equations for common and widespread species. *Urban Forestry & Urban Greening*, 20, 282-294. doi:10.1016/j.ufug.2016.09.009
- Boddy, L. (1994). Latent Decay Fungi: The Hidden Foe? *Arboricultural Journal*, 18(2), 113-135. doi:10.1080/03071375.1994.9747007
- Boukili, V. K. S., Bebb, D. P., Mortimer, T., Venicx, G., Lefcourt, D., Chandler, M., & Eisenberg, C. (2017). Assessing the performance of urban forest carbon sequestration models using direct measurements of tree growth. *Urban Forestry & Urban Greening*, 24, 212-221. doi:10.1016/j.ufug.2017.03.015
- Bowman, D. M., Brien, R. J., Gloor, E., Phillips, O. L., & Prior, L. D. (2013). Detecting trends in tree growth: not so simple. *Trends Plant Sci*, 18(1), 11-17. doi:10.1016/j.tplants.2012.08.005
- Brack, C. L. (2002). Pollution mitigation and carbon sequestration by an urban forest. *Environmental Pollution*, 116, S195-S200.
- Brack, C. L. (2006). Updating urban forest inventories: An example of the DISMUT model. *Urban Forestry & Urban Greening*, 5(4), 189-194. doi:10.1016/j.ufug.2006.09.001
- Brazee, N. J., Marra, R. E., Gocke, L., & Van Wassenae, P. (2010). Non-destructive assessment of internal decay in three hardwood species of northeastern North America using sonic and electrical impedance tomography. *Forestry*, 84(1), 33-39. doi:10.1093/forestry/cpq040
- Bunn, A. G. (2008). A dendrochronology program library in R (dplR). *Dendrochronologia*, 26(2), 115-124. doi:10.1016/j.dendro.2008.01.002
- Callow, D., May, P., & Johnstone, D. (2018). Tree Vitality Assessment in Urban Landscapes. *Forests*, 9(5). doi:10.3390/f9050279
- Cancino, J., & Saborowski, J. (2005). Comparison of Randomized Branch Sampling with and without Replacement at the First Stage. *Silva Fennica*, 39(2), 201-216.
- Cancino, J., & Saborowski, J. (2007). Improving RBS estimates – effects of the auxiliary variable, stratification of the crown, and deletion of segments on the precision of estimates. *Journal of Forest Science*, 53(7), 320-333.
- Carbone, M. S., Czimczik, C. I., Keenan, T. F., Murakami, P. F., Pederson, N., Schaberg, P. G., . . . Richardson, A. D. (2013). Age, allocation and availability of nonstructural carbon in mature red maple trees. *New Phytol*, 200(4), 1145-1155. doi:10.1111/nph.12448

- Casella, E., & Sinoquet, H. (2003). A method for describing the canopy architecture of coppice poplar with allometric relationships. *Tree Physiology*, 12, 1153-1170.
- Castagneri, D., Nola, P., Motta, R., & Carrer, M. (2014). Summer climate variability over the last 250 years differently affected tree species radial growth in a mesic *Fagus–Abies–Picea* old-growth forest. *Forest Ecology and Management*, 320, 21-29. doi:10.1016/j.foreco.2014.02.023
- Castello, L. R., & Quarles, L. S. (1999). Detection of wood decay in blue gum and elm: an evaluation of the resistograph and the portable drill. *Journal of Arboriculture*, 25(6), 311-318.
- Catton, H. A., Geroge, S. S., & Remphrey, W. R. (2007). An Evaluation of Bur Oak (*Quercus macrocarpa*) Decline in the Urban Forest of Winnipeg, Manitoba, Canada. *Arboriculture & Urban Forestry*, 33(1), 22-30.
- Cedro, A., & Nowak, G. (2006). Effects of climatic conditions on annual tree ring growth of the *Platanus x hispanica* 'Acerifolia' under urban conditions of Szczecin. *Dendrobiology*, 55, 11-17.
- Chaojnacky, D. C., Heath, L. S., & Jenkins, J. C. (2014). Updated generalized biomass equations for North American tree species. *Forestry*, 87, 129-151. doi:10.1093/forestry/cpt053
- Chave, J., Coomes, D., Jansen, S., Lewis, S. L., Swenson, N. G., & Zanne, A. E. (2009). Towards a worldwide wood economics spectrum. *Ecol Lett*, 12(4), 351-366. doi:10.1111/j.1461-0248.2009.01285.x
- Chave, J., Rejou-Mechain, M., Burquez, A., Chidumayo, E., Colgan, M. S., Delitti, W. B., . . . Vieilledent, G. (2014). Improved allometric models to estimate the aboveground biomass of tropical trees. *Glob Chang Biol*, 20(10), 3177-3190. doi:10.1111/gcb.12629
- Chen, Z., He, X., Cui, M., Davi, N., Zhang, X., Chen, W., & Sun, Y. (2010). The effect of anthropogenic activities on the reduction of urban tree sensitivity to climatic change: dendrochronological evidence from Chinese pine in Shenyang city. *Trees*, 25(3), 393-405. doi:10.1007/s00468-010-0514-x
- Chen, Z., Xu, B., & Gao, B. (2015). Assessing visual green effects of individual urban trees using airborne Lidar data. *Sci Total Environ*, 536, 232-244. doi:10.1016/j.scitotenv.2015.06.142
- Cherubini, P., Gartner, B. L., Tognetti, R., Braker, O. U., Schoch, W., & Innes, J. L. (2003). Identification, measurement and interpretation of tree rings in woody species from mediterranean climates. *Biological Review*, 78, 119-148.
- Chirici, G., Puletti, N., Salvati, R., Arbi, F., Zolli, C., & Corona, P. (2014). Is randomized branch sampling suitable to assess wood volume of temperate broadleaved old-growth forests? *Forest Ecology and Management*, 312, 225-230. doi:10.1016/j.foreco.2013.10.001
- Cho, S.-H., Kim, T., Roberts, R. K., Hellwinckel, C., Kim, S. G., & Wilson, B. (2014). Developing an amenity value calculator for urban forest landscapes. *Computers, Environment and Urban Systems*, 43, 34-41. doi:10.1016/j.compenvurbsys.2013.10.005
- Churkina, G., Brown, D. G., & Keoleian, G. (2010). Carbon stored in human settlements: the conterminous United States. *Global Change Biology*, 16(1), 135-143. doi:10.1111/j.1365-2486.2009.02002.x
- Cienciala, E., Russ, R., Santruckova, H., Altman, J., Kopacek, J., Hunova, I., . . . Stahl, G. (2016). Discerning environmental factors affecting current tree growth in Central Europe. *Sci Total Environ*, 573, 541-554. doi:10.1016/j.scitotenv.2016.08.115

- Cieslak, M., Seleznyova, A. N., Prusinkiewicz, P., & Hanan, J. (2011). Towards aspect-oriented functional--structural plant modelling. *Ann Bot*, 108(6), 1025-1041. doi:10.1093/aob/mcr121
- City of Melbourne. (2012). Urban Forest Strategy: Making a great city greener 2012-2032. melbourne.vic.gov.au/urbanforest.
- Clark, J., Wolosin, M., Dietze, M., Ibanez, I., LaDeau, S., Welsh, M., & Kloeppel, B. (2007). Tree Growth Inference and Prediction from Diameter Censuses and Ring Widths. *Ecological Applications*, 17(7), 1942-1953.
- Costello, L. R., Scott, S. R., & Drake, C. M. (2004). A 10-year evaluation of the performance of four elm cultivars in California, U.S. *Journal of Arboriculture*, 30(2), 114-122.
- Cousins, S. J. M., Battles, J. J., Sanders, J. E., & York, R. A. (2015). Decay patterns and carbon density of standing dead trees in California mixed conifer forests. *Forest Ecology and Management*, 353, 136-147. doi:10.1016/j.foreco.2015.05.030
- Cropper, J. P. (1979). Tree-Ring Skeleton Plotting by Computer. *Tree-Ring Bulletin*, 39, 47-60.
- Dahle, G. A., Gallagher, F. J., Gershenson, D., Schäfer, K. V. R., & Grabosky, J. C. (2014). Allometric and mass relationships of *Betula populifolia* in a naturally assembled urban brownfield: implications for carbon modeling. *Urban Ecosystems*, 17(4), 1147-1160. doi:10.1007/s11252-014-0377-9
- Dahle, G. A., & Grabosky, J. (2009). Review of Literature on the Function and Allometric Relationships of Tree Stems and Branches. *Arboriculture & Urban Forestry*, 35(6), 311-320.
- Dahle, G. A., & Grabosky, J. (2010). Allometric patterns in *Acer platanoides* (Aceraceae) branches. *Trees*, 24(2), 321-326. doi:10.1007/s00468-009-0401-5
- Dale, V. H., Doyle, T. W., & Shugart, H. H. (1985). A comparison of tree growth models. *Ecological Modelling*, 29, 145-169.
- Dănescu, A., Ehring, A., Bauhus, J., Albrecht, A., & Hein, S. (2015). Modelling discoloration and duration of branch occlusion following green pruning in *Acer pseudoplatanus* and *Fraxinus excelsior*. *Forest Ecology and Management*, 335, 87-98. doi:10.1016/j.foreco.2014.09.027
- Davies, H. J., Doick, K. J., Hudson, M. D., & Schreckenberg, K. (2017). Challenges for tree officers to enhance the provision of regulating ecosystem services from urban forests. *Environ Res*, 156, 97-107. doi:10.1016/j.envres.2017.03.020
- Davies, Z. G., Edmondson, J. L., Heinemeyer, A., Leake, J. R., & Gaston, K. J. (2011). Mapping an urban ecosystem service: quantifying above-ground carbon storage at a city-wide scale. *Journal of Applied Ecology*, 48(5), 1125-1134. doi:10.1111/j.1365-2664.2011.02021.x
- Day, S. D., & Amateis, R. L. (2011). Predicting canopy and trunk cross-sectional area of silver linden (*Tilia tomentosa*) in confined planting cutouts. *Urban Forestry & Urban Greening*, 10(4), 317-322. doi:10.1016/j.ufug.2011.08.001
- Day, S. D., Wiseman, P. E., Dickinson, S. B., & Harris, R. J. (2010). Tree Root Ecology in the Urban Environment and Implications for a Sustainable Rhizosphere. *Arboriculture & Urban Forestry*, 36(5), 193-205.
- Deflorio, G., Hein, S., Fink, S., Spiecker, H., & Willis Mathew Robert Schwarze, F. (2005). The application of wood decay fungi to enhance annual ring detection in three diffuse-porous hardwoods. *Dendrochronologia*, 22(2), 123-130. doi:10.1016/j.dendro.2005.02.002
- Diaz-Porras, D. F., Gaston, K. J., & Evans, K. L. (2014). 110 Years of change in urban tree stocks and associated carbon storage. *Ecol Evol*, 4(8), 1413-1422. doi:10.1002/ece3.1017

- Diaz, S., Kattge, J., Cornelissen, J. H., Wright, I. J., Lavorel, S., Dray, S., . . . Gorne, L. D. (2016). The global spectrum of plant form and function. *Nature*, 529(7585), 167-171. doi:10.1038/nature16489
- Dobbertin, M. (2005). Tree growth as indicator of tree vitality and of tree reaction to environmental stress: a review. *European Journal of Forest Research*, 124, 319-333. doi:10.1007/s10342-005-0085-3
- Dobbs, C., Escobedo, F. J., & Zipperer, W. C. (2011a). A framework for developing urban forest ecosystem services and goods indicators. *Landscape and Urban Planning*, 99(3-4), 196-206. doi:10.1016/j.landurbplan.2010.11.004
- Dobbs, C., Hernández, J., & Escobedo, F. (2011b). Above ground biomass and leaf area models based on a non destructive method for urban trees of two communes in Central Chile. *Bosque (Valdivia)*, 32(3), 287-296. doi:10.4067/s0717-92002011000300010
- Dobbs, C., Kendal, D., & Nitschke, C. (2013). The effects of land tenure and land use on the urban forest structure and composition of Melbourne. *Urban Forestry & Urban Greening*, 12(4), 417-425. doi:10.1016/j.ufug.2013.06.006
- Dolanc, C. R., Westfall, R. D., Safford, H. D., Thorne, J. H., & Schwartz, M. W. (2013). Growth-climate relationships for six subalpine tree species in a Mediterranean climate. *Canadian Journal of Forest Research*, 43(12), 1114-1126. doi:10.1139/cjfr-2013-0196
- Dolwin, J. A., Lonsdale, D., & Barnett, J. (1998). Detection of decay in trees. *The Commonwealth Forestry Review*, 77(4), 277-280.
- Dorendorf, J., Eschenbach, A., Schmidt, K., & Jensen, K. (2015). Both tree and soil carbon need to be quantified for carbon assessments of cities. *Urban Forestry & Urban Greening*, 14(3), 447-455. doi:10.1016/j.ufug.2015.04.005
- Downes, G. M., Drew, D., Battaglia, M., & Schulze, D. (2009). Measuring and modelling stem growth and wood formation: An overview. *Dendrochronologia*, 27(2), 147-157. doi:10.1016/j.dendro.2009.06.006
- Downes, G. M., Wimmer, R., & Evans, R. (2002). Understanding wood formation: gains to commercial forestry through tree-ring research. *Dendrochronologia*, 20(1-2), 37-51. doi:10.1078/1125-7865-00006
- Duan, A., Zhang, J., Zhang, X., & He, C. (2015). Relationship between Modelling Accuracy and Inflection Point Attributes of Several Equations while Modelling Stand Diameter Distributions. *PLoS One*, 10(5), e0126831. doi:10.1371/journal.pone.0126831
- Ducey, M. J., Zarin, D. J., Vasconcelos, S. S., & Araujo, M. M. (2009). Biomass equations for forest regrowth in the eastern Amazon using randomized branch sampling. *Acta Amazonica*, 39(3), 349 - 360.
- Duryea, M. L., Kampf, E., Littel, R. C., & Rodriguez-Pedraza, C. D. (2007). Hurricanes and the urban forest: II. effects on tropical and subtropical tree species. *Arboriculture & Urban Forestry*, 33(2), 98-112.
- Dutca, I., Negruțu, F., Blujdea, V. N., Ioras, F., Maher, K., & Alexandru, L. (2014). The Influence of Age, Location and Soil Conditions on the Allometry of Young Norway Spruce (*Picea abies* L. Karst.) Trees. *Not Bot Horti Agrobot*, 42(2), 579-582. doi:10.1583/nbha4229714
- Dwyer, J. F., Nowak, D. J., & Noble, M. H. (2003). Sustaining urban forests. *Journal of Arboriculture*, 29(1), 49-55.
- Eilmann, B., & Rigling, A. (2012). Tree-growth analyses to estimate tree species' drought tolerance. *Tree Physiol*, 32(2), 178-187. doi:10.1093/treephys/tps004

- Eiserhardt, W. L., Couvreur, T. L. P., & Baker, W. J. (2017). Plant phylogeny as a window on the evolution of hyperdiversity in the tropical rainforest biome. *New Phytol*, 214(4), 1408-1422. doi:10.1111/nph.14516
- Eisner, N., Gilman, F. E., & Grabosky, J. C. (2002). Branch morphology impacts compartmentalization of pruning wounds. *Journal of Arboriculture*, 28(2).
- Ellison, M. J. (2005). Quantified tree risk assessment used in the management of amenity trees. *Journal of Arboriculture*, 31(2), 57-65.
- Escobedo, F. J., Kroeger, T., & Wagner, J. E. (2011). Urban forests and pollution mitigation: analyzing ecosystem services and disservices. *Environ Pollut*, 159(8-9), 2078-2087. doi:10.1016/j.envpol.2011.01.010
- Escobedo, F. J., Varela, S., Zhao, M., Wagner, J. E., & Zipperer, W. (2010). Analyzing the efficacy of subtropical urban forests in offsetting carbon emissions from cities. *Environmental Science & Policy*, 13(5), 362-372. doi:10.1016/j.envsci.2010.03.009
- Escobedo, F. J., Wagner, J. E., Nowak, D. J., De la Maza, C. L., Rodriguez, M., & Crane, D. E. (2008). Analyzing the cost effectiveness of Santiago, Chile's policy of using urban forests to improve air quality. *J Environ Manage*, 86(1), 148-157. doi:10.1016/j.jenvman.2006.11.029
- Evans, A. M., & Gregoire, T. G. (2007). The tree crown distribution of hemlock woolly adelgid, *Adelges tsugae* (Hem., Adelgidae) from randomized branch sampling. *Journal of Applied Entomology*, 131(1), 26-33. doi:10.1111/j.1439-0418.2006.01121.x
- Fahey, R. T., Bialecki, M. B., & Carter, D. R. (2013). Tree growth and resilience to extreme drought across an urban land-use gradient. *Arboriculture & Urban Forestry*, 39(6), 279-285.
- FAO. (2013). Towards the Assessment of Trees Outside Forests. *Forest Resources Assessment Working Paper. FAO*, 183, 345.
- Fatemi, F. R., Yanai, R. D., Hamburg, S. P., Vadeboncoeur, M. A., Arthur, M. A., Briggs, R. D., & Levine, C. R. (2011). Allometric equations for young northern hardwoods: the importance of age-specific equations for estimating aboveground biomass. *Canadian Journal of Forest Research*, 41(4), 881-891. doi:10.1139/x10-248
- Fernández-Sarria, A., Martínez, L., Velázquez-Martí, B., Sajdak, M., Estornell, J., & Recio, J. A. (2013). Different methodologies for calculating crown volumes of *Platanus hispanica* trees using terrestrial laser scanner and a comparison with classical dendrometric measurements. *Computers and Electronics in Agriculture*, 90, 176-185. doi:10.1016/j.compag.2012.09.017
- Fink, S. (2009). Hazard Tree Identification by Visual Tree Assessment (Vta): Scientifically Solid and Practically Approved. *Arboricultural Journal*, 32(3), 139-155. doi:10.1080/03071375.2009.9747570
- Fitter, H. A., & Stickland, T. R. (1992). Fractal Characterization of Root System Architecture. *Functional Ecology*, 6(6), 632-635.
- Fleurant, C., Duchesne, J., & Raimbault, P. (2004). An allometric model for trees. *Journal of Theoretical Biology*, 227(1), 137-147.
- Fournier, R. A., Luther, J. E., Guindon, L., Lambert, M. C., Piercey, D., Hall, R. J., & Wulder, M. A. (2003). Mapping aboveground tree biomass at the stand level from inventory information: test cases in Newfoundland and Quebec. *Canadian Journal of Forest Research*, 33(10), 1846-1863. doi:10.1139/x03-099
- Fournier, R. A., Rich, P. M., & Landry, R. (1997). Hierarchical characterization of canopy architecture for boreal forest. *Journal of Geophysical Research: Atmospheres*, 102(D24), 29445-29454. doi:10.1029/96jd03879

- Frank, J., Castle, M. E., Westfall, J. A., Weiskittel, A. R., MacFarlane, D. W., Baral, S. K., . . . Pelletier, G. (2018). Variation in occurrence and extent of internal stem decay in standing trees across the eastern US and Canada: evaluation of alternative modelling approaches and influential factors. *Forestry: An International Journal of Forest Research*, 91(3), 382-399. doi:10.1093/forestry/cpx054
- Frank, S., Glenn, W., Beer, R., & Peter, M. (2006). An Analysis of the Street Tree Population of Greater Melbourne at the Beginning of the 21st Century. *Arboriculture and Urban Forestry*, 32(4), 155-163.
- Freedman, B., Love, S., & O'Neil, B. (1996). Tree species composition, structure, and carbon storage in stands of urban forest of varying character in Halifax, Nova Scotia. *Canadian Field-Naturalist*, 110(4), 675-682.
- Gao, S., Wang, X., Wiemann, M. C., Brashaw, B. K., Ross, R. J., & Wang, L. (2017). A critical analysis of methods for rapid and nondestructive determination of wood density in standing trees. *Annals of Forest Science*, 74(2). doi:10.1007/s13595-017-0623-4
- García-Suárez, A. M., Butler, C. J., & Baillie, M. G. L. (2009). Climate signal in tree-ring chronologies in a temperate climate: A multi-species approach. *Dendrochronologia*, 27(3), 183-198. doi:10.1016/j.dendro.2009.05.003
- Gayon, J. (2000). History of the concept of Allometry. *American Zoologist*, 40, 748-758.
- Gebuek, T., Robitschek, K., & Milasowszky, N. (2008). A tree of many faces: Why are there different crown types in Norway spruce (*Picea abies* [L.] Karst.)? *Flora*, 203, 126-133. doi:10.1016/j.flora.2007.01.003
- Gilbert, E. A., & Smiley, T. E. (2004). Picus sonic tomography for the quantification of decay in white Oak (*Quercus Alba*) and Hickory (*Carya* Spp.). *Journal of Arboriculture*, 30(5), 277-281.
- Gilbert, G. S., Ballesteros, J. O., Barrios-Rodriguez, C. A., Bonadies, E. F., Cedeno-Sanchez, M. L., Fossatti-Caballero, N. J., . . . Hubbell, S. P. (2016). Use of sonic tomography to detect and quantify wood decay in living trees. *Appl Plant Sci*, 4(12). doi:10.3732/apps.1600060
- Gillner, S., Bräuning, A., & Roloff, A. (2014). Dendrochronological analysis of urban trees: climatic response and impact of drought on frequently used tree species. *Trees*, 28(4), 1079-1093. doi:10.1007/s00468-014-1019-9
- Gillner, S., Vogt, J., & Roloff, A. (2013). Climatic response and impacts of drought on oaks at urban and forest sites. *Urban Forestry & Urban Greening*, 12(4), 597-605. doi:10.1016/j.ufug.2013.05.003
- Gilman, F. E., & Grabosky, J. C. (2006). Branch union morphology affects decay following pruning. *Arboricultural and Urban Forestry*, 32(2), 74-79.
- Giroud, G., Cloutier, A., & Alteyrac, J. (2008). Occurrence, proportion, and vertical distribution of red heartwood in paper birch. *Canadian Journal of Forest Research*, 38(7), 1996-2002. doi:10.1139/x08-043
- Godin, C., & Sinoquet, H. (2005). Functional-structural plant modelling. *New Phytologist*, 166, 705-708.
- Goldblum, D. (2010). The geography of white oak's (*Quercus alba* L.) response to climatic variables in North America and speculation on its sensitivity to climate change across its range. *Dendrochronologia*, 28(2), 73-83. doi:10.1016/j.dendro.2009.07.001
- Good, M. N., Paterson, M., Brack, C., & Mergensen, K. (2001). Estimating tree component biomass using variable probability sampling methods. *Journal of Agricultura, Biological and Environmental Statistics*, 6(2), 258-267.
- Goodman, R. C., Philips, O. L., & Baker, T. R. (2014). The importance of crown dimensions to improve tropical tree biomass estimates. *Ecological Applications*, 24(4), 680-698.

- Gove, J. H., Ducey, M. J., & Valentine, T. (2002). Multistage point relascope and randomized branch sampling for downed coarse woody debris estimation. *Forest Ecol Manag.*, 155, 153-162.
- Grabosky, J., Gilman, E., & Harchick, C. (2007). Use of branch cross-sectional area for predicting pruning dose in young field-grown *Quercus virginiana* 'Cathedral' in Florida, US. *Urban Forestry & Urban Greening*, 6(3), 159-167. doi:10.1016/j.ufug.2007.06.002
- Gratani, L., & Varone, L. (2006). Carbon sequestration by *Quercus ilex* L. and *Quercus pubescens* Willd. and their contribution to decreasing air temperature in Rome. *Urban Ecosystems*, 9, 27-37. doi:10.1007/s11252-006-5527-2
- Gregoire, G. T., Valentine, H. T., & Furnival, G. M. (1995). Sampling Methods to Estimate Foliage and Other Characteristics of Individual Trees. *Ecology*, 75(4), 1181-1194.
- Gregoire, T. G., & Valentine, H. T. (1996). Sampling methods to estimate stem length and surface area of tropical tree species. *Forest Ecol Manag.*, 83, 229-235.
- Grissino-Mayer, H. D. (1993). An Updated List of Species Used in Tree-Ring Research. *Tree Ring Bulletin*, 53(17-28).
- Grissino-Mayer, H. D. (2001). Evaluating crossdating accuracy: A manual and tutorial for the computer program COFECHA. *TreeRing Research*, 57(2), 205-221.
- Guller, B., Guller, A., & Kazaz, G. (2012). Is resistograph an appropriate tool for the annual ring measurement of *Pinus brutia*? *Defektoskopie, NDE for safety*, 89-94.
- Harmon, M. E., Fasth, B., Woodall, C. W., & Sexton, J. (2013). Carbon concentration of standing and downed woody detritus: Effects of tree taxa, decay class, position, and tissue type. *Forest Ecology and Management*, 291, 259-267. doi:10.1016/j.foreco.2012.11.046
- Harper, M. J., McCarthy, M. A., & van der Ree, R. (2005). The abundance of hollow-bearing trees in urban dry sclerophyll forest and the effect of wind on hollow development. *Biological Conservation*, 122(2), 181-192. doi:10.1016/j.biocon.2004.07.003
- Hartmann, H., Adams, H. D., Anderegg, W. R., Jansen, S., & Zeppel, J. B. (2015). Research frontiers in drought-induced tree mortality: crossing scales and disciplines. *New Phytology*, 205, 965-969.
- Hecht, R., Meinel, G., & Buchroithner, M. F. (2008). Estimation of Urban Green Volume Based on Single-Pulse LiDAR Data. *IEEE Transactions on Geoscience and Remote Sensing*, 46(11), 3832-3840. doi:10.1109/tgrs.2008.2001771
- Heikura, T., Terho, M., Perttunen, J., & Sievänen, R. (2008). A computer-based tool to link decay information to 3D architecture of urban trees. *Urban Forestry & Urban Greening*, 7(4), 233-239. doi:10.1016/j.ufug.2008.07.001
- Heinrich, I., & Allen, K. (2013). Current Issues and Recent Advances in Australian Dendrochronology: Where to Next? *Geographical Research*, 51(2), 180-191. doi:10.1111/j.1745-5871.2012.00786.x
- Helama, S., Laanela, A., Raisio, J., & Tuomenvirta, H. (2012). Mortality of urban pines in Helsinki explored using tree rings and climate records. *Trees*, 26, 353-362. doi:10.1007/s00468-011-0597-z
- Helama, S., Läänela, A., Raisio, J., & Tuomenvirta, H. (2008). Oak decline in Helsinki portrayed by tree-rings, climate and soil data. *Plant and Soil*, 319(1-2), 163-174. doi:10.1007/s11104-008-9858-z
- Helliwell, D. R. (2007). A Short Note on Effects of Boring Holes in Trees. *Arboricultural Journal*, 30(3), 245-248. doi:10.1080/03071375.2007.9747499
- Henry, M., Besnard, A., Asante, W. A., Eshun, J., Adu-Bredu, S., Valentini, R., . . . Saint-André, L. (2010). Wood density, phytomass variations within and among trees, and

- allometric equations in a tropical rainforest of Africa. *Forest Ecology and Management*, 260(8), 1375-1388. doi:10.1016/j.foreco.2010.07.040
- Heredia, F., Morera, G., Robledo, G., Cagnolo, L., & Urcelay, C. (2014). Interacciones entre hongos de la madera (Agaricomycete) y árboles nativos y exóticos de un ecosistema urbano (Córdoba, Argentina). *Bosque (Valdivia)*, 35(3), 391-398. doi:10.4067/s0717-92002014000300013
- Hermans, C., Smeyers, M., Rodriguez, R. M., Eyletters, M., Strasser, R. J., & Delhay, J. P. (2003). Quality assessment of urban trees: a comparative study of physiological characterisation, airborne imaging and on site fluorescence monitoring by the OJIP-test. *J Plant Physiol*, 160(1), 81-90. doi:10.1078/0176-1617-00917
- Hess, C., Bienert, A., Härdtle, W., & von Oheimb, G. (2015). Does Tree Architectural Complexity Influence the Accuracy of Wood Volume Estimates of Single Young Trees by Terrestrial Laser Scanning? *Forests*, 6(11), 3847-3867. doi:10.3390/f6113847
- Horn, J., Escobedo, F. J., Hinkle, R., Hostetler, M., & Timilsina, N. (2015). The role of composition, invasives, and maintenance emissions on urban forest carbon stocks. *Environ Manage*, 55(2), 431-442. doi:10.1007/s00267-014-0400-1
- Hounzandji, A. P. I., Jonard, M., Nys, C., Saint-André, L., & Ponette, Q. (2014). Improving the robustness of biomass functions: from empirical to functional approaches. *Annals of Forest Science*, 72(6), 795-810. doi:10.1007/s13595-014-0423-z
- Hu, J., Herbohn, J., Chazdon, R. L., Baynes, J., Wills, J., Meadows, J., & Soheli, M. S. I. (2018). Recovery of species composition over 46 years in a logged Australian tropical forest following different intensity silvicultural treatments. *Forest Ecology and Management*, 409, 660-666. doi:10.1016/j.foreco.2017.11.061
- Hutyra, L. R., Yoon, B., & Alberti, M. (2011). Terrestrial carbon stocks across a gradient of urbanization: a study of the Seattle, WA region. *Global Change Biology*, 17(2), 783-797. doi:10.1111/j.1365-2486.2010.02238.x
- Huyler, A., Chappelka, A. H., Prior, S. A., & Somers, G. L. (2014). Influence of aboveground tree biomass, home age, and yard maintenance on soil carbon levels in residential yards. *Urban Ecosystems*, 17(3), 787-805. doi:10.1007/s11252-014-0350-7
- Iakovoglou, V., & Thompson, J. (2001). Factors related to tree growth across urban-rural gradients in the Midwest, USA. *Urban Ecosystems*, 5, 71-85.
- İÇEL, B., & GÜLER, G. (2016). Nondestructive determination of spruce lumber wood density using drilling resistance (Resistograph) method. *Turkish Journal of Agriculture and Forestry*, 40, 900-907. doi:10.3906/tar-1606-76
- IML-Norteamerica. (2016). Measured Variables of the IML-RESI PowerDrill®. www.iml-na.com, 15, 1-4.
- Isaac, B., White, J., Ierodiaconou, D., & Cooke, R. (2014). Urban to forest gradients: Suitability for hollow bearing trees and implications for obligate hollow nesters. *Austral Ecology*, 39(8), 963-972. doi:10.1111/aec.12164
- Ise, T., & Moorcroft, P. R. (2008). Quantifying local factors in medium-frequency trends of tree ring records: Case study in Canadian boreal forests. *Forest Ecology and Management*, 256(1-2), 99-105. doi:10.1016/j.foreco.2008.04.007
- Isik, F., & Li, B. (2003). Rapid assessment of wood density of live trees using the Resistograph for selection in tree improvement programs. *Canadian Journal of Forest Research*, 33(12), 2426-2435. doi:10.1139/x03-176
- James, K. R., Dhale, G. A., Grabosky, J. C., Kane, B., & Detter, A. (2014). Tree biomechanics literature review: Dynamics. *Arboriculture & Urban Forestry*, 40(1), 1-15.

- Jara, M. C., & Cuenca, M. H. M. R.-M. C. M. Z.-C. D. P. F. A. G. H. C. L. E. C. L. R. (2015). Guidelines for documenting and reporting tree allometric equations. *Annals of Forest Science*, 72, 763-768. doi:10.1007/s13595-014-0415-z
- Jenkins, J. C., Chojnacky, D. C., Heath, L. S., & Birdsey, R. A. (2003). National-scale biomass estimators for United States Tree Species. *Forest Science*, 49(1), 12-35.
- Jenkins, J. C., Chojnacky, D. C., Heath, L. S., & Birdsey, R. A. (2004). Comprehensive Database of Diameter-based Biomass Regressions for North American Tree Species. *USDA Forest Service, General Technical Report*(NE-319), 1-45.
- Jessen, R. J. (1955). Determining the fruit count on a tree by Randomized Branch Sampling. *Biometrics*, 11(1), 99-109.
- Jim, C. Y., & Chen, W. Y. (2008). Assessing the ecosystem service of air pollutant removal by urban trees in Guangzhou (China). *J Environ Manage*, 88(4), 665-676. doi:10.1016/j.jenvman.2007.03.035
- Johnstone, D., Ades, P., Moore, G., & Smith, I. W. (2011). Using an IML-Resi drill to assess wood density in *Eucalyptus globulus* subsp. *pseudoglobulus*. *Australian Forestry*, 74(3), 190-196.
- Johnstone, D., Ades, P. K., Moore, G., & Smith, I. W. (2007). Predicting Wood Decay in Eucalypts Using an Expert System and the IML-Resistograph Drill. *Arboriculture & Urban Forestry*, 33(2), 76-82.
- Johnstone, D., Moore, G., Tausz, M., & Nicolas, M. (2010a). The measurement of wood decay in landscape trees. *Arboriculture & Urban Forestry*, 36(3), 121-127.
- Johnstone, D., Moore, G., Tausz, M., & Nicolas, M. (2013). The measurement of plant vitality in landscape trees. *Arboricultural Journal*, 35(1), 18-27. doi:10.1080/03071375.2013.783746
- Johnstone, D., Tausz, M., Moore, G., & Nicolas, M. (2010b). Quantifying wood decay in Sydney bluegum (*Eucalyptus saligna*) trees. *Arboriculture & Urban Forestry*, 36(6), 243-252.
- Johnstone, D., Tausz, M., Moore, G., & Nicolas, M. (2012). Chlorophyll fluorescence of the trunk rather than leaves indicates visual vitality in *Eucalyptus saligna*. *Trees*, 26(5), 1565-1576. doi:10.1007/s00468-012-0730-7
- Jucker, T., Bouriaud, O., Coomes, D. A., & Baltzer, J. (2015). Crown plasticity enables trees to optimize canopy packing in mixed-species forests. *Functional Ecology*, 29(8), 1078-1086. doi:10.1111/1365-2435.12428
- Jung, S.-E., Kwak, D.-A., Park, T., Lee, W.-K., & Yoo, S. (2011). Estimating Crown Variables of Individual Trees Using Airborne and Terrestrial Laser Scanners. *Remote Sensing*, 3(12), 2346-2363. doi:10.3390/rs3112346
- Kane, B., Dennis, H., & Ryan, D. (2004). The accuracy of formulas used to assess strength loss due to decay in trees. *Journal of Arboriculture*, 30(6), 347-356.
- Kane, B., Modarres-Sadeghi, Y., James, K. R., & Reiland, M. (2013). Effects of crown structure on the sway characteristics of large decurrent trees. *Trees*, 28(1), 151-159. doi:10.1007/s00468-013-0938-1
- Kane, C. P., & Ryan, D. P. (2003). Examining formulas that assess strength loss due to decay in tree: woundwood touchness improvement in red maple (*Acer rubrum*). *Journal of Arboriculture*, 29(4), 209-217.
- Kankare, V., Holopainen, M., Vastaranta, M., Puttonen, E., Yu, X., Hyypä, J., . . . Alho, P. (2013). Individual tree biomass estimation using terrestrial laser scanning. *ISPRS Journal of Photogrammetry and Remote Sensing*, 75, 64-75. doi:10.1016/j.isprsjprs.2012.10.003
- Kato, A., Moskal, L. M., Schiess, P., Swanson, M. E., Calhoun, D., & Stuetzle, W. (2009). Capturing tree crown formation through implicit surface reconstruction using airborne

- lidar data. *Remote Sensing of Environment*, 113(6), 1148-1162.
doi:10.1016/j.rse.2009.02.010
- Kendal, D., Dobbs, C., & Lohr, V. I. (2014). Global patterns of diversity in the urban forest: Is there evidence to support the 10/20/30 rule? *Urban Forestry & Urban Greening*, 13(3), 411-417. doi:10.1016/j.ufug.2014.04.004
- Kennard, D. K., Putz, F. E., & Niederhofer, M. (1996). The predictability of tree decay based on visual assessments. *Journal of Arboriculture*, 22(6), 249-254.
- Kermavnar, J., & Vilhar, U. (2017). Canopy precipitation interception in urban forests in relation to stand structure. *Urban Ecosystems*. doi:10.1007/s11252-017-0689-7
- Kersten, W., & Schwarze, F. W. M. R. (2005). Development of Decay in the Sapwood of Trees Wounded by the Use of Decay Detecting Devices. *Arboricultural Journal*, 28(3), 165-181. doi:10.1080/03071375.2005.9747417
- Kim, H.-J., & Lee, S.-H. (2016). Developing the volume models for 5 major species of street trees in Gwangju metropolitan city of Korea. *Urban Forestry & Urban Greening*, 18, 53-58. doi:10.1016/j.ufug.2016.05.004
- Ko, Y., Lee, J.-H., McPherson, E. G., & Roman, L. A. (2015). Long-term monitoring of Sacramento Shade program trees: Tree survival, growth and energy-saving performance. *Landscape and Urban Planning*, 143, 183-191.
doi:10.1016/j.landurbplan.2015.07.017
- Koeser, A. K., Gilman, E. F., Paz, M., & Harchick, C. (2014). Factors influencing urban tree planting program growth and survival in Florida, United States. *Urban Forestry & Urban Greening*, 13(4), 655-661. doi:10.1016/j.ufug.2014.06.005
- Koeser, A. K., Hauer, R. J., Klein, R. W., & Miesbauer, J. W. (2017). Assessment of likelihood of failure using limited visual, basic, and advanced assessment techniques. *Urban Forestry & Urban Greening*, 24, 71-79. doi:10.1016/j.ufug.2017.03.024
- Koeser, K. A., McLean, D. C., Hasing, G., & Allison, R. B. (2016). Frequency, Severity, and Detectability of Internal Trunk Decay in Street Tree *Quercus* spp. in Tampa, Florida, U.S. *Arboriculture & Urban Forestry*, 42(4), 217-226.
- Kraler, A., Beikirecher, W., & Zingerle, P. (2012). Suitability of drill resistance measurements for dendrochronological determination. *World Conference of Timber Engineering, July-16-19*, 1-8.
- Kuittinen, M., Moinel, C., & Adalgeirsdottir, K. (2016). Carbon sequestration through urban ecosystem services: A case study from Finland. *Sci Total Environ*, 563-564, 623-632. doi:10.1016/j.scitotenv.2016.03.168
- Lamlom, S. H., & Savidge, R. A. (2003). A reassessment of carbon content in wood: variation within and between 41 North American species. *Biomass and Bioenergy*, 25(4), 381-388. doi:10.1016/s0961-9534(03)00033-3
- Laplamme, G. (1979). Discoloured wood of aspen caused by increment boring. *European Journal of Forest Research*, 9, 15-18.
- Lara, W., Bravo, F., & Sierra, C. A. (2015). measuRing: An R package to measure tree-ring widths from scanned images. *Dendrochronologia*, 34, 43-50.
doi:10.1016/j.dendro.2015.04.002
- Larsen, K. F., & Kristoffersen, P. (2002). Tilius's physical dimensions over time. *Journal of Arboriculture*, 28(5), 209-214.
- Larsson, B., Bengtsson, B., & Gustafsson, M. (2004). Nondestructive detection of decay in living trees. *Tree Physiology*, 24, 853-858.
- Lawrence, A. B., Escobedo, F. J., Staudhammer, C. L., & Zipperer, W. (2012). Analyzing growth and mortality in a subtropical urban forest ecosystem. *Landscape and Urban Planning*, 104(1), 85-94. doi:10.1016/j.landurbplan.2011.10.004

- Leal, S., Campelo, F., Luz, A. L., Carneiro, M. F., & Santos, J. A. (2015). Potential of oak tree-ring chronologies from Southern Portugal for climate reconstructions. *Dendrochronologia*, 35, 4-13. doi:10.1016/j.dendro.2015.05.003
- Lee, J.-H., Ko, Y., & McPherson, E. G. (2016). The feasibility of remotely sensed data to estimate urban tree dimensions and biomass. *Urban Forestry & Urban Greening*, 16, 208-220. doi:10.1016/j.ufug.2016.02.010
- Lefsky, M. A., & Machale, M. (2008). Volume estimates of trees with complex architecture from terrestrial laser scanning. *Journal of Applied Remote Sensing*, 2(1), 023521.
- Lehnebach, R., Beyer, R., Letort, V., & Heuret, P. (2018). The pipe model theory half a century on: a review. *Ann Bot*, 121(5), 773-795. doi:10.1093/aob/mcx194
- Leong, E.-C., Burcham, D. C., & Fong, Y.-K. (2012). A purposeful classification of tree decay detection tools. *Arboricultural Journal*, 34(2), 91-115. doi:10.1080/03071375.2012.701430
- Lin, C.-J., Huang, Y.-H., Huang, G.-S., & Wu, M.-L. (2015). Detection of decay damage in iron-wood living trees by nondestructive techniques. *Journal of Wood Science*, 62(1), 42-51. doi:10.1007/s10086-015-1520-9
- Lin, C.-J., Lee, C.-J., & Tsai, M.-J. (2016). Inspection and Evaluation of Decay Damage in Japanese Cedar Trees Through Nondestructive Techniques. *Arboriculture & Urban Forestry*, 42(3), 201-212.
- Liu, C., & Li, X. (2012). Carbon storage and sequestration by urban forests in Shenyang, China. *Urban Forestry & Urban Greening*, 11(2), 121-128. doi:10.1016/j.ufug.2011.03.002
- Livesley, S. J., McPherson, E. G., & Calfapietra, C. (2016). The Urban Forest and Ecosystem Services: Impacts on Urban Water, Heat, and Pollution Cycles at the Tree, Street, and City Scale. *J Environ Qual*, 45(1), 119-124. doi:10.2134/jeq2015.11.0567
- Lombardi, F., Cherubini, P., Lasserre, B., Tognetti, R., & Marchetti, M. (2008). Tree rings used to assess time since death of deadwood of different decay classes in beech and silver fir forests in the central Apennines (Molise, Italy). *Canadian Journal of Forest Research*, 38(4), 821-833. doi:10.1139/x07-195
- López-López, S. F., Martínez-Trinidad, T., Benavides-Meza, H., Garcia-Nieto, M., & de los Santos-Posadas, H. M. (2017). Non-destructive method for above-ground biomass estimation of *Fraxinus uhdei* (Wenz.) Lingelsh in an urban forest. *Urban Forestry & Urban Greening*, 24, 62-70. doi:10.1016/j.ufug.2017.03.025
- Lorenz, R. (1949). Discolorations and decay resulting from increment boring in hardwoods. *Journal of Forestry*, 7, 37-43.
- Lovell, J. L., Jupp, D. L. B., Newnham, G. J., & Culvenor, D. S. (2011). Measuring tree stem diameters using intensity profiles from ground-based scanning lidar from a fixed viewpoint. *ISPRS Journal of Photogrammetry and Remote Sensing*, 66(1), 46-55. doi:10.1016/j.isprsjprs.2010.08.006
- Lukaszkiwicz, J., Kosmala, M., Chrapka, M., & Borowski, J. (2005). Determine the age of the streetside *Tilia cordata* trees with a DBH-based model. *Journal of Arboriculture*, 31(5), 280-284.
- Luley, C. J., Nowak, D. J., & Greenfiel, E. J. (2009). Frequency and Severity of Trunk Decay in Street Tree Maples in Four New York Cities. *Arboriculture & Urban Forestry*, 35(2), 94-99.
- Lynch, J. (1995). Root architecture and plant productivity. *Plant Physiology*, 109, 7-13.
- MacFarlane, D. W. (2007). Quantifying Urban Saw Timber Abundance and Quality in Southeastern Lower Michigan, U.S. *Arboriculture & Urban Forestry*, 33(4), 253-263.

- MacFarlane, D. W. (2009). Potential availability of urban wood biomass in Michigan: Implications for energy production, carbon sequestration and sustainable forest management in the U.S.A. *Biomass and Bioenergy*, 33(4), 628-634. doi:10.1016/j.biombioe.2008.10.004
- MacFarlane, D. W., Kane, B., & Larjavaara, M. (2017). Neighbour effects on tree architecture: functional trade-offs balancing crown competitiveness with wind resistance. *Functional Ecology*, 31(8), 1624-1636. doi:10.1111/1365-2435.12865
- Makela, A. (2002). Derivation of stem taper from the pipe theory in a carbon balance framework. *Tree Physiology*, 22, 281-905.
- Makela, A., Landsberg, J., Ek, A. R., Burk, T., Ter-Mikaelian, M., Agren, G. I., . . . Puttonen, P. (2000). Process-based models for forest ecosystem management: current state of the art and challenges for practical implementation. *Tree Physiology*, 20, 289-298.
- Manuri, S., Brack, C., Rusolono, T., Noor'an, F., Verchot, L., Maulana, S. I., . . . Soraya, E. (2017). Effect of species grouping and site variables on aboveground biomass models for lowland tropical forests of the Indo-Malay region. *Annals of Forest Science*, 74(1). doi:10.1007/s13595-017-0618-1
- Marion, L., Gričar, J., & Oven, P. (2007). Wood formation in urban Norway maple trees studied by the micro-coring method. *Dendrochronologia*, 25(2), 97-102. doi:10.1016/j.dendro.2007.05.001
- Marra, R. E., Brazee, N. J., & Fraver, S. (2018). Estimating carbon loss due to internal decay in living trees using tomography: implications for forest carbon budgets. *Environmental Research Letters*, 13(10). doi:10.1088/1748-9326/aae2bf
- Martin, N. A., Chappelka, A. H., Loewenstein, E. F., Keever, G. J., & Somers, G. (2012). Predictive Open-grown Crown Width Equations for Three Oak Species Planted in a Southern Urban Locale. *Arboriculture & Urban Forestry*, 38(2), 58-73.
- Martinez-Trinidad, T., Watson, W. T., Arnold, M. A., Lombardini, L., & Appel, D. N. (2010). Comparing various techniques to measure tree vitality of live oaks. *Urban Forestry & Urban Greening*, 9(3), 199-203. doi:10.1016/j.ufug.2010.02.003
- Marziliano, P. A., Laforteza, R., Colangelo, G., Davies, C., & Sanesi, G. (2013). Structural diversity and height growth models in urban forest plantations: A case-study in northern Italy. *Urban Forestry & Urban Greening*, 12(2), 246-254. doi:10.1016/j.ufug.2013.01.006
- Mascaro, J., Uowolo, A., Litton, C. M., Schnitzer, S. A., & Hughe, R. F. (2014). Is logarithmic transformation necessary in allometry? Ten, one-hundred, one-thousand-times yes. *Biological Journal of the Linnean Society*, 111, 230-233.
- Mattheck, C., & Bethge, K. (2005). A Critic of the Static Integrated Analysis (SIA) Method. *Arboricultural Journal*, 28(3), 191-199. doi:10.1080/03071375.2005.9747419
- Mattheck, C., Bethge, K., & Albrecht, W. (1997). How to Read the Results of Resistograph M. *Arboricultural Journal*, 21(4), 331-346. doi:10.1080/03071375.1997.9747179
- Mattheck, C., & Breloer, H. (1994). Field Guide for Visual Tree Assessment (VTA). *Arboricultural Journal*, 18(1), 1-23. doi:10.1080/03071375.1994.9746995
- Maxwell, R. S., Wixom, J. A., & Hessler, A. E. (2011). A comparison of two techniques for measuring and crossdating tree rings. *Dendrochronologia*, 29(4), 237-243. doi:10.1016/j.dendro.2010.12.002
- May, P., Stephen, L. J., & Shears, I. (2013). Managing and Monitoring Tree Health and Soil Water Status During Extreme Drought in Melbourne, Victoria. *Arboriculture & Urban Forestry*, 39(3), 136-145.
- Mbow, C., Chhin, S., Sambou, B., & Skole, D. (2013). Potential of dendrochronology to assess annual rates of biomass productivity in savanna trees of West Africa. *Dendrochronologia*, 31(1), 41-51. doi:10.1016/j.dendro.2012.06.001

- McFarlane, D. (2011). Allometric Scaling of Large Branch Volume in Hardwood Trees in Michigan, USA: Implications for Aboveground Forest Carbon Stock Inventories. *Forest Science*, 57(6), 451-459.
- McHale, M., Burke, I., Lefsky, M., Peper, P., & McPherson, G. (2009). Urban forest biomass estimates: it is important to use allometric relationships developed specifically for urban trees? *Urban Ecology*, 12, 95-113.
- McHale, M., McPherson, E. G., & Burke, I. (2007). The potential of urban tree plantings to be cost effective in carbon credit markets. *Urban Forestry & Urban Greening*, 6(1), 49-60. doi:10.1016/j.ufug.2007.01.001
- McHugh, N., Edmondson, J. L., Gaston, K. J., Leake, J. R., O'Sullivan, O. S., & Cadotte, M. (2015). Modelling short-rotation coppice and tree planting for urban carbon management - a citywide analysis. *Journal of Applied Ecology*, 52(5), 1237-1245. doi:10.1111/1365-2664.12491
- McPherson, G. E., & Peper, P. J. (2012). Urban Tree Growth Modeling. *Arboriculture & Urban Forestry*, 38(5), 172-180.
- McPhearson, T., Kremer, P., & Hamstead, Z. A. (2013). Mapping ecosystem services in New York City: Applying a social-ecological approach in urban vacant land. *Ecosystem Services*, 5, 11-26. doi:10.1016/j.ecoser.2013.06.005
- McPherson, E. G., Berry, A. M., & van Doorn, N. S. (2018). Performance testing to identify climate-ready trees. *Urban Forestry & Urban Greening*, 29, 28-39. doi:10.1016/j.ufug.2017.09.003
- McPherson, E. G., Kendall, A., & Albers, S. (2015). Life cycle assessment of carbon dioxide for different arboricultural practices in Los Angeles, CA. *Urban Forestry & Urban Greening*, 14(2), 388-397. doi:10.1016/j.ufug.2015.04.004
- McPherson, E. G., Nowak, D., Grimmond, S., Souch, C., Grant, R., & Rowtree, R. (1997). Quantifying urban forest structure, function, and value: the Chicago Urban Forest Climate Project. *Urban Ecosystems*, 1, 59-61.
- McPherson, E. G., Xiao, Q., & Aguaron, E. (2013). A new approach to quantify and map carbon stored, sequestered and emissions avoided by urban forests. *Landscape and Urban Planning*, 120, 70-84. doi:10.1016/j.landurbplan.2013.08.005
- McPherson, G. E. (1988). Geometric Solids for Simulations of Tree Crowns. *Landscape and Urban Planning*, 15, 79-83.
- McPherson, G. E. (1998). Atmospheric carbon dioxide reduction by Sacramento's urban forest. *Journal of Arboriculture*, 24(4), 215-223.
- McPherson, G. E. (2003). A benefit-cost analysis of ten street tree species in Modesto, California, U.S. *Journal of Arboriculture*, 29(1), 1-8.
- McPherson, G. E., & Peper, P. J. (2012). Urban Tree Growth Modeling. *Arboriculture & Urban Forestry*, 38(5), 172-180.
- Meir, P., Mencuccini, M., & Dewar, R. C. (2015). Drought-related tree mortality: addressing the gaps in understanding and prediction. *New Phytol*, 207(1), 28-33. doi:10.1111/nph.13382
- Menalled, F. D., & Kelt, M. J. (2001). Crown Structure and Biomass Allocation Strategies of Three Juvenile Tropical Tree Species. *Plant Ecology*, 152(1), 1-11.
- Miesbauer, J. W., Gilman, E., & Giurcanu, M. (2014). Effects of Tree Crown Structure on Dynamic Properties of *Acer rubrum* L. 'Florida Flame. *Arboriculture & Urban Forestry*, 40(4), 218-229.
- Miles, P. D., & Smith, B. W. (2009). Specific Gravity and Other Properties of Wood and Bark for 156 Tree Species Found in North America. *USDA Forest Service, Research Note(NRS-38)*, 39.

- Montagu, K. D., Düttmer, K., Barton, C. V. M., & Cowie, A. L. (2005). Developing general allometric relationships for regional estimates of carbon sequestration—an example using *Eucalyptus pilularis* from seven contrasting sites. *Forest Ecology and Management*, 204(1), 115-129. doi:10.1016/j.foreco.2004.09.003
- Moore, G. (2009). People, trees, landscapes and climate change. *Climate Change on for Young and Old*, www.futureleaders.com.au, 131-149.
- Moore, G. M. (2012). The importance and value of urban forests as climate changes. *The Victorian Naturalist*, 129(5), 167-174.
- Moser, A., Rahman, M. A., Pretzsch, H., Pauleit, S., & Rotzer, T. (2017). Inter- and intraannual growth patterns of urban small-leaved lime (*Tilia cordata* mill.) at two public squares with contrasting microclimatic conditions. *Int J Biometeorol*, 61(6), 1095-1107. doi:10.1007/s00484-016-1290-0
- Moser, A., Rötzer, T., Pauleit, S., & Pretzsch, H. (2015). Structure and ecosystem services of small-leaved lime (*Tilia cordata* Mill.) and black locust (*Robinia pseudoacacia* L.) in urban environments. *Urban Forestry & Urban Greening*, 14(4), 1110-1121. doi:10.1016/j.ufug.2015.10.005
- Moser, A., Rötzer, T., Pauleit, S., & Pretzsch, H. (2016). The Urban Environment Can Modify Drought Stress of Small-Leaved Lime (*Tilia cordata* Mill.) and Black Locust (*Robinia pseudoacacia* L.). *Forests*, 7(3). doi:10.3390/f7030071
- Mucciardi, A. N., Luley, C. J., & Gormally, K. H. (2011). Preliminary Evidence for Using Statisticai Classification of Vibration Waveforms as an Initial Decay Detection Tool. *Arboriculture & Urban Forestry*, 37(5), 191-199.
- Mullaney, J., Lucke, T., & Trueman, S. J. (2015). A review of benefits and challenges in growing street trees in paved urban environments. *Landscape and Urban Planning*, 134, 157-166. doi:10.1016/j.landurbplan.2014.10.013
- Muukkonen, P. (2007). Generalized allometric volume and biomass equations for some tree species in Europe. *European Journal of Forest Research*, 126(2), 157-166. doi:10.1007/s10342-007-0168-4
- Neil, K., & Wu, J. (2006). Effects of urbanization on plant flowering phenology: A review. *Urban Ecosystems*, 9, 243-257. doi:10.1007/s11252-006-9354-2
- Nicolotti, G., Socco, L. V., Martinis, R., Godio, A., & Sambuelli, L. (2003). Application and comparison of three tomographic techniques for detection of decay in trees. *Journal of Arboriculture*, 29(2), 66-78.
- Nikolova, P. S., Zang, C., & Pretzsch, H. (2011). Combining tree-ring analyses on stems and coarse roots to study the growth dynamics of forest trees: a case study on Norway spruce (*Picea abies* [L.] H. Karst). *Trees*, 25(5), 859-872. doi:10.1007/s00468-011-0561-y
- Nitschke, C. R., Nichols, S., Allen, K., Dobbs, C., Livesley, S. J., Baker, P. J., & Lynch, Y. (2017). The influence of climate and drought on urban tree growth in southeast Australia and the implications for future growth under climate change. *Landscape and Urban Planning*, 167, 275-287. doi:10.1016/j.landurbplan.2017.06.012
- North, E. A., D'Amato, A. W., Russell, M. B., & Johnson, G. R. (2017). The influence of sidewalk replacement on urban street tree growth. *Urban Forestry & Urban Greening*, 24, 116-124. doi:10.1016/j.ufug.2017.03.029
- Nowak, D. J. (1993). Atmosoheric carbon reduction by urban trees. *Journal of Environmental Management*, 37, 207-217.
- Nowak, D. J. (1996). Estimating Leaf Area and Leaf Biomass of Open-Grown Deciduous Urban Trees. *Forest Science*, 42(4), 504-507.

- Nowak, D. J. (2006). Institutionalizing urban forestry as a “biotechnology” to improve environmental quality. *Urban Forestry & Urban Greening*, 5(2), 93-100. doi:10.1016/j.ufug.2006.04.002
- Nowak, D. J., & Crane, D. E. (2002a). Carbon storage and sequestration by urban trees in the USA. *Environmental Pollution*, 116, 381-389.
- Nowak, D. J., Crane, D. E., & Stevens, J. C. (2006). Air pollution removal by urban trees and shrubs in the United States. *Urban Forestry & Urban Greening*, 4(3-4), 115-123. doi:10.1016/j.ufug.2006.01.007
- Nowak, D. J., Crane, D. E., Stevens, J. C., Hoehn, R. E., Walton, J. T., & Bond, J. (2008). A Ground-Based Method of Assessing Urban Forest Structure and Ecosystem Services. *Arboriculture & Urban Forestry*, 34(6), 347-358.
- Nowak, D. J., Greenfield, E. J., Hoehn, R. E., & Lapoint, E. (2013). Carbon storage and sequestration by trees in urban and community areas of the United States. *Environ Pollut*, 178, 229-236. doi:10.1016/j.envpol.2013.03.019
- Nowak, D. J., Kuroda, M., & Crane, D. E. (2004). Tree mortality rates and tree population projections in Baltimore, Maryland, USA. *Urban Forestry & Urban Greening*, 2(3), 139-147. doi:10.1078/1618-8667-00030
- Nowak, D. J., Stevens, J. C., Sisinni, S. M., & Luley, C. (2002b). Effects of urban tree management and species selection on atmospheric carbon dioxide. *Journal of Arboriculture*, 28(3), 113-122.
- O'Donoghue, A., & Shackleton, C. M. (2013). Current and potential carbon stocks of trees in urban parking lots in towns of the Eastern Cape, South Africa. *Urban Forestry & Urban Greening*, 12(4), 443-449. doi:10.1016/j.ufug.2013.07.001
- Oldfield, E. E., Felson, A. J., Auyeung, D. S. N., Crowther, T. W., Sonti, N. F., Harada, Y., . . . Bradford, M. A. (2015). Growing the urban forest: tree performance in response to biotic and abiotic land management. *Restoration Ecology*, 23(5), 707-718. doi:10.1111/rec.12230
- Oliva, J., Julio Camarero, J., & Stenlid, J. (2012). Understanding the role of sapwood loss and reaction zone formation on radial growth of Norway spruce (*Picea abies*) trees decayed by *Heterobasidion annosum* s.l. *Forest Ecology and Management*, 274, 201-209. doi:10.1016/j.foreco.2012.02.026
- Oliva, J., Romeralo, C., & Stenlid, J. (2011). Accuracy of the Rotfinder instrument in detecting decay on Norway spruce (*Picea abies*) trees. *Forest Ecology and Management*, 262(8), 1378-1386. doi:10.1016/j.foreco.2011.06.033
- Oliveira, J. T. d. S., Wang, X., & Vidaurre, G. B. (2017). Assessing specific gravity of young Eucalyptus plantation trees using a resistance drilling technique. *Holzforschung*, 71(2). doi:10.1515/hf-2016-0058
- Olson, M. E., Soriano, D., Rosell, J. A., Anfodillo, T., Donoghue, M. J., Edwards, E. J., . . . Mendez-Alonzo, R. (2018). Plant height and hydraulic vulnerability to drought and cold. *Proc Natl Acad Sci U S A*, 115(29), 7551-7556. doi:10.1073/pnas.1721728115
- Omasa, K., Hosoi, F., Uenishi, T. M., Shimizu, Y., & Akiyama, Y. (2007). Three-Dimensional Modeling of an Urban Park and Trees by Combined Airborne and Portable On-Ground Scanning LIDAR Remote Sensing. *Environmental Modeling & Assessment*, 13(4), 473-481. doi:10.1007/s10666-007-9115-5
- Ordóñez, C., & Duinker, P. N. (2014). Assessing the vulnerability of urban forests to climate change. *Environmental Reviews*, 22(3), 311-321. doi:10.1139/er-2013-0078
- Orozco-Aguilar, L., Johnstone, D., Livesley, S. J., & Brack, C. (2018). The overlooked carbon loss due to decayed wood in urban trees. *Urban Forestry & Urban Greening*, 29, 142-153. doi:10.1016/j.ufug.2017.09.008

- Osada, N. (2012). Crown exposure to light and tree allometry of 11 tree species in a snowy cool-temperate forest in Japan. *Plant Ecology*, 213(5), 783-794. doi:10.1007/s11258-012-0041-5
- Ossola, A., & Hopton, M. E. (2017). Measuring urban tree loss dynamics across residential landscapes. *Sci Total Environ*, 612, 940-949. doi:10.1016/j.scitotenv.2017.08.103
- Ostberg, J., Deshammar, T., Wistrom, B., & Nielsen, A. B. (2013). Grading of Parameters for Urban Tree Inventories by City Officials, Arborists, and Academics Using the Delphi Method. *Environmental Management*, 51, 694-708. doi:10.1007/s00267-012-9973-8
- Osunkoya, O., Omar-Ali, K., Amir, N., Dayan, J., Daud, D., & Sheng, T. (2007). Comparative height-crown allometry and mechanical design in 22 tree species of Kuala Belalong rainforest, Brunel, Borneo. *American Journal of Botany*, 94(12), 1951-1962.
- Paletto, A., & Tosi, V. (2009). Forest canopy cover and canopy closure: comparison of assessment techniques. *European Journal of Forest Research*, 128(3), 265-272. doi:10.1007/s10342-009-0262-x
- Pandit, R., Polyakov, M., Tapsuwan, S., & Moran, T. (2013). The effect of street trees on property value in Perth, Western Australia. *Landscape and Urban Planning*, 110, 134-142. doi:10.1016/j.landurbplan.2012.11.001
- Pasher, J., McGovern, M., Khoury, M., & Duffe, J. (2014). Assessing carbon storage and sequestration by Canada's urban forests using high resolution earth observation data. *Urban Forestry & Urban Greening*, 13(3), 484-494. doi:10.1016/j.ufug.2014.05.001
- Pearce, R. B. (2000). Decay development and its restrictions in trees. *Journal of Arboriculture*, 26(1), 1-11.
- Peñuelas, J. (2003). BVOCs: plant defense against climate warming? *Trends in Plant Science*, 8(3), 105-109. doi:10.1016/s1360-1385(03)00008-6
- Peñuelas, J., & Staudt, M. (2010). BVOCs and global change. *Trends Plant Sci*, 15(3), 133-144. doi:10.1016/j.tplants.2009.12.005
- Peper, P. J., Alzate, C. P., McNeil, J. W., & Hashemi, J. (2014). Allometric equations for urban ash trees (*Fraxinus* spp.) in Oakville, Southern Ontario, Canada. *Urban Forestry & Urban Greening*, 13(1), 175-183. doi:10.1016/j.ufug.2013.07.002
- Peper, P. J., & McPerson, G. E. (1998). Comparison of four foliar and woody biomass estimation methods applied to open-grown deciduous trees. *Journal of Arboriculture*, 24(4), 191-200.
- Peper, P. J., McPerson, G. E., & Mori, S. M. (2001). Predictive equations for dimensions and leaf area of coastal southern California street trees. *Journal of Arboriculture*, 27(4), 169-179.
- Peper, P. J., & McPherson, E. G. (2003). Evaluation of four methods for estimating leaf area of isolated trees. *Urban Forestry & Urban Greening*, 2(1), 19-29. doi:10.1078/1618-8667-00020
- Picard, N., Rutishauser, E., Ploton, P., Ngomanda, A., & Henry, M. (2015). Should tree biomass allometry be restricted to power models? *Forest Ecology and Management*, 353, 156-163. doi:10.1016/j.foreco.2015.05.035
- Pickett, S. T., & Kempf, J. S. (1980). Branching pattern in forest shrubs and understory trees in relation to habitat. *New Phytologist*, 86, 219-228.
- Plomion, C., Leprovost, G., & Stokes, A. (2001). Wood Formation in Trees. *Plant Physiology*, 127(4), 1513-1523. doi:10.1104/pp.010816
- Poorter, H., Jagodzinski, A. M., Ruiz-Peinado, R., Kuyah, S., Luo, Y., Oleksyn, J., . . . Sack, L. (2015). How does biomass distribution change with size and differ among species? An analysis for 1200 plant species from five continents. *New Phytologist*. doi:10.1111/nph.13571

- Poorter, H., Niklas, K. J., Reich, P. B., Oleksyn, J., Poot, P., & Mommer, L. (2012). Biomass allocation to leaves, stems and roots: meta-analyses of interspecific variation and environmental control. *New Phytol*, 193(1), 30-50. doi:10.1111/j.1469-8137.2011.03952.x
- Poudyal, N. C., Siry, J. P., & Bowker, J. M. (2011). Quality of urban forest carbon credits. *Urban Forestry & Urban Greening*, 10(3), 223-230. doi:10.1016/j.ufug.2011.05.005
- Pretzsch, H. (2014). Canopy space filling and tree crown morphology in mixed-species stands compared with monocultures. *Forest Ecology and Management*, 327, 251-264. doi:10.1016/j.foreco.2014.04.027
- Pretzsch, H., Biber, P., Uhl, E., Dahlhausen, J., Rötzer, T., Caldentey, J., . . . Pauleit, S. (2015). Crown size and growing space requirement of common tree species in urban centres, parks, and forests. *Urban Forestry & Urban Greening*, 14(3), 466-479. doi:10.1016/j.ufug.2015.04.006
- Pretzsch, H., Biber, P., Uhl, E., Dahlhausen, J., Schutze, G., Perkins, D., . . . Lefer, B. (2017). Climate change accelerates growth of urban trees in metropolises worldwide. *Sci Rep*, 7(1), 15403. doi:10.1038/s41598-017-14831-w
- Price, C. (2003). Quantifying the aesthetic benefits of urban forestry. *Urban Forestry & Urban Greening*, 1(3), 123-133. doi:10.1078/1618-8667-00013
- Purves, D. W., Lichstein, J. W., & Pacala, S. W. (2007). Crown plasticity and competition for canopy space: a new spatially implicit model parameterized for 250 North American tree species. *PLoS One*, 2(9), e870. doi:10.1371/journal.pone.0000870
- Quigley, M. (2004). Street trees and rural conspecifics: Will long-lived trees reach full size in urban conditions? *Urban Ecosystems*, 7, 29-39.
- R Core Team. (2015). R: A language and environment for statistical computing. Vienna, Austria: R Foundation for Statistical Computing. . Retrieved from <http://www.R-project.org/>.
- Rabe, C., Ferner, D., Fink, S., & Schwarze, F. W. M. R. (2004). Detection of Decay in Trees with Stress Waves and Interpretation of Acoustic Tomograms. *Arboricultural Journal*, 28(1-2), 3-19. doi:10.1080/03071375.2004.9747399
- Raciti, S. M., Hutyrá, L. R., & Newell, J. D. (2014). Mapping carbon storage in urban trees with multi-source remote sensing data: relationships between biomass, land use, and demographics in Boston neighborhoods. *Sci Total Environ*, 500-501, 72-83. doi:10.1016/j.scitotenv.2014.08.070
- Rautiainen, M., Mattus, M., Stenberg, P., & Ervasti, S. (2008). Crown Envelope Shape Measurements and Models. *Silva Fennica*, 42(1), 19-33.
- Real, R., & Vargas, J. M. (1996). The Probabilistic Basis of Jaccard's Index of Similarity. *Society of Systematic Biologist*, 45(3), 380-385.
- Reich, P. B., Luo, Y., Bradford, J. B., Poorter, H., Perry, C. H., & Oleksyn, J. (2014). Temperature drives global patterns in forest biomass distribution in leaves, stems, and roots. *Proc Natl Acad Sci U S A*, 111(38), 13721-13726. doi:10.1073/pnas.1216053111
- Riikonen, A., Lindén, L., Pulkkinen, M., & Nikinmaa, E. (2011). Post-transplant crown allometry and shoot growth of two species of street trees. *Urban Forestry & Urban Greening*, 10(2), 87-94. doi:10.1016/j.ufug.2010.09.001
- Rinn, F. (2012). Basics of micro-resistance drilling for timber inspection. *Holztechnologie*, 53, 24-29.
- Rinn, F., Schweingruber, F. H., & Schar, E. (1996). Resistograph and X-ray density chart of wood comparative evaluation of drill resistance profiles and x-ray density charts of different wood species. *Holzforschung*, 50, 303-311.

- Robles, C. A., Lopez, S. E., McCargo, P. D., & Carmarán, C. C. (2015). Relationships between fungal endophytes and wood-rot fungi in wood of *Platanus acerifolia* in urban environments. *Canadian Journal of Forest Research*, 45(7), 929-936. doi:10.1139/cjfr-2014-0560
- Rogers, K., Lawrence, V., & Hutching, T. R. (2014). Determining tree growth in the urban forest. *Trees, people and the built environment*, 2, 72-81.
- Roman, L. A., Battles, J. J., & McBride, J. R. (2014). Determinants of establishment survival for residential trees in Sacramento County, CA. *Landscape and Urban Planning*, 129, 22-31. doi:10.1016/j.landurbplan.2014.05.004
- Rouvinen, S., & Kuuluvainen, T. (1997). Structure and asymmetry of tree crowns in relation to local competition in a natural mature Scots pine forest. *Canadian Journal of Forest Research*, 27, 890-902.
- Rozendaal, D. M., Brien, R. J., Soliz-Gamboa, C. C., & Zuidema, P. A. (2010). Tropical tree rings reveal preferential survival of fast-growing juveniles and increased juvenile growth rates over time. *New Phytol*, 185(3), 759-769. doi:10.1111/j.1469-8137.2009.03109.x
- Ruiz-Peinado, R., Montero, G., & del Rio, M. (2012). Biomass models to estimate carbon stock for hardwood tree species. *Forest Systems*, 21(1), 42-52. doi:10.5424/fs/2112211-02193
- Russell, M. B., Fraver, S., Aakala, T., Gove, J. H., Woodall, C. W., D'Amato, A. W., & Ducey, M. J. (2015). Quantifying carbon stores and decomposition in dead wood: A review. *Forest Ecology and Management*, 350, 107-128. doi:10.1016/j.foreco.2015.04.033
- Russo, A., Escobedo, F. J., Timilsina, N., Schmitt, A. O., Varela, S., & Zerbe, S. (2014). Assessing urban tree carbon storage and sequestration in Bolzano, Italy. *International Journal of Biodiversity Science, Ecosystem Services & Management*, 10(1), 54-70. doi:10.1080/21513732.2013.873822
- Rust, S. (2014). Analysis of regional variation of height growth and slenderness in populations of six urban tree species using a quantile regression approach. *Urban Forestry & Urban Greening*, 13(2), 336-343. doi:10.1016/j.ufug.2013.12.003
- Ryder, C. M., & Moore, G. M. (2013). The arboricultural and economic benefits of formative pruning street trees. *Arboriculture & Urban Forestry*, 39(1), 17-24.
- Sajdak, M., & Velázquez-Martí, B. (2012). Estimation of pruned biomass from dendrometric parameters on urban forests: Case study of *Sophora japonica*. *Renewable Energy*, 47, 188-193. doi:10.1016/j.renene.2012.04.002
- Sajdak, M., Velázquez-Martí, B., López-Cortés, I., Fernández-Sarría, A., & Estornell, J. (2014). Prediction models for estimating pruned biomass obtained from *Platanus hispanica* Münchh. used for material surveys in urban forests. *Renewable Energy*, 66, 178-184. doi:10.1016/j.renene.2013.12.005
- Salzer, M. W., Hughes, M. K., Bunn, A. G., & Kipfmüller, K. F. (2009). Recent unprecedented tree-ring growth in bristlecone pine at the highest elevations and possible causes. *Proc Natl Acad Sci U S A*, 106(48), 20348-20353. doi:10.1073/pnas.0903029106
- Sambuelli, L., Socco, L. V., Godio, A., Nicolotti, G., & Martinis, R. (2003). Ultrasonic, electric and radar measurements for living trees assessment. *BOLLETTINO DI GEOFISICA TEORICA ED APPLICATA*, 44(3-4), 253-279.
- Sanders, J., Grabosky, J. C., & Cowie, P. (2013). Establishing maximum size expectations for urban trees with regard to designed space. *Arboriculture & Urban Forestry*, 39(2), 68-73.

- Scharnweber, T., Manthey, M., Criegee, C., Bauwe, A., Schröder, C., & Wilmking, M. (2011). Drought matters – Declining precipitation influences growth of *Fagus sylvatica* L. and *Quercus robur* L. in north-eastern Germany. *Forest Ecology and Management*, 262(6), 947-961. doi:10.1016/j.foreco.2011.05.026
- Schlecht, R. M., & Affleck, D. L. R. (2014). Branch aggregation and crown allometry condition the precision of randomized branch sampling estimators of conifer crown mass. *Canadian Journal of Forest Research*, 44(5), 499-508. doi:10.1139/cjfr-2013-0388
- Schmidt, O., Gaiser, O., & Dujesiefken, D. (2012). Molecular identification of decay fungi in the wood of urban trees. *European Journal of Forest Research*, 131(3), 885-891. doi:10.1007/s10342-011-0562-9
- Schnell, S., Altrel, D., Stahl, G., & Kleinn, C. (2015). The contribution of trees outside forests to national tree biomass and carbon stocks--a comparative study across three continents. *Environ Monit Assess*, 187(1), 4197. doi:10.1007/s10661-014-4197-4
- Schroeder, H., Flannigan, J., & Coles, R. (2006). Residents' Attitudes Toward Street Trees in the UK and U.S. Communities. *Arboriculture & Urban Forestry*, 32(5), 236-246.
- Schwarze, F. W. M. R., & Heuser, C. (2006). Stem Wounds—Potential Entry Courts for Wood Decay Fungi? *Arboricultural Journal*, 29(2), 101-119. doi:10.1080/03071375.2006.9747449
- Schwendenmann, L., & Mitchell, C. (2014). Carbon accumulation by native trees and soils in an urban park, Auckland. *New Zealand Journal of Ecology*, 38(2), 213-220.
- Schwets, T. L., & Brown, R. D. (2000). Form and structure of maple trees in urban environments. *Landscape and Urban Planning*, 46, 191-201.
- Searle, S. Y., Turnbull, M. H., Boelman, N. T., Schuster, W. S., Yakir, D., & Griffin, K. L. (2012). Urban environment of New York City promotes growth in northern red oak seedlings. *Tree Physiol*, 32(4), 389-400. doi:10.1093/treephys/tps027
- Sedmák, R., Sedmáková, D., Bošela, M., Marušák, R., Ježík, M., Murgaš, V., & Blaženec, M. (2014). Age estimation of Norway spruce using incomplete increment cores: Testing new and improved methods. *Dendrochronologia*, 32(4), 327-335. doi:10.1016/j.dendro.2014.07.005
- Sellier, D., & Fourcaud, T. (2009). Crown structure and wood properties: Influence on tree sway and response to high winds. *Am J Bot*, 96(5), 885-896. doi:10.3732/ajb.0800226
- Semenzato, P., Cattaneo, D., & Dainese, M. (2011). Growth prediction for five tree species in an Italian urban forest. *Urban Forestry & Urban Greening*, 10(3), 169-176. doi:10.1016/j.ufug.2011.05.001
- Sharapov, E., Wang, X., Smirnova, E., & Wacker, J. P. (2018). Wear behavior of drill bits in wood drilling resistance measurements. *Wood and Fiber Science*, 502, 2-12.
- Shigo, A. L. (1965). The pattern of decays and discolorations in northern hardwoods. *Phytopathology*, 55, 648-652.
- Shortle, W. C. (1979). Detection of decay in trees. *Journal of Arboriculture*, 5(10), 226-232.
- Shrestha, R., & Wynne, R. H. (2012). Estimating Biophysical Parameters of Individual Trees in an Urban Environment Using Small Footprint Discrete-Return Imaging Lidar. *Remote Sensing*, 4(12), 484-508. doi:10.3390/rs4020484
- Shukla, R. P., & Ramakrishnan, P. S. (1986). Architecture and growth strategies of tropical trees in relation to succesional status. *Journal of Ecology*, 74, 33-46.
- Silvera Seamans, G. (2013). Mainstreaming the environmental benefits of street trees. *Urban Forestry & Urban Greening*, 12(1), 2-11. doi:10.1016/j.ufug.2012.08.004
- Simpson, J. R., & McPherson, G. E. (1998). Simulation of tree shade impacts on residential energy use for space conditioning in Sacramento. *Atmospheric Environment*, 32(1), 69-74.

- Sjöman, H., Östberg, J., & Bühler, O. (2012). Diversity and distribution of the urban tree population in ten major Nordic cities. *Urban Forestry & Urban Greening*, 11(1), 31-39. doi:10.1016/j.ufug.2011.09.004.”
- Smiley, T. E., & Fraedrich, B. R. (1992). Determining strength loss from decay. *Journal of Arboriculture*, 18(4), 201-204.
- Smith, F. W., & Lonh, J. N. (2001). Age-related decline in forest growth: an emergent property. *Forest Ecol Manag.*, 144, 175-181.
- Smith, K. T. (2006). Compartmentalization Today. *Arboricultural Journal*, 29(3), 173-184. doi:10.1080/03071375.2006.9747457
- Soares, A. L., Rego, F. C., McPherson, E. G., Simpson, J. R., Peper, P. J., & Xiao, Q. (2011). Benefits and costs of street trees in Lisbon, Portugal. *Urban Forestry & Urban Greening*, 10(2), 69-78. doi:10.1016/j.ufug.2010.12.001
- Staudhammer, C. L., Escobedo, F. J., Lawrence, A., Duryea, M., Smith, P., & Merrit, M. (2011). Rapid assessment of change and hurricane impacts to Houston’s urban forest structure. *Arboriculture & Urban Forestry*, 37(2), 60-66.
- Steenberg, J. W., Millward, A. A., Nowak, D. J., Robinson, P. J., & Ellis, A. (2017). Forecasting Urban Forest Ecosystem Structure, Function, and Vulnerability. *Environ Manage*, 59(3), 373-392. doi:10.1007/s00267-016-0782-3
- Stephenson, N. L., Das, A. J., Condit, R., Russo, S. E., Baker, P. J., Beckman, N. G., . . . Zavala, M. A. (2014). Rate of tree carbon accumulation increases continuously with tree size. *Nature*, 507(7490), 90-93. doi:10.1038/nature12914
- Sterken, P. (2006). Prognosis of the development of decay and the tructure-safety of hollow trees. *Arboricultural Journal*, 29, 245-267. doi:10.1080/03071375.2006.9747466
- Stevens, J. P. (2013). *Intermediate Statistics: A modern approach* (Vol. Third Edition). United States of America: Taylor and Francis.
- Stoffberg, G. H., van Rooyen, M. W., van der Linde, M. J., & Groeneveld, H. T. (2008). Predicting the growth in tree height and crown size of three street tree species in the City of Tshwane, South Africa. *Urban Forestry & Urban Greening*, 7(4), 259-264. doi:10.1016/j.ufug.2008.05.002
- Stoffberg, G. H., van Rooyen, M. W., van der Linde, M. J., & Groeneveld, H. T. (2010). Carbon sequestration estimates of indigenous street trees in the City of Tshwane, South Africa. *Urban Forestry & Urban Greening*, 9(1), 9-14. doi:10.1016/j.ufug.2009.09.004
- Stravinskienė, V., Snieškienė, V., & Stankevičienė, A. (2015). Health condition of *Tilia cordata* Mill. trees growing in the urban environment. *Urban Forestry & Urban Greening*, 14(1), 115-122. doi:10.1016/j.ufug.2014.12.006
- Strohbach, M. W., Arnold, E., & Haase, D. (2012a). The carbon footprint of urban green space—A life cycle approach. *Landscape and Urban Planning*, 104(2), 220-229. doi:10.1016/j.landurbplan.2011.10.013
- Strohbach, M. W., & Haase, D. (2012b). Above-ground carbon storage by urban trees in Leipzig, Germany: Analysis of patterns in a European city. *Landscape and Urban Planning*, 104(1), 95-104. doi:10.1016/j.landurbplan.2011.10.001
- Suzuki, M., & Hiura, T. (2000). Allometric differences between current-year shoots and large branches of deciduous broad-leaved tree species. *Tree Physiology*, 20, 203-209.
- Swoczyna, T., Kalaji, H. M., Pietkiewicz, S., Borowski, J., & Zaráś-Januszkiewicz, E. (2010). Photosynthetic apparatus efficiency of eight tree taxa as an indicator of their tolerance to urban environments. *Dendrobiology*, 63, 65-75.
- Szewczyk, G., Wąsik, R., Leszczyński, K., & Podlaski, R. (2018). Age estimation of different tree species using a special kind of an electrically recording resistance drill. *Urban Forestry & Urban Greening*, 34, 249-253. doi:10.1016/j.ufug.2018.07.010

- Tahvanainen, T., & Forss, E. (2008). Individual tree models for the crown biomass distribution of Scots pine, Norway spruce and birch in Finland. *Forest Ecology and Management*, 255(3-4), 455-467. doi:10.1016/j.foreco.2007.09.035
- Taneda, H., & Tateno, M. (2004). The criteria for biomass partitioning of current shoot:water transport versus mechanical support. *American Journal of Botany*, 91(12), 1949-1959.
- Tanhuanpää, T., Kankare, V., Setälä, H., Yli-Pelkonen, V., Vastaranta, M., Niemi, M. T., . . . Holopainen, M. (2017). Assessing above-ground biomass of open-grown urban trees: A comparison between existing models and a volume-based approach. *Urban Forestry & Urban Greening*, 21, 239-246. doi:10.1016/j.ufug.2016.12.011
- Tardif, J. C., & Conciatori, F. (2006). A comparison of ring-width and event-year chronologies derived from white oak (*Quercus alba*) and northern red oak (*Quercus rubra*), southwestern Quebec, Canada. *Dendrochronologia*, 23(3), 133-138. doi:10.1016/j.dendro.2005.10.001
- Templeton, M., & Putz, F. E. (2003). Crown encroachment on southern live oaks in suburban settings: tree status and homeowner concerns. *Journal of Arboriculture*, 29(6), 337-342.
- Terho, M. (2009). An assessment of decay among urban *Tilia*, *Betula*, and *Acer* trees felled as hazardous. *Urban Forestry & Urban Greening*, 8(2), 77-85. doi:10.1016/j.ufug.2009.02.004
- Terho, M., & Hallaksela, A. (2005). Potential hazard characteristics of *Tilia*, *Betula*, and *Acer* trees removed in the Helsinki City Area during 2001–2003. *Urban Forestry & Urban Greening*, 3(2), 113-120. doi:10.1016/j.ufug.2004.07.002
- Terho, M., & Hallaksella, A. (2008). Decay characteristics of hazardous *Tilia*, *Betula*, and *Acer* trees felled by municipal urban tree managers in the Helsinki City Area. *Forestry*, 2(1), 151-159. doi:10.1093/forestry/cpn002
- Terho, M., Hantula, J., & Hallaksella, A. M. (2007). Occurrence and decay patterns of common wood-decay fungi in hazardous trees felled in the Helsinki City. *Foresy Pathology*, 37, 420-432. doi:10.1111/j.1439-0329.2007.00518.x
- Timilsina, N., Staudhammer, C. L., Escobedo, F. J., & Lawrence, A. (2014). Tree biomass, wood waste yield, and carbon storage changes in an urban forest. *Landscape and Urban Planning*, 127, 18-27. doi:10.1016/j.landurbplan.2014.04.003
- Trichon, V. (2001). Crown Typology and the Identification of Rain Forest Trees on Large-Scale Aerial Photographs. *Plant Ecology*, 153(1-2), 301-312.
- Troxel, B., Piana, M., Ashton, M. S., & Murphy-Dunning, C. (2013). Relationships between bole and crown size for young urban trees in the northeastern USA. *Urban Forestry & Urban Greening*, 12(2), 144-153. doi:10.1016/j.ufug.2013.02.006
- Tubby, K. V., & Webber, J. F. (2010). Pests and diseases threatening urban trees under a changing climate. *Forestry*, 83(4), 451-459. doi:10.1093/forestry/cpq027
- Ukrainetz, N. K., & O'Neill, G. A. (2010). An analysis of sensitivities contributing measurement error to Resistograph values. *Canadian Journal of Forest Research*, 40(4), 806-811. doi:10.1139/x10-019
- Urban, J., Čermák, J., & Ceulemans, R. (2014). Above- and below-ground biomass, surface and volume, and stored water in a mature Scots pine stand. *European Journal of Forest Research*, 134(1), 61-74. doi:10.1007/s10342-014-0833-3
- Urban, J., Holušová, K., Menšík, L., Čermák, J., & Kantor, P. (2012). Tree allometry of Douglas fir and Norway spruce on a nutrient-poor and a nutrient-rich site. *Trees*, 27(1), 97-110. doi:10.1007/s00468-012-0771-y
- Vaccari, F. P., Gioli, B., Toscano, P., & Perrone, C. (2013). Carbon dioxide balance assessment of the city of Florence (Italy), and implications for urban planning.

- Landscape and Urban Planning*, 120, 138-146.
doi:10.1016/j.landurbplan.2013.08.004
- Valentine, H. T., & Makela, A. (2005). Bridging process-based and empirical approaches to modeling tree growth. *Tree Physiology*, 25, 769-779.
- Valentine, H. T., Tritton, L. M., & Furnival, G. M. (1984). Sampling trees for biomass, volume or mineral content. *Forest Science*, 30(3), 673-681.
- van der Maaten-Theunissen, M., van der Maaten, E., & Bouriaud, O. (2015). pointRes: An R package to analyze pointer years and components of resilience. *Dendrochronologia*, 35, 34-38. doi:10.1016/j.dendro.2015.05.006
- van Mantgem, P. J., & Stephenson, N. L. (2004). Does coring contribute to tree mortality? *Canadian Journal of Forest Research*, 34(11), 2394-2398. doi:10.1139/x04-120
- van Noordwijk, M., & Mulia, R. (2002). Functional branch analysis as tool for fractal scaling above- and belowground trees for their additive and non-additive properties. *Ecological Modelling*, 149, 41-51.
- Vaz Monteiro, M., Doick, K. J., & Handley, P. (2016). Allometric relationships for urban trees in Great Britain. *Urban Forestry & Urban Greening*, 19, 223-236.
doi:10.1016/j.ufug.2016.07.009
- Vaz Monteiro, M., Levanič, T., & Doick, K. J. (2017). Growth rates of common urban trees in five cities in Great Britain: A dendrochronological evaluation with an emphasis on the impact of climate. *Urban Forestry & Urban Greening*, 22, 11-23.
doi:10.1016/j.ufug.2017.01.003
- Velasco, E., Roth, M., Norford, L., & Molina, L. T. (2016). Does urban vegetation enhance carbon sequestration? *Landscape and Urban Planning*, 148, 99-107.
doi:10.1016/j.landurbplan.2015.12.003
- Velázquez-Martí, B., Sajdak, M., & López-Cortés, I. (2013). Available residual biomass obtained from pruning *Morus alba* L. trees cultivated in urban forest. *Renewable Energy*, 60, 27-33. doi:10.1016/j.renene.2013.04.001
- Vermeulen, P. J. (2014). Crown depth as a result of evolutionary games: decreasing solar angle should lead to shallower, not deeper crowns. *New Phytol*, 202(4), 1249-1256.
doi:10.1111/nph.12729
- Vinciguerra, V., Napoli, A., Bistoni, A., Petrucci, G., & Sgherzi, R. (2007). Wood decay characterization of a naturally infected London plane-tree in urban environment using Py-GC/MS. *Journal of Analytical and Applied Pyrolysis*, 78(1), 228-231.
doi:10.1016/j.jaap.2006.06.003
- VLSAC. (2011). *Victorian Local Sustainability Accord: Urban Forestry Background Issue Paper*. Melbourne, Victoria, Australia: Victorian Government Retrieved from www.dse.vic.gov.au.
- Vogt, J., Gillner, S., Hofmann, M., Tharang, A., Dettmann, S., Gerstenberg, T., . . . Roloff, A. (2017). Citree: A database supporting tree selection for urban areas in temperate climate. *Landscape and Urban Planning*, 157, 14-25.
doi:10.1016/j.landurbplan.2016.06.005
- Vogt, J. M., Watkins, S. L., Mincey, S. K., Patterson, M. S., & Fischer, B. C. (2015). Explaining planted-tree survival and growth in urban neighborhoods: A social-ecological approach to studying recently-planted trees in Indianapolis. *Landscape and Urban Planning*, 136, 130-143. doi:10.1016/j.landurbplan.2014.11.021
- Volgusheva, A. A., Yakovleva, O. V., Kukarskikh, G. P., Riznichenko, G. Y., & Krendeleva, T. E. (2011). Performance index in assessing the physiological state of trees in urban ecosystems. *Biophysics*, 56(1), 90-95. doi:10.1134/s0006350911010246

- Vonderach, C., Vögtle, T., Adler, P., & Norra, S. (2012). Terrestrial laser scanning for estimating urban tree volume and carbon content. *International Journal of Remote Sensing*, 33(21), 6652-6667. doi:10.1080/01431161.2012.692888
- Wang, S.-Y., Chiu, C.-M., & Lin, C.-J. (2003). Application of the drilling resistance method for annual ring characteristics: evaluation of Taiwania (Taiwania cryptomerioides) trees grown with different thinning and pruning treatments. *Journal of Wood Science*, 49, 116-124.
- Wang, X., & Allison, B. (2008). Decay Detection in Red Oak Trees Using a Combination of Visual Inspection, Acoustic Testing, and Resistance Microdrilling. *Arboriculture & Urban Forestry*, 34(1), 1-4.
- Wang, X., Divos, F., Pilon, C., Brashaw, B. K., Ross, R. J., & Pellerin, R. F. (2004). Assessment of Decay in Standing Timber Using Stress Wave Timing Nondestructive Evaluation Tools: A Guide for Use and Interpretation. *USDA-Forest Service, General Technical Report(FPL-GTR-147)*, 1-14.
- Wardlaw, T. J., & Neilsen, W. A. (1999). Decay and other defects associated with pruned branches of Eucalyptus nitens. *TasForest*, 11(49), 49-57.
- Watson, G. (2008). Discoloration and Decay in Severed Tree Roots. *Arboriculture & Urban Forestry*, 34(4), 260-264.
- Way, D. A., & Oren, R. (2010). Differential responses to changes in growth temperature between trees from different functional groups and biomes: a review and synthesis of data. *Tree Physiol*, 30(6), 669-688. doi:10.1093/treephys/tpq015
- Weber, K., & Mattheck, C. (2006). The effects of excessive drilling diagnosis on decay propagation in trees. *Trees*, 20(2), 224-228. doi:10.1007/s00468-005-0029-z
- Weiner, J. (2004). Allocation, plasticity and allometry in plants. *Perspectives in Plant Ecology, Evolution and Systematics*, 6(4), 207-215. doi:10.1078/1433-8319-00083
- Weissert, L. F., Salmond, J. A., & Schwendenmann, L. (2014). A review of the current progress in quantifying the potential of urban forests to mitigate urban CO₂ emissions. *Urban Climate*, 8, 100-125. doi:10.1016/j.uclim.2014.01.002
- Welles, J. M. (1990). Some indirect methods of estimating canopy structure. *Remote Sensing Reviews*, 5(1), 31-43. doi:10.1080/02757259009532120
- Wessels, C. B., Malan, F. S., & Rypstra, T. (2011). A review of measurement methods used on standing trees for the prediction of some mechanical properties of timber. *European Journal of Forest Research*, 130(6), 881-893. doi:10.1007/s10342-011-0484-6
- West, G. B., Brown, J. H., & Enquist, B. J. (1999). A general model for the structure and allometry of plant vascular systems. *Nature*, 400(12), 665-667.
- Wilkinson, D. M. (1995). Modelling Tree Crowns as Geometric Solids. *Arboricultural Journal*, 19(4), 387-393. doi:10.1080/03071375.1995.9747085
- Wilson, B. (1990). The development of tree form. *Horticultural Science*, 25(1), 52-54.
- Woodall, C. W., Nowak, D. J., Liknes, G. C., & Westfall, J. A. (2010). Assessing the potential for urban trees to facilitate forest tree migration in the eastern United States. *Forest Ecology and Management*, 259, 1447-1454. doi:10.1016/j.foreco.2010.01.018
- Worbes, M., Staschel, R., Roloff, A., & Junk, W. J. (2003). Tree ring analysis reveals age structure, dynamics and wood production of a natural forest stand in Cameroon. *Forest Ecol Manag.*, 173, 105-123.
- Wunder, J., Manusch, C., Queloz, V., Brang, P., Ringwald, V., & Bugmann, H. (2013). Does increment coring enhance tree decay? New insights from tomography assessments. *Canadian Journal of Forest Research*, 43(8), 711-718. doi:10.1139/cjfr-2012-0450

- Wunder, J., Reineking, B., Hillgarter, F.-W., Bigler, C., & Bugmann, H. (2011). Long-term effects of increment coring on Norway spruce mortality. *Canadian Journal of Forest Research*, 41(12), 2326-2336. doi:10.1139/x11-150
- Xiao, Q., McPherson, G. E., Ustin, S. L., Grismer, M. E., & Simpson, J. R. (2000). Winter rainfall interception by two open-grown trees in Davis, California. *Hydrological Process*, 14, 763-784.
- Xiao, Y., Jokela, E. J., & White, T. L. (2003). Species differences in crown structure and growth performance of juvenile loblolly and slash pine. *Forest Ecology and Management*, 174, 295-313.
- Xu, W., Su, Z., Feng, Z., Xu, H., Jiao, Y., & Yan, F. (2013). Comparison of conventional measurement and LiDAR-based measurement for crown structures. *Computers and Electronics in Agriculture*, 98, 242-251. doi:10.1016/j.compag.2013.08.015
- Yamaguchi, T., Sasaki, K., & Sakamoto, Y. (2001). Evaluation of a Stress-wave Timer for the Minimally Destructive Detection of Decay in Living Trees in Northern-Japanese Forests. *Journal of Forestry Research*, 6, 117-120.
- Yao, X., Zhao, M., & Escobedo, F. J. (2017). What Causal Drivers Influence Carbon Storage in Shanghai, China's Urban and Peri-Urban Forests? *Sustainability*, 9(4). doi:10.3390/su9040577
- Yoon, T. K., Park, C.-W., Lee, S. J., Ko, S., Kim, K. N., Son, Y., . . . Son, Y. (2013). Allometric equations for estimating the aboveground volume of five common urban street tree species in Daegu, Korea. *Urban Forestry & Urban Greening*, 12(3), 344-349. doi:10.1016/j.ufug.2013.03.006
- Yu, Q., Yang, D.-Q., Zhang, S. Y., Beaulieu, J., & Duchesne, I. (2003). Genetic variation in decay resistance and its correlation to wood density and growth in white spruce. *Canadian Journal of Forest Research*, 33(11), 2177-2183. doi:10.1139/x03-150
- Yue, C., Kahle, H.-P., Kohnle, U., Zhang, Q., & Kang, X. (2014). Detecting trends in diameter growth of Norway spruce on long-term forest research plots using linear mixed-effects models. *European Journal of Forest Research*, 133(5), 783-792. doi:10.1007/s10342-014-0795-5
- Zeide, B. (1998). Fractal analysis of foliage distribution in loblolly pine crowns. *Canadian Journal of Forest Research*, 28, 106-114.
- Zhang, Q., Wang, C., Wang, X., & Quan, X. (2009). Carbon concentration variability of 10 Chinese temperate tree species. *Forest Ecology and Management*, 258(5), 722-727. doi:10.1016/j.foreco.2009.05.009
- Zhao, M., Kong, Z. H., Escobedo, F. J., & Gao, J. (2010). Impacts of urban forests on offsetting carbon emissions from industrial energy use in Hangzhou, China. *J Environ Manage*, 91(4), 807-813. doi:10.1016/j.jenvman.2009.10.010
- Zhao, S., Tang, Y., & Chen, A. (2016). Carbon Storage and Sequestration of Urban Street Trees in Beijing, China. *Frontiers in Ecology and Evolution*, 4. doi:10.3389/fevo.2016.00053
- Zhou, T., Koomen, E., & van Leeuwen, E. S. (2018). Residents' preferences for cultural services of the landscape along the urban-rural gradient. *Urban Forestry & Urban Greening*, 29, 131-141. doi:10.1016/j.ufug.2017.11.011

Appendices

Appendix 1. Appendix to chapter 3

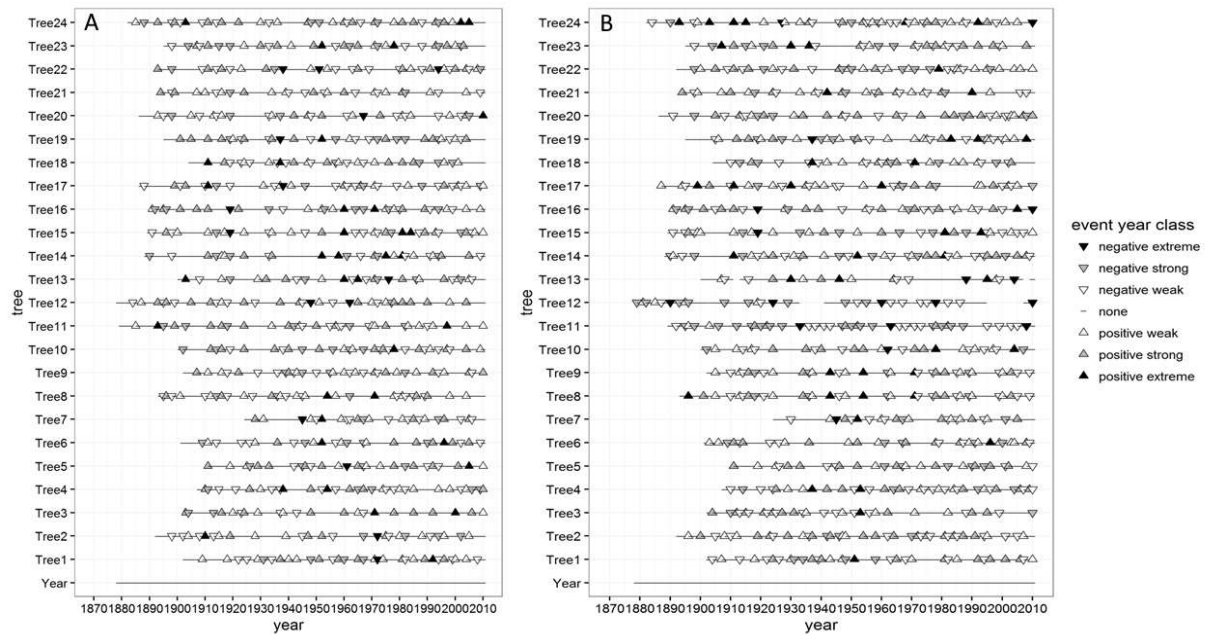
Appendix to results from chapter 3.

Appendix 3.1. Average annual ring width (mm) and age (years) of *U. procera*, *P. x acerifolia* and *Q. robur* urban trees) estimated by core-measurements (Core) and resistance drilling (Resi).

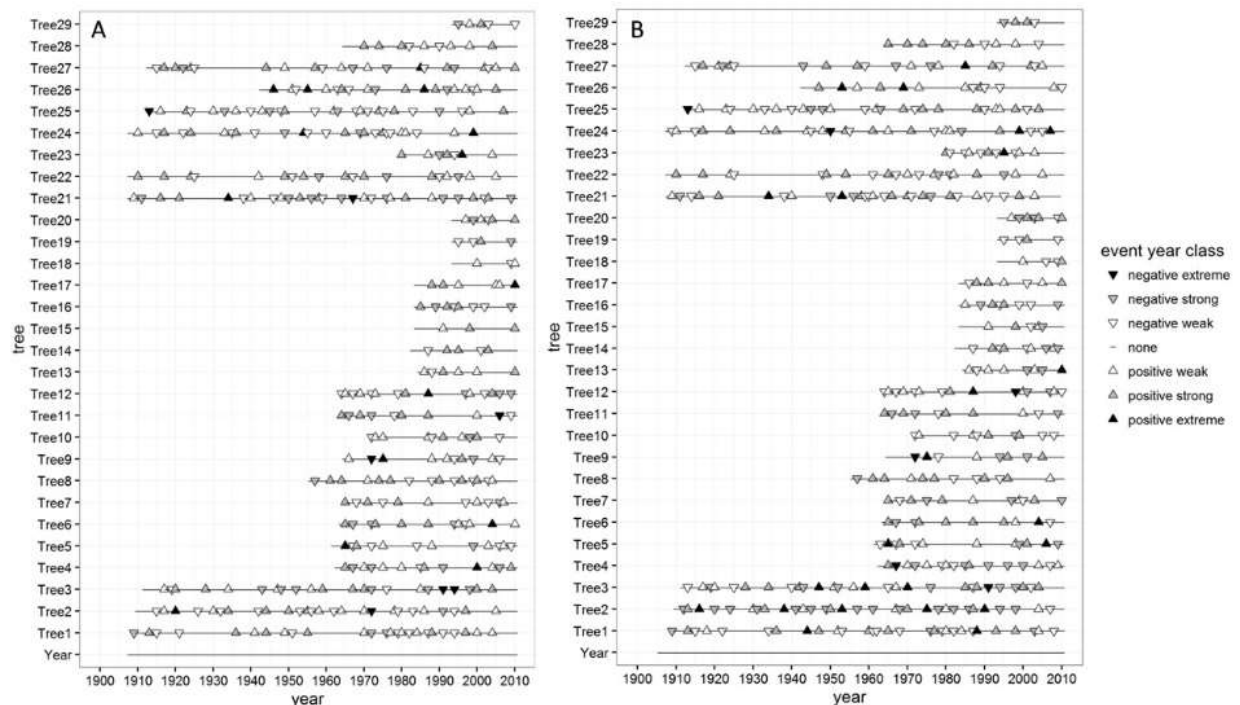
Tree	<i>U. procera</i>			<i>P. x x acerifolia</i>			<i>Q. robur</i>		
	Age	Core	Resi	Age	Core	Resi	Age	Core	Resi
1	227	1.62	1.79	205	2.34	2.49	126	3.31	3.35
2	235	1.68	1.85	210	1.80	2.14	167	3.22	3.23
3	225	1.32	1.42	212	2.51	2.56	102	3.66	3.70
4	195	3.47	3.43	99	3.68	3.73	106	3.58	3.60
5	211	3.39	3.29	97	4.56	4.68	240	1.87	1.95**
6	216	2.45	2.48	98	3.00	3.09	242	0.97	1.28
7	183	3.16	3.07	103	3.70	3.84	249	1.71	1.79
8	242	2.26	2.33	112	4.45	4.53	103	1.33	1.41
9	216	3.04	2.65*	93	5.00	5.03	244	1.60	1.71
10	227	3.17	3.10	95	4.72	4.71	106	1.98	2.01
11	253	1.50	1.52	99	4.76	2.51	262	1.80	1.90
12	267	2.74	0.83*	100	5.31	5.33	267	1.12	1.37**
13	233	2.25	1.00*	62	2.80	2.89	253	1.38	1.49
14	259	2.05	2.10	64	2.53	1.45*	251	1.69	1.82
15	251	1.09	1.14	62	2.33	2.50	146	2.12	2.16
16	251	1.83	1.89	62	4.27	4.28	273	1.76	1.83
17	254	2.44	2.43	59	5.49	5.46	222	1.66	1.69
18	222	2.98	2.95	40	4.12	4.15	225	1.33	1.44
19	231	2.48	2.13**	40	5.08	5.09	230	1.79	1.86
20	233	2.71	2.67	42	3.33	3.35	213	2.64	2.63
21	249	2.24	2.30	205	3.00	3.04	212	1.12	1.19
22	244	1.65	1.77	207	2.75	2.83	206	1.81	1.79
23	243	2.08	2.12	70	3.82	3.97	218	1.88	1.86
24	260	2.19	2.29	210	2.70	2.78	212	1.50	1.69
25	-	-	-	202	2.61	2.73	225	2.55	2.51
26	-	-	-	147	0.84	1.15	-	-	-
27	-	-	-	179	3.86	3.93	-	-	-
28	-	-	-	97	3.48	3.62	-	-	-
29	-	-	-	92	7.96	7.95	-	-	-

Note: Significant differences are shown with * $p < 0.05$ and **= $p < 0.01$.

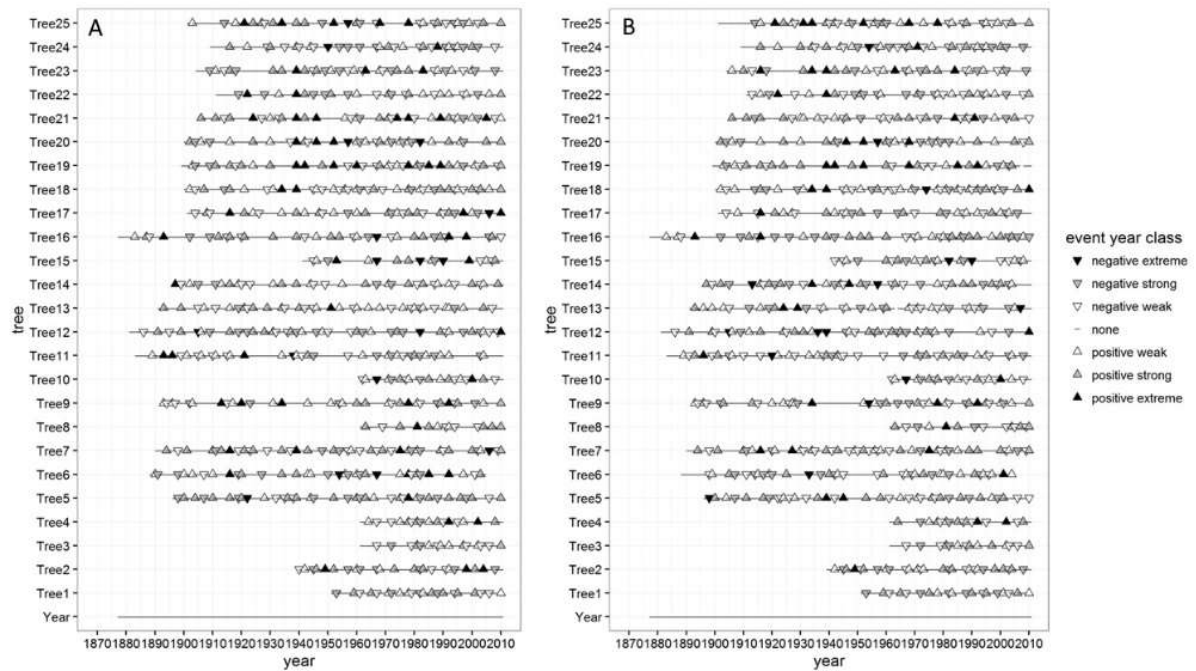
Appendix 3.2. Event year classes for *U. procera* trees (n=24) estimated by core sampling (A) and resistance drilling (B). Both from North drill axi.



Appendix 3.3. Event year classes for *P. x acerifolia* trees (n=29) estimated by core sampling (A) and resistance drilling (B). Both from North drill axi.



Appendix 3.4. Event year classes for *Q. robur* trees (n=25) estimated by core sampling (A) and resistance drilling (B). Both from North drill axi.



Appendix 3.5. Location and general features of resistance-drilled trees in parks and streets of the City of Melbourne, Australia.

Asset-ID	GIS_ID	Site	Species	Canopy-DIA (m)	DBH (cm)	Stem Decay (Y = 1)	# Cores Sampled
24077	1023075	Street	<i>Platanus x acerifolia</i>	6.2	16	0	2NS
24093	1023078	Street	<i>Platanus x acerifolia</i>	4.0	16	0	2NS
25312	1023089	Street	<i>Platanus x acerifolia</i>	6.6	18	0	2NS
24034	1023073	Street	<i>Platanus x acerifolia</i>	7.7	28	0	2NS
24036	1021816	Street	<i>Platanus x acerifolia</i>	10.0	33	0	2NS
24050	1023112	Street	<i>Platanus x acerifolia</i>	9.6	33	1	2NS
25314	1023118	Street	<i>Platanus x acerifolia</i>	4.5	15	0	2NS
25315	1023129	Street	<i>Platanus x acerifolia</i>	3.0	15	0	2NS
24035	1023134	Street	<i>Platanus x acerifolia</i>	3.5	13	0	2NS
25330	1023113	Street	<i>Platanus x acerifolia</i>	6.3	21	0	2NS
25312	1029524	Street	<i>Platanus x acerifolia</i>	14.0	40	1	2NW
25314	1029526	Street	<i>Platanus x acerifolia</i>	14.5	48	0	2NW
25315	1029527	Street	<i>Platanus x acerifolia</i>	14.0	54	0	2NW
24050	1028003	Street	<i>Platanus x acerifolia</i>	15.7	44	1	2NW
24036	1027989	Street	<i>Platanus x acerifolia</i>	16.7	54	0	2NW
24035	1027988	Street	<i>Platanus x acerifolia</i>	16.4	54	0	2NW
24093	1028109	Street	<i>Platanus x acerifolia</i>	18.5	55	0	2NW
30639	1035551	Park	<i>Quercus robur</i>	13.7	57	0	2 NW
30633	1035545	Park	<i>Quercus robur</i>	14.5	46	0	2 NW
30632	1035544	Park	<i>Quercus robur</i>	13.0	58	0	2 NW
30647	1035559	Park	<i>Quercus robur</i>	10.8	50	0	2 NW
30624	1035536	Park	<i>Quercus robur</i>	14.3	43	0	2 NW
30569	1035481	Park	<i>Quercus robur</i>	12.1	45	0	2 NW
30534	1035446	Park	<i>Quercus robur</i>	18.4	60	0	2 NW
30537	1035449	Park	<i>Quercus robur</i>	11.7	43	0	2 NE

28295	1032880	Park	<i>Quercus robur</i>	14.8	68	0	2 NW
28274	1032859	Park	<i>Quercus robur</i>	10.2	59	0	2 NW
28329	1032915	Park	<i>Quercus robur</i>	0.0	69	0	2 NW
28723	1033356	Park	<i>Quercus robur</i>	0.0	97	0	2 NW
29254	1034061	Park	<i>Quercus robur</i>	10.0	50	1	2 NW
29255	1034062	Park	<i>Quercus robur</i>	7.5	35	1	2 NW
29260	1034067	Park	<i>Quercus robur</i>	10.7	48	1	2 NW
29265	1034072	Park	<i>Quercus robur</i>	8.9	68	1	2 NW
29270	1034077	Park	<i>Quercus robur</i>	7.0	34	1	2 NW
29271	1034078	Park	<i>Quercus robur</i>	9.0	46	1	2 NW
29274	1034082	Park	<i>Quercus robur</i>	13.1	52	1	2 NW
29275	1034083	Park	<i>Ulmus procera</i>	0.0	71	1	2 NS
29279	1034087	Park	<i>Ulmus procera</i>	0.0	86	1	2 NS
29284	1034092	Park	<i>Quercus robur</i>	18.2	76	1	2 NW
29287	1034095	Park	<i>Quercus robur</i>	13.2	63	1	2 NW
29252	1034059	Park	<i>Ulmus procera</i>	0.0	83	1	2 NW
29250	1034057	Park	<i>Ulmus procera</i>	0.0	107	1	2 ES
29247	1034054	Park	<i>Ulmus procera</i>	0.0	92	1	2 NS
29240	1034047	Park	<i>Ulmus procera</i>	0.0	81	1	2 WE
29230	1034037	Park	<i>Ulmus procera</i>	0.0	95	1	2 NW
30810	1035730	Park	<i>Ulmus procera</i>	14.0	90	0	2NW
30337	1035249	Park	<i>Ulmus procera</i>	19.0	80	0	2NW
30334	1035246	Park	<i>Ulmus procera</i>	20.0	84	0	2NW
30353	1035265	Park	<i>Ulmus procera</i>	9.0	75	0	2NW
30354	1035266	Park	<i>Ulmus procera</i>	11.4	63	1	2NW
30355	1035267	Park	<i>Ulmus procera</i>	12.5	70	1	2NW
30524	1035436	Park	<i>Ulmus procera</i>	11.6	83	1	2NW
30452	1035364	Park	<i>Ulmus procera</i>	22.2	83	1	2NW
30811	1035731	Park	<i>Ulmus procera</i>	15.2	90	0	2NW

30769	1035688	Park	<i>Ulmus procera</i>	9.6	73	0	2NW
30768	1035687	Park	<i>Ulmus procera</i>	6.0	75	0	2NW
30767	1035686	Park	<i>Ulmus procera</i>	13.0	59	0	2NW
31958	1037001	Park	<i>P x acerifolia</i>	12.9	56	0	2NW
31960	1037003	Park	<i>P x acerifolia</i>	8.8	62	0	2NW
31961	1037004	Park	<i>P x acerifolia</i>	8.0	69	0	2NW
32034	1037096	Park	<i>Quercus robur</i>	9.5	85	1	2SE
32052	1037121	Park	<i>Quercus robur</i>	7.5	63	1	2NW
32039	1037101	Park	<i>Quercus robur</i>	13.7	71	0	2NW
31857	1036870	Park	<i>Quercus robur</i>	12.0	58	1	2NW
32054	1037125	Park	<i>Quercus robur</i>	8.0	75	0	2NW
32040	1037103	Park	<i>Quercus robur</i>	11.7	46	1	2NW
32035	1037097	Park	<i>Quercus robur</i>	10.2	64	1	2NW
32049	1037118	Park	<i>Quercus robur</i>	2.5	67	0	2NW
30534	1035446	Park	<i>Quercus robur</i>	18.4	60	0	2NW
30647	1035559	Park	<i>Quercus robur</i>	10.8	50	0	2NW
30537	1035449	Park	<i>Quercus robur</i>	11.7	43	0	2NE
30633	1035545	Park	<i>Quercus robur</i>	14.5	46	0	2NW
30569	1035481	Park	<i>Quercus robur</i>	12.1	45	0	2NW
30632	1035544	Park	<i>Quercus robur</i>	13.0	58	0	2NW
30480	1035392	Park	<i>Quercus robur</i>	9.0	0	1	2NW

Appendix to chapter 4.

Appendix to methods used in chapter 4.

Appendix 4.1. Detailed description of the decay assessment followed in this study.

The process for decay assessment was done following the next steps:

1. Drilling distance as shown in the X axis in the above image is the actual drilling depth across the tree's diameter. The drilling depth of the IML PowerDrill® is 40 cm.
2. The y-axis of the drilling profile describes the drilling resistance in % (amplitude height) and the x-axis describes the actual drilled depth in cm.
3. Each drilling profile was separated into six sections as follow: 1) sound wood, 2) intermediate decay, 3) advanced decay, 4) decayed wood and 5) absence of wood. All sections were color-coded and labelled. The length of each section within drilling profiles was recorded in cm (Figure 1).
4. A minimum distance for which variations of wood resistance (either positive or negative) showed in the drilling profile will be set up. In this study, only segments of decayed wood or segments of absence of wood greater than 1 cm were considered relevant for decay assessments.

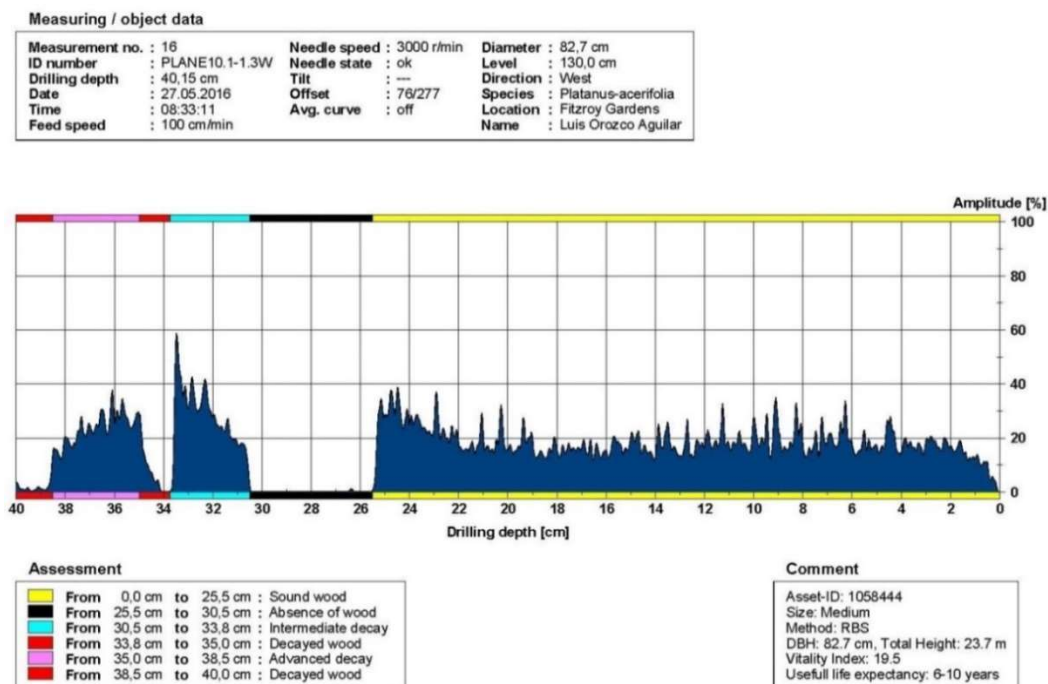


Figure 1. Drilling profiles from the IML PowerDrill® used to assess decayed wood in sampled urban trees.

5. Those sections within the drilling profiles showing absence of “annual rings” were also considered as being decayed wood.
6. In each drilling profile, the “average curve” function in the IML PowerDrill® assessing tools package was activated to capture the overall trend in wood resistance corresponding to the species under study regardless of the drilling point and tree size.
7. Once the average curve was devised, decayed wood assessments were done identifying and labelling segments within the drilling profiles showing “evident” decrease in wood resistance.
8. A segment with amplitude value 5% and 10% below the “average curve” was considered as intermediate and advanced decay, respectively.
9. The drilling amplitude for the tree below which decayed wood will registered was set up. Here we suggested that amplitude below 5% is recorded as decayed wood.
10. An amplitude value of 0% was considered as “absence of wood” within the drilling profile. In order to account for volume loss calculations, both categories (decayed wood + absence of wood) of decayed were labelled and added as DECAYED WOOD in each drilling point.
11. From the drilling profile showed in Figure 8 we can identified the following decay classes: from 0 to 25.5 cm is sound wood, denoted as yellow, from 25.5-30.5 cm is absence of wood, presented as black, from 30.5 to 33.75 cm is intermediate decay labelled as light green, from 33.75 to 35 cm is decayed wood reported as red, from 35 to 38.5 is advanced decay recorded as purple and from 38.5 to 40 cm is mapped again as decayed wood.
12. In this study, “pockets” of decayed wood identified was not considered linear but in fact circular or rounded. Thus, the area of decayed wood (expressed in cm²) in each drilling point was calculated using the formulae of either a circle or ellipse.
13. All drawings and area calculations were done in AutoCAD 2016. Figure 2 shows the resulting drawings combining four drilling points (N, S, E, W) taken from a medium size *P x acerifolia* sampled tree.

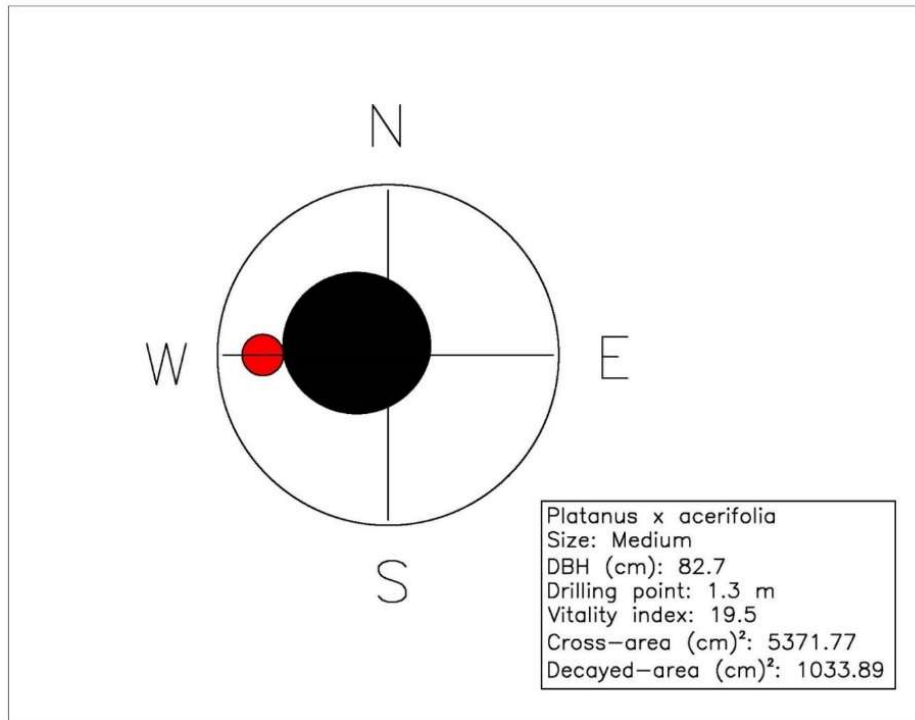
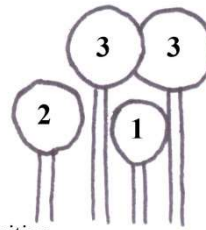


Figure 2. Visual representation of the cross-sectional area and decayed area calculated using AutoCAD2016. The drawing correspond to a medium size *P x acerifolia* tree, with diameter of 82.7 cm and a low vitality index of 19.5. The calculated cross-sectional area was 5371.7 and the resulted decayed area was 1033.8 (19.25%) of the cross-sectional area at the DBH (1.3 m) point. The black circle represents absence of wood and the red circle denotes decayed wood.

Crown position:

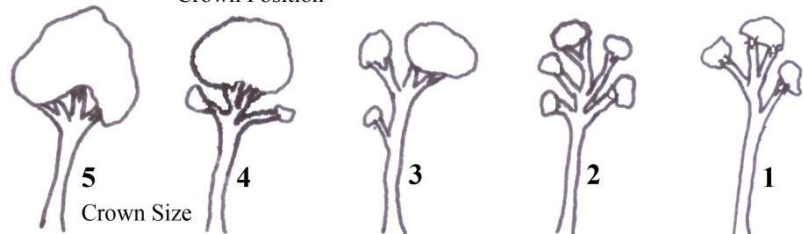
- 3 - Upper crown surface exposed, some side competition
- 2 - Part of upper crown exposed mostly side light
- 1 - Some side light only



Crown Position

Crown size:

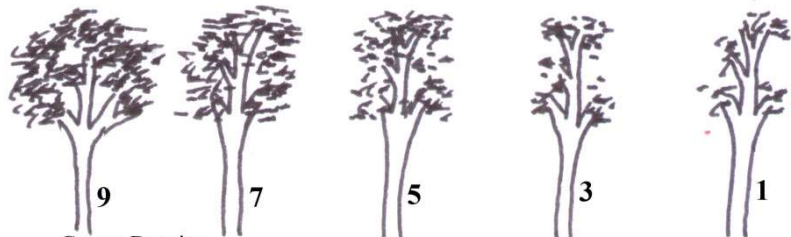
- 5 - Full
- 3 - Moderate
- 1 - Very sparse



Crown Size

Crown density:

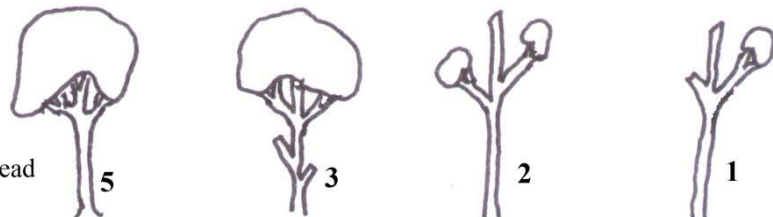
- 9 - Very dense
- 7 - Dense
- 5 - Average
- 3 - Sparse
- 1 - Very sparse



Crown Density

Dead branches:

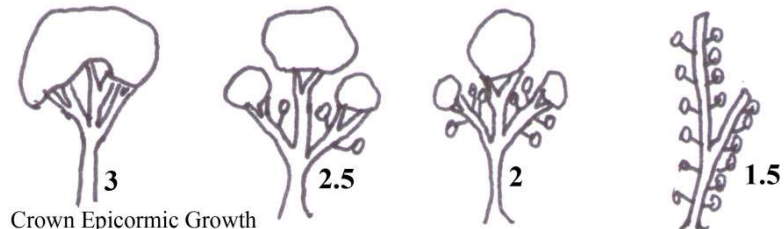
- 5 - Nil
- 4 - Branchlets dead
- 3 - Dead branches retained
- 2 - Some main growing branches dead
- 1 - A more severe case of 2



Dead Branches

Crown epicormic growth:

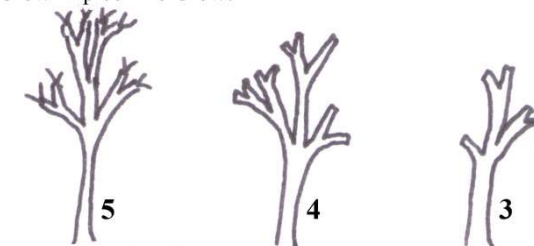
- 3 - Nil
- 2.5 - Slight
- 2 - Moderate
- 1.5 - Severe on stem



Crown Epicormic Growth

Dead tree classification:

- 5 - Crown intact sometimes with branchlets and dead leaves
- 4 - No branchlets, main branches still retained
- 3 - 0-25% top broken off, branches remain as stumps only



Dead Tree Classification

Appendix 4.2. Diagrammatic representation of the visual vitality index assessment followed in this study as proposed by Johnstone et al. (2012).

Appendix 4.3. Summary statistics of cross-sectional area and the extent of decayed wood along the stem of urban trees (*Ulmus procera*, *Platanus x acerifolia*, *Corymbia maculata*) growing in the city of Melbourne, Australia.

Species	Drilling Point	Mean cross-sectional area (cm ²)*	Mean cross-sectional extent of decayed wood*(cm ²)	<u>Mean proportion of decayed area (%)</u>	Maximum extent of decay (% from cross-sectional area)
<i>U. procera</i>	Base (n=15)	7325.5 (4197.4)	1424.4 (879.2)	19.6 (5.7)	28.6
	DBH (n=15)	5471.3 (3315.2)	982.9 (625.2)	17.6 (5.9)	29.2
	Trunk (n=15)	5582.0 (3448.9)	908.9 (599.3)	15.8 (6.6)	27.2
	Crown (n=15)	5610.2 (3217.2)	969.8 (426.2)	18.9 (4.5)	27.4
<i>P. x acerifolia</i>	Base (n=13)	6837.9 (4404.8)	829.0 (1432.9)	8.4 (13.6)	49.3
	DBH (n=13)	4573.0 (3268.8)	359.5 (545.2)	6.2 (9.6)	32.6
	Trunk (n=13)	4551.9 (3433.3)	283.7 (332.2)	5.2 (5.8)	18.2
	Crown (n=5)	4382.7 (2587.7)	473.6 (480.5)	9.5 (10.6)	26.0
<i>C. maculata</i>	Base (n=15)	4589.3 (3590.8)	418.8 (399.2)	8.6 (3.4)	14.2
	DBH (n=15)	5249.7 (8242.1)	255.6 (234.4)	8.1 (3.0)	15.6
	Trunk (n=15)	2975.0 (2477.7)	227.2 (255.0)	7.5 (3.6)	13.0
	Crown (n=11)	2567.3 (2515.6)	146.8 (193.4)	5.1 (3.4)	10.2

*Values in parenthesis represent the standard deviation of each calculation.

Appendix 4.4. List of trees, location, size class (S-small, M-medium, L-large), method used for volume calculation (Full tree measurement/RBS-Randomized branch sampling), visual vitality index (VVI), diameter, total volume yield and volume loss due to internal decay.

Asset	Species	Tree	Location	Size	Method	VVI	DBH (cm)	Total-Vol (m ³)	Vol-loss (m ³)
1058080	<i>Corymbia macualta</i>	1	Fitzroy	L	Full	25.0	107.0	12.6	0.3
1059982	<i>Corymbia macualta</i>	2	Fitzroy	M	Full	24.0	77.0	10.2	0.7
1033330	<i>Corymbia macualta</i>	3	KingsD	M	Full	25.0	84.2	13.6	0.2
1033323	<i>Corymbia macualta</i>	4	KingsD	M	RBS	23.5	72.3	3.5	0.1
1033298	<i>Corymbia macualta</i>	5	KingsD	M	RBS	24.0	72.5	1.5	0.2
1033299	<i>Corymbia macualta</i>	6	KingsD	M	RBS	25.0	66.6	2.9	0.2
1062128	<i>Corymbia macualta</i>	7	Wellington	M	Full	25.0	40.0	3.0	0.5
1034640	<i>Corymbia macualta</i>	8	Wellington	S	Full	24.0	45.0	1.1	0.0
1034630	<i>Corymbia macualta</i>	9	Wellington	S	Full	23.0	35.7	1.3	0.2
1034632	<i>Corymbia macualta</i>	10	Jolimont	M	RBS	25.0	45.2	2.9	0.2
1059982	<i>Corymbia macualta</i>	11	Fitzroy	M	Full	24.5	48.0	4.1	0.4
1439856	<i>Corymbia macualta</i>	12	Jolimont	L	RBS	25.0	95.5	11.4	0.7
1069184	<i>Corymbia macualta</i>	13	Jolimont	S	RBS	24.0	32.6	1.8	0.0
1058410	<i>Corymbia macualta</i>	14	Jolimont	L	RBS	25.0	98.6	11.6	0.4
1037185	<i>Corymbia macualta</i>	15	Carlton-N	M	Full	25.0	75.0	9.5	0.4
1058180	<i>Platanus x acerifolia</i>	1	Fitzroy	L	Full	24.5	105.2	7.6	0.4
1032403	<i>Platanus x acerifolia</i>	2	ShrineR	M	Full	24.5	62.2	4.8	0.3
1032385	<i>Platanus x acerifolia</i>	3	ShrineR	L	RBS	24.5	107.0	3.8	0.0
1032393	<i>Platanus x acerifolia</i>	4	ShrineR	M	Full	23.5	63.3	1.8	0.0
1032398	<i>Platanus x acerifolia</i>	5	ShrineR	L	RBS	24.5	115.0	4.9	0.4
1454686	<i>Platanus x acerifolia</i>	6	AlexAv	S	RBS	23.0	27.3	0.2	0.0
1027508	<i>Platanus x acerifolia</i>	7	AlexAv	S	RBS	24.0	20.5	0.1	0.0

Asset	Species	Tree	Location	Size	Method	VVI	DBH (cm)	Total-Vol (m³)	Vol-loss (m³)
1060693	<i>Platanus x acerifolia</i>	8	AlexAv	S	Full	24.5	32.5	0.4	0.0
1058428	<i>Platanus x acerifolia</i>	9	Fitzroy	M	RBS/Full	18.5	83.5	5.0	0.6
1058444	<i>Platanus x acerifolia</i>	10	Fitzroy	M	RBS	19.5	82.7	5.6	0.7
1036516	<i>Platanus x acerifolia</i>	11	Carlton-N	L	RBS	22.0	74.5	4.8	0.3
1036541	<i>Platanus x acerifolia</i>	12	Carlton-N	L	RBS	22.5	77.8	5.0	0.4
1035394	<i>Platanus x acerifolia</i>	13	Fawkner	M	Full	22.0	60.0	1.8	0.1
1035394	<i>Platanus x acerifolia</i>	14	Fawkner	M	Full	21.0	63.0	1.9	0.1
1040342	<i>Ulmus procera</i>	1	Fitzroy	M	Full	23.5	48.0	0.7	0.0
1040504	<i>Ulmus procera</i>	2	Fitzroy	S	Full	20.5	41.5	1.8	0.3
1040487	<i>Ulmus procera</i>	3	Fitzroy	L	Full	24.0	84.0	2.8	0.4
1040100	<i>Ulmus procera</i>	4	Treasury	L	Full	21.5	110.0	7.4	0.7
1032850	<i>Ulmus procera</i>	5	Kings-D	M	Full	20.0	94.6	3.6	0.5
1032849	<i>Ulmus procera</i>	6	Kings-D	M	RBS	21.0	55.3	3.6	0.3
1032807	<i>Ulmus procera</i>	7	Kings-D	M	RBS	19.0	63.4	2.6	0.3
1032861	<i>Ulmus procera</i>	8	Kings-D	M	RBS	17.0	60.2	1.9	0.3
1035570	<i>Ulmus procera</i>	9	Fawkner	M	RBS	17.5	80.5	2.9	0.7
1035571	<i>Ulmus procera</i>	10	Fawkner	L	RBS	18.0	83.5	2.8	0.4
1035574	<i>Ulmus procera</i>	11	Fawkner	L	RBS	17.5	100.5	5.7	0.7
1035574	<i>Ulmus procera</i>	12	Fawkner	L	RBS	19.0	111.5	5.1	0.7
1035170	<i>Ulmus procera</i>	13	Fawkner	L	RBS	22.0	115.0	5.3	0.7
1035169	<i>Ulmus procera</i>	14	Fawkner	L	RBS	18.5	105.0	5.5	0.6
1040432	<i>Ulmus procera</i>	15	Fitzroy	S	Full	22.0	29.8	0.9	0.0

Appendix 4.5. List of trees, location, size class (S-small, M-medium, L-large), method (Full tree measurement/RBS-Randomized branch sampling), visual vitality index (VVI), diameter, total volume yield, decayed wood and decayed volume loss due to internal decay.

Asset	Species	Tree	Location	Size	Method	VVI	Diam-cm	Vol-m ³	C.-Area (cm ²)	Point	Decayed-Area (cm ²)	Proportion
1040342	<i>Ulmus</i>	1	Fitzroy	M	Full	23.50	52.50	0.67	2164.75	Base	304.73	14.1
1040342	<i>Ulmus</i>	1	Fitzroy	M	Full	23.50	48.00	0.67	1809.56	DBH	128.82	7.1
1040342	<i>Ulmus</i>	1	Fitzroy	M	Full	23.50	47.00	0.67	1734.94	Trunk	55.56	3.2
1040504	<i>Ulmus</i>	2	Fitzroy	S	Full	20.50	49.50	1.84	1924.42	Base	161.34	8.4
1040504	<i>Ulmus</i>	2	Fitzroy	S	Full	20.50	41.50	1.84	1352.65	DBH	105.95	7.8
1040504	<i>Ulmus</i>	2	Fitzroy	S	Full	20.50	36.50	1.84	1046.35	Trunk	25.13	2.4
1040487	<i>Ulmus</i>	3	Fitzroy	L	Full	24.00	112.00	2.80	9852.03	Base	1594.84	16.2
1040487	<i>Ulmus</i>	3	Fitzroy	L	Full	24.00	84.00	2.80	5541.77	DBH	686.56	12.4
1040487	<i>Ulmus</i>	3	Fitzroy	L	Full	24.00	72.00	2.80	4071.50	Trunk	551.38	13.5
1040487	<i>Ulmus</i>	3	Fitzroy	L	Full	24.00	75.00	2.80	4417.86	Crown	653.10	14.8
1040100	<i>Ulmus</i>	4	Treasury	L	Full	21.5	120.00	7.43	11309.73	Base	2502.37	22.1
1040100	<i>Ulmus</i>	4	Treasury	L	Full	21.50	110.00	7.43	9503.32	DBH	1726.64	18.2
1040100	<i>Ulmus</i>	4	Treasury	L	Full	21.50	100.00	7.43	7893.98	Trunk	1594.73	20.2
1040100	<i>Ulmus</i>	4	Treasury	L	Full	21.50	92.00	7.43	6647.61	Crown	1150.14	17.3
1032850	<i>Ulmus</i>	5	Kings-D	M	Full	20.00	113.50	3.58	10117.70	Base	1837.12	18.2
1032850	<i>Ulmus</i>	5	Kings-D	M	Full	20.00	94.60	3.58	7028.65	DBH	1227.10	17.5
1032850	<i>Ulmus</i>	5	Kings-D	M	Full	20.00	92.60	3.58	6734.60	Trunk	1071.84	15.9
1032850	<i>Ulmus</i>	5	Kings-D	M	Full	20.00	100.00	3.58	7853.98	Crown	1495.65	19.0
1032849	<i>Ulmus</i>	6	Kings-D	M	RBS	21.00	67.20	3.59	3546.73	Base	912.90	25.7
1032849	<i>Ulmus</i>	6	Kings-D	M	RBS	21.00	55.30	3.59	2401.82	DBH	604.17	25.2
1032849	<i>Ulmus</i>	6	Kings-D	M	RBS	21.00	56.60	3.59	2516.07	Trunk	515.52	20.5
1032849	<i>Ulmus</i>	6	Kings-D	M	RBS	21.00	49.80	3.59	1947.82	Crown	432.76	22.2

Asset	Species	Tree	Location	Size	Method	VVI	Diam-cm	Vol-m ³	C.-Area (cm ²)	Point	Decayed-Area (cm ²)	Proportion
1032807	<i>Ulmus</i>	7	Kings-D	M	RBS	19.00	75.20	2.61	4441.45	Base	1075.62	24.2
1032807	<i>Ulmus</i>	7	Kings-D	M	RBS	19.00	63.40	2.61	3156.96	DBH	713.16	22.6
1032807	<i>Ulmus</i>	7	Kings-D	M	RBS	19.00	67.50	2.61	3578.47	Trunk	674.82	18.9
1032807	<i>Ulmus</i>	7	Kings-D	M	RBS	19.00	59.50	2.61	2780.51	Crown	500.38	18.0
1032861	<i>Ulmus</i>	8	Kings-D	M	RBS	17.00	74.50	1.94	4359.16	Base	1016.85	23.3
1032861	<i>Ulmus</i>	8	Kings-D	M	RBS	17.00	60.20	1.94	2846.31	DBH	635.58	22.3
1032861	<i>Ulmus</i>	8	Kings-D	M	RBS	17.00	54.40	1.94	2324.28	Trunk	490.87	21.1
1032861	<i>Ulmus</i>	8	Kings-D	M	RBS	17.00	55.00	1.94	2375.83	Crown	512.24	21.6
1035570	<i>Ulmus</i>	9	Fawkner	M	RBS	17.50	91.20	2.88	6532.50	Base	1868.42	28.6
1035570	<i>Ulmus</i>	9	Fawkner	M	RBS	17.50	80.50	2.88	5089.58	DBH	1484.88	29.2
1035570	<i>Ulmus</i>	9	Fawkner	M	RBS	17.50	81.70	2.88	5242.45	Trunk	1419.90	27.1
1035570	<i>Ulmus</i>	9	Fawkner	M	RBS	17.50	62.80	2.88	3097.48	Crown	850.52	27.5
1035571	<i>Ulmus</i>	10	Fawkner	L	RBS	18.00	100.00	2.84	7853.98	Base	1212.90	15.4
1035571	<i>Ulmus</i>	10	Fawkner	L	RBS	18.00	83.50	2.84	5475.98	DBH	892.63	16.3
1035571	<i>Ulmus</i>	10	Fawkner	L	RBS	18.00	92.70	2.84	6749.15	Trunk	1001.42	14.8
1035571	<i>Ulmus</i>	10	Fawkner	L	RBS	18.00	62.60	2.84	3077.79	Crown	605.08	19.7
1035573	<i>Ulmus</i>	11	Fawkner	L	RBS	17.50	114.50	5.74	10296.77	Base	1716.07	16.7
1035573	<i>Ulmus</i>	11	Fawkner	L	RBS	17.50	100.50	5.74	7932.72	DBH	1459.56	18.4
1035573	<i>Ulmus</i>	11	Fawkner	L	RBS	17.50	102.70	5.74	8283.82	Trunk	1213.37	14.6
1035574	<i>Ulmus</i>	11	Fawkner	L	RBS	17.50	117.30	5.74	10806.52	Crown	1635.85	15.1
1035574	<i>Ulmus</i>	12	Fawkner	L	RBS	19.00	137.50	5.13	14741.14	Base	3492.27	23.7
1035574	<i>Ulmus</i>	12	Fawkner	L	RBS	19.00	111.50	5.13	9764.97	DBH	1326.95	13.6
1035574	<i>Ulmus</i>	12	Fawkner	L	RBS	19.00	114.20	5.13	10242.88	Trunk	1652.64	16.1
1035574	<i>Ulmus</i>	12	Fawkner	L	RBS	19.00	79.30	5.13	4938.97	Crown	1215.98	24.6
1035170	<i>Ulmus</i>	13	Fawkner	L	RBS	22.00	120.00	5.25	11309.73	Base	1766.53	15.6
1035170	<i>Ulmus</i>	13	Fawkner	L	RBS	22.00	115.00	5.25	10386.89	DBH	2145.87	20.7
1035170	<i>Ulmus</i>	13	Fawkner	L	RBS	22.00	117.00	5.25	10751.32	Trunk	1689.56	15.7
1035170	<i>Ulmus</i>	13	Fawkner	L	RBS	22.00	127.00	5.25	8992.02	Crown	1359.80	15.1

Asset	Species	Tree	Location	Size	Method	VVI	Diam-cm	Vol-m ³	C.-Area (cm ²)	Point	Decayed-Area (cm ²)	Proportion
1035169	<i>Ulmus</i>	14	Fawkner	L	RBS	18.50	115.00	5.45	10386.89	Base	1621.62	15.6
1035169	<i>Ulmus</i>	14	Fawkner	L	RBS	18.50	107.00	5.45	8992.02	DBH	1479.96	16.5
1035169	<i>Ulmus</i>	14	Fawkner	L	RBS	18.50	117.00	5.45	10751.32	Trunk	1537.30	14.3
1035169	<i>Ulmus</i>	14	Fawkner	L	RBS	18.50	115.00	5.45	10386.89	Crown	1226.86	11.8
1040432	<i>Ulmus</i>	15	Fitzroy	S	Full	22.00	36.50	0.94	1046.35	Base	282.74	27.0
1040432	<i>Ulmus</i>	15	Fitzroy	S	Full	22.00	30.00	0.94	786.86	DBH	126.70	16.1
1040432	<i>Ulmus</i>	15	Fitzroy	S	Full	22.00	27.70	0.94	1809.56	Trunk	140.84	7.8
1058180	<i>Platanus</i>	1	Fitzroy	L	Full	25.50	135.50	7.61	14420.11	Base	1213.92	8.4
1058180	<i>Platanus</i>	1	Fitzroy	L	Full	25.50	105.20	7.61	8692.03	DBH	459.58	5.3
1058180	<i>Platanus</i>	1	Fitzroy	L	Full	25.50	101.30	7.61	8059.51	Trunk	468.40	5.8
1058180	<i>Platanus</i>	1	Fitzroy	L	Full	25.50	106.20	7.61	8858.07	Crown	934.42	10.5
1032385	<i>Platanus</i>	2	ShrineR	M	Full	26.00	75.30	4.77	4453.28	Base	57.07	1.3
1032385	<i>Platanus</i>	2	ShrineR	M	Full	26.00	62.30	4.77	3048.36	DBH	46.03	1.5
1032385	<i>Platanus</i>	2	ShrineR	M	Full	26.50	58.50	4.77	2687.83	Trunk	39.27	1.5
1032385	<i>Platanus</i>	2	ShrineR	M	Full	26.50	60.00	4.77	2827.43	Crown	0.00	0.0
1032393	<i>Platanus</i>	3	ShrineR	L	RBS	25.50	109.00	3.81	9331.32	Base	0.00	0.0
1032393	<i>Platanus</i>	3	ShrineR	L	RBS	26.50	107.00	3.81	8999.02	DBH	0.00	0.0
1032393	<i>Platanus</i>	3	ShrineR	L	RBS	25.50	110.00	3.81	9503.32	Trunk	0.00	0.0
1032398	<i>Platanus</i>	4	ShrineR	M	Full	25.50	80.50	7.61	5089.58	Base	0.00	0.0
1032398	<i>Platanus</i>	4	ShrineR	M	Full	25.50	62.50	7.61	3067.96	DBH	0.00	0.0
1032398	<i>Platanus</i>	4	ShrineR	M	Full	25.50	65.50	7.61	3369.55	Trunk	0.00	0.0
1454686	<i>Platanus</i>	5	ShrineR	L	RBS	24.50	125.00	4.93	12271.85	Base	834.59	6.8
1454686	<i>Platanus</i>	5	ShrineR	L	RBS	24.50	115.00	4.93	10386.89	DBH	815.97	7.9
1454686	<i>Platanus</i>	5	ShrineR	L	RBS	24.50	120.00	4.93	11309.73	Trunk	765.65	6.8
1027508	<i>Platanus</i>	6	AlexAv	S	RBS	24.00	34.50	0.20	934.82	Base	0.00	0.0
1027508	<i>Platanus</i>	6	AlexAv	S	RBS	24.00	27.30	0.20	585.35	DBH	0.00	0.0
1027508	<i>Platanus</i>	6	AlexAv	S	RBS	24.00	24.20	0.20	459.96	Trunk	7.07	1.5
1060693	<i>Platanus</i>	7	AlexAv	S	RBS	24.00	26.50	0.14	551.55	Base	0.00	0.0

Asset	Species	Tree	Location	Size	Method	VVI	Diam-cm	Vol-m ³	C.-Area (cm ²)	Point	Decayed-Area (cm ²)	Proportion
1060693	<i>Platanus</i>	7	AlexAv	S	RBS	24.00	20.50	0.14	330.06	DBH	0.00	0.0
1060693	<i>Platanus</i>	7	AlexAv	S	RBS	24.00	17.50	0.14	240.53	Trunk	0.00	0.0
1060693	<i>Platanus</i>	8	AlexAv	S	Full	24.50	49.50	0.38	1924.42	Base	0.00	0.0
1060693	<i>Platanus</i>	8	AlexAv	S	Full	24.50	32.50	0.38	829.58	DBH	0.00	0.0
1060693	<i>Platanus</i>	8	AlexAv	S	Full	24.50	28.80	0.38	651.44	Trunk	0.00	0.0
1058428	<i>Platanus</i>	9	Fitzroy	M	RBS/Full	18.50	115.00	5.01	10386.89	Base	5123.67	49.3
1058428	<i>Platanus</i>	9	Fitzroy	M	RBS/Full	18.50	83.50	5.01	5475.99	DBH	1785.35	32.6
1058428	<i>Platanus</i>	9	Fitzroy	M	RBS/Full	18.50	85.50	5.01	5741.46	Trunk	785.16	13.7
1058444	<i>Platanus</i>	10	Fitzroy	M	RBS	19.50	115.50	5.57	10477.41	Base	2058.89	19.7
1058444	<i>Platanus</i>	10	Fitzroy	M	RBS	19.50	82.70	5.57	5371.77	DBH	1033.89	19.2
1058444	<i>Platanus</i>	10	Fitzroy	M	RBS	19.50	77.60	5.57	4729.48	Trunk	858.87	18.2
1058444	<i>Platanus</i>	10	Fitzroy	M	RBS	19.50	69.50	5.57	3793.67	Crown	985.54	26.0
1036516	<i>Platanus</i>	11	Carlton-N	L	RBS	22.00	94.50	4.82	7013.80	Base	232.22	3.3
1036516	<i>Platanus</i>	11	Carlton-N	L	RBS	22.00	74.50	4.82	4359.16	DBH	196.08	4.5
1036516	<i>Platanus</i>	11	Carlton-N	L	RBS	22.00	71.50	4.82	4015.15	Trunk	326.79	8.1
1036516	<i>Platanus</i>	11	Carlton-N	L	RBS	22.00	55.50	4.82	2419.22	Crown	0.00	0.0
1036541	<i>Platanus</i>	12	Carlton-N	L	RBS	22.50	98.50	4.95	7620.13	Base	809.96	10.6
1036541	<i>Platanus</i>	12	Carlton-N	L	RBS	22.50	83.50	4.95	5475.98	DBH	78.54	1.4
1036541	<i>Platanus</i>	12	Carlton-N	L	RBS	22.50	80.50	4.95	5089.58	Trunk	157.08	3.1
1036541	<i>Platanus</i>	12	Carlton-N	L	RBS	22.50	71.50	4.95	4015.15	Crown	448.32	11.2
1035394	<i>Platanus</i>	13	Fawkner	M	Full	23.00	75.00	1.70	4417.86	Base	447.05	10.1
1035394	<i>Platanus</i>	13	Fawkner	M	Full	23.00	60.00	1.70	2827.43	DBH	258.24	9.1
1035394	<i>Platanus</i>	13	Fawkner	M	Full	23.00	65.00	1.70	3318.31	Trunk	280.34	8.4
1058080	<i>Corymbia</i>	1	Fitzroy	L	Full	25.50	125.00	12.63	12271.85	Base	1164.93	9.5
1058080	<i>Corymbia</i>	1	Fitzroy	L	Full	26.00	107.00	12.63	8992.02	DBH	746.42	8.3
1058080	<i>Corymbia</i>	1	Fitzroy	L	Full	25.50	103.00	12.63	8332.29	Trunk	692.84	8.3
1058080	<i>Corymbia</i>	1	Fitzroy	L	Full	26.00	96.00	12.63	7238.23	Crown	428.12	5.9
1058081	<i>Corymbia</i>	1	Fitzroy	L	Full	25.50	125.00	12.63	2596.72	Base	284.12	10.9

Asset	Species	Tree	Location	Size	Method	VVI	Diam-cm	Vol-m ³	C.-Area (cm ²)	Point	Decayed-Area (cm ²)	Proportion
1058410	<i>Corymbia</i>	2	Fitzroy	M	Full	26.00	48.00	4.11	1809.56	DBH	201.22	11.1
1058410	<i>Corymbia</i>	2	Fitzroy	M	Full	26.00	46.50	4.11	1698.23	Trunk	197.18	11.6
1058410	<i>Corymbia</i>	2	Fitzroy	M	Full	26.00	40.80	4.11	1320.25	Crown	135.09	10.2
1033330	<i>Corymbia</i>	3	Kings-D	M	Full	25.00	112.30	13.64	9852.03	Base	942.98	9.6
1033330	<i>Corymbia</i>	3	Kings-D	M	Full	25.00	84.20	13.64	5541.77	DBH	353.24	6.4
1033330	<i>Corymbia</i>	3	Kings-D	M	Full	25.00	83.20	13.64	5410.61	Trunk	463.67	8.6
1033323	<i>Corymbia</i>	4	Kings-D	M	RBS	24.00	75.40	3.53	4465.11	Base	406.41	9.1
1033323	<i>Corymbia</i>	4	Kings-D	M	RBS	24.00	60.30	3.53	2855.78	DBH	205.92	7.2
1033323	<i>Corymbia</i>	4	Kings-D	M	RBS	24.00	56.00	3.53	2463.02	Trunk	233.15	9.5
1033323	<i>Corymbia</i>	4	Kings-D	M	RBS	24.00	53.00	3.53	2206.18	Crown	70.07	3.2
1033298	<i>Corymbia</i>	5	Kings-D	M	RBS	24.00	100.00	1.54	7853.93	Base	1109.85	14.1
1033298	<i>Corymbia</i>	5	Kings-D	M	RBS	24.00	72.50	1.54	4128.25	DBH	314.16	7.6
1033298	<i>Corymbia</i>	5	Kings-D	M	RBS	24.00	66.50	1.54	3473.23	Trunk	145.17	4.2
1033298	<i>Corymbia</i>	5	Kings-D	M	RBS	24.00	50.50	1.54	1963.50	Crown	110.74	5.6
1033299	<i>Corymbia</i>	6	Kings-D	M	RBS	25.00	80.00	2.85	5026.55	Base	159.42	3.2
1033299	<i>Corymbia</i>	6	Kings-D	M	RBS	25.00	66.60	2.85	33483.68	DBH	123.95	3.6
1033299	<i>Corymbia</i>	6	Kings-D	M	RBS	25.00	70.30	2.85	3881.52	Trunk	0.00	0.0
1062128	<i>Corymbia</i>	7	Wellington	S	Full	25.00	40.00	2.99	1156.64	Base	151.15	13.1
1062128	<i>Corymbia</i>	7	Wellington	S	Full	25.00	35.00	2.99	962.12	DBH	98.02	10.2
1062128	<i>Corymbia</i>	7	Wellington	S	Full	25.00	30.00	2.99	706.86	Trunk	88.41	12.5
1062128	<i>Corymbia</i>	7	Wellington	S	Full	25.00	22.00	2.99	380.13	Crown	34.07	9.0
1034640	<i>Corymbia</i>	8	Wellington	S	Full	24.00	45.00	1.12	1590.43	Base	196.55	12.4
1034640	<i>Corymbia</i>	8	Wellington	S	Full	24.00	40.00	1.12	1256.64	DBH	105.24	8.4
1034640	<i>Corymbia</i>	8	Wellington	S	Full	24.00	35.00	1.12	962.11	Trunk	57.33	6.0
1034640	<i>Corymbia</i>	8	Wellington	S	Full	24.00	30.00	1.12	706.86	Crown	32.20	4.6
1034630	<i>Corymbia</i>	9	Wellington	S	Full	23.00	40.00	1.25	1256.64	Base	88.75	7.1
1034630	<i>Corymbia</i>	9	Wellington	S	Full	23.00	35.70	1.25	1000.98	DBH	47.91	4.8
1034630	<i>Corymbia</i>	9	Wellington	S	Full	23.00	31.00	1.25	754.77	Trunk	32.20	4.3

Asset	Species	Tree	Location	Size	Method	VVI	Diam-cm	Vol-m ³	C.-Area (cm ²)	Point	Decayed-Area (cm ²)	Proportion
1034630	<i>Corymbia</i>	9	Wellington	S	Full	23.00	29.00	1.25	660.52	Crown	28.27	4.3
1059982	<i>Corymbia</i>	11	Fitzroy	M	Full	24.00	50.00	1.16	1963.50	Base	106.03	5.4
1059982	<i>Corymbia</i>	11	Fitzroy	M	Full	24.00	45.00	1.16	1590.43	DBH	106.81	6.7
1059982	<i>Corymbia</i>	11	Fitzroy	M	Full	24.00	38.00	1.16	1134.11	Trunk	104.46	9.2
1059982	<i>Corymbia</i>	11	Fitzroy	M	Full	24.00	35.00	1.16	962.11	Crown	0.00	0.0
1037185	<i>Corymbia</i>	15	Carlton-G	M	Full	26.00	55.00	9.50	2375.83	Base	79.33	3.3
1037185	<i>Corymbia</i>	15	Carlton-G	M	Full	25.50	44.00	9.50	1520.53	DBH	237.64	15.6
1037185	<i>Corymbia</i>	15	Carlton-G	M	Full	26.00	39.00	9.50	1256.64	Trunk	127.19	10.1
1439856	<i>Corymbia</i>	12	Jolimont-R	L	RBS	25.00	95.50	11.35	7313.82	Base	597.84	8.2
1439856	<i>Corymbia</i>	12	Jolimont-R	L	RBS	25.00	90.00	11.35	6361.73	DBH	343.02	5.4
1439856	<i>Corymbia</i>	12	Jolimont-R	L	RBS	25.00	85.00	11.35	5674.50	Trunk	284.89	5.0
1439856	<i>Corymbia</i>	12	Jolimont-R	L	RBS	25.00	80.00	11.35	5026.55	Crown	178.54	3.6
No-ID	<i>Corymbia</i>	10	Jolimont-R	M	RBS	25.00	50.00	2.88	2223.02	Base	95.03	4.3
No-ID	<i>Corymbia</i>	10	Jolimont-R	M	RBS	25.00	45.50	2.88	1116.05	DBH	83.25	7.5
No-ID	<i>Corymbia</i>	10	Jolimont-R	M	RBS	25.00	45.50	2.88	1113.04	Trunk	42.42	3.8
No-ID	<i>Corymbia</i>	14	Jolimont-R	L	RBS	25.50	100.00	11.63	7779.89	Base	805.85	10.4
No-ID	<i>Corymbia</i>	14	Jolimont-R	L	RBS	26.00	98.60	11.63	7238.23	DBH	807.52	11.2
No-ID	<i>Corymbia</i>	14	Jolimont-R	L	RBS	26.00	93.00	11.63	6664.88	Trunk	864.34	13.0
No-ID	<i>Corymbia</i>	14	Jolimont-R	L	RBS	25.50	90.00	11.63	6664.88	Crown	598.27	9.0
1069184	<i>Corymbia</i>	13	Jolimont-R	S	RBS	24.00	40.00	1.75	1113.75	Base	93.46	8.4
1069184	<i>Corymbia</i>	13	Jolimont-R	S	RBS	24.00	32.60	1.75	888.00	DBH	60.48	6.8
1069184	<i>Corymbia</i>	13	Jolimont-R	S	RBS	24.00	35.00	1.75	1100.11	Trunk	73.04	6.6
1069184	<i>Corymbia</i>	13	Jolimont-R	S	RBS	24.00	35.00	1.75	1111.12	Crown	0.00	0.0

Appendix to chapter 5.

Appendix for results from chapter 5.

Appendix 5.1. Mean and standard error ($\pm$) of canopy structural parts of sampled trees in parks, Melbourne, Australia. Data derived from six fully measured trees per species (18 trees in total).

Species/features	Scaffolds	1 st order branch	2 nd order branch	3 rd order branch
<i>U. procera</i>				
Number	12 $\pm$ 2	27 $\pm$ 17	19 $\pm$ 16	99 $\pm$ 23
Diameter (cm)	20.6 $\pm$ 14.5	11.5 $\pm$ 6.1	9.1 $\pm$ 3.7	5.3 $\pm$ 1.1
Length (m)	5.6 $\pm$ 3.2	3.1 $\pm$ 1.7	2.3 $\pm$ 1.2	2.4 $\pm$ 0.8
Volume (m ³)	0.15 $\pm$ 0.25	0.06 $\pm$ 0.03	0.01 $\pm$ 0.01	0.001 $\pm$ 0.001
Slenderness	0.62 $\pm$ 0.25	0.60 $\pm$ 0.21	0.56 $\pm$ 0.37	0.53 $\pm$ 0.27
BR*	3.8 $\pm$ 0.6			
<i>P. x acerifolia</i>				
Number	14 $\pm$ 4	39 $\pm$ 19	21 $\pm$ 11	134 $\pm$ 79
Diameter (cm)	28.8 $\pm$ 16.5	9.8 $\pm$ 4.5	8.2 $\pm$ 2.9	5.6 $\pm$ 1.4
Length (m)	8.9 $\pm$ 4.6	3.7 $\pm$ 1.9	2.5 $\pm$ 1.2	2.2 $\pm$ 0.5
Volume (m ³)	0.42 $\pm$ 0.34	0.07 $\pm$ 0.04	0.01 $\pm$ 0.01	0.001 $\pm$ 0.001
Slenderness	0.64 $\pm$ 0.15	0.65 $\pm$ 0.30	0.79 $\pm$ 0.31	0.81 $\pm$ 0.21
BR	3.1 $\pm$ 0.5			
<i>C. maculata</i>				
Number	15 $\pm$ 4	21 $\pm$ 16	37 $\pm$ 12	149 $\pm$ 89
Diameter (cm)	22.3 $\pm$ 14.2	11.9 $\pm$ 6.6	9.1 $\pm$ 3.7	5.4 $\pm$ 1.7
Length (m)	5.5 $\pm$ 3.5	3.2 $\pm$ 1.8	2.3 $\pm$ 1.0	1.2 $\pm$ 0.7
Volume (m ³)	0.18 $\pm$ 0.29	0.05 $\pm$ 0.09	0.01 $\pm$ 0.01	0.001 $\pm$ 0.001
Slenderness	0.53 $\pm$ 0.23	0.59 $\pm$ 0.24	0.60 $\pm$ 0.37	0.75 $\pm$ 0.31
BR	2.3 $\pm$ 1.3			

* BR: branching ratio of tree crown.

Appendix 5.2. Descriptive statistics of scaffolds' dimensions per species and tree size class.

Species	Size (# per tree)	Variable	Average	Standard deviation	Minimum	Maximum
<i>Corymbia maculata</i>	L (n=36)	D (cm)*	31.3	16.3	8.5	73.2
		L (m)**	7.0	3.8	1.2	16.7
		S***	0.48	0.21	0.1	0.8
	M (n=22)	D (cm)	17.6	7.6	10.0	35.5
		L (m)	5.2	2.6	1.4	10.3
		S	0.6	0.26	0.3	1.3
	S (28)	D (cm)	13.9	6.2	6.5	40.3
		L (m)	3.73	2.7	0.8	12.3
		S	0.53	0.26	0.10	1.3
<i>Platanus x acerifolia</i>	L (n=38)	D (cm)	38.6	16.3	12.2	69.7
		L (m)	11.6	4.8	3.2	19.1
		S	0.62	0.1	0.5	0.8
	M (n=26)	D (cm)	26.2	9.6	8.8	49.0
		L (m)	8.6	2.8	3.0	12.5
		S	0.67	0.15	0.4	0.9
	S (n=18)	D (cm)	12.9	5.1	7.5	27.3
		L (m)	4.3	1.3	1.5	6.1
		S	0.65	0.21	0.3	1.0
<i>Ulmus procera</i>	L (n=24)	D (cm)	34.8	16.6	10.5	70.0
		L (m)	8.5	3.7	2.2	16.6
		S	0.5	0.14	0.3	0.8
	M (n=26)	D (cm)	17.0	7.7	7.5	40.5
		L (m)	4.3	1.9	1.6	7.5
		S	0.55	0.28	0.3	1.7
	S (n=28)	D (cm)	11.4	3.9	6.0	19.7
		L (m)	4.3	1.5	1.3	8.1
		S	0.79	0.21	0.3	1.1

Notes: L: large, M: medium and S: small. *D: diameter (cm), **L: length (m) and ***S: Slenderness.

Appendix 5.3. Descriptive statistics of 1st order branch dimensions per species and tree size class.

Species	Size (# per tree)	Variable	Average	Standard deviation	Minimum	Maximum
<i>Corymbia maculata</i>	L (n=83)	D (cm)*	13.8	7.0	4.1	35.0
		L (m)**	3.7	2.1	1.2	11.4
		S***	0.57	0.28	0.1	2.0
	M (n=21)	D (cm)	8.0	2.0	4.1	12.6
		L (m)	2.8	0.5	2.0	3.5
		S	0.73	0.19	0.40	1.2
	S (n=24)	D (cm)	8.5	4.2	3.8	20.5
		L (m)	2.24	1.5	1.3	8.6
		S	0.56	0.22	0.30	1.20
<i>Platanus x acerifolia</i>	L (n=80)	D (cm)	12.3	5.4	5.5	32.1
		L (m)	4.3	2.3	0.5	10.6
		S	0.69	0.31	0.1	2.1
	M (n=98)	D (cm)	9.6	3.2	5.0	19.2
		L (m)	4.0	1.8	1.0	10.8
		S	0.86	0.30	0.30	2.1
	S (n=37)	D (cm)	5.72	1.1	3.5	7.5
		L (m)	2.11	0.53	1.5	4.5
		S	0.76	0.28	0.50	1.6
<i>Ulmus procera</i>	L (n=96)	D (cm)	12.8	7.0	5.0	44.0
		L (m)	3.3	2.1	1.0	10.8
		S	0.52	0.22	0.20	1.6
	M (n=40)	D (cm)	9.5	3.6	5.0	18.0
		L (m)	2.6	1.15	1.0	5.0
		S	0.55	0.19	0.30	1.1
	S (n=27)	D (cm)	6.9	1.2	5.0	9.2
		L (m)	2.4	0.7	1.5	4.0
		S	0.70	0.17	0.4	1.0

Notes: L: large, M: medium and S: small. *D: diameter (cm), **L: length (m) and ***S: Slenderness.

Appendix 5.4. Descriptive statistics of 2nd (A) and 3rd (B) order branch dimensions per species and tree size class.

A) 2rd order branches dimensions

Species	Size (# per tree)	Variable	Average	Standard deviation	Minimum	Maximum
<i>Corymbia maculata</i>	L (n=52)	D (cm)*	10.36	4.8	4.5	27.1
		L (m)**	2.7	1.6	1.0	7.0
		S***	0.58	0.32	0.10	1.6
	M (n=67)	D (cm)	5.4	1.3	3.0	9.0
		L (m)	2.0	0.9	1.0	5.0
		S	0.76	0.32	0.30	1.8
	S (n=63)	D (cm)	5.8	2.2	3.2	18.5
		L (m)	1.8	0.8	1.0	6.0
		S	0.62	0.22	0.20	1.20
<i>Platanus x acerifolia</i>	L (n=96)	D (cm)	8.7	3.5	4.5	18.5
		L (m)	2.5	1.2	0.70	8.0
		S	0.62	0.32	0.20	1.9
	M (n=24)	D (cm)	7.3	2.0	5.0	13.2
		L (m)	2.6	1.3	1.5	6.5
		S	0.75	0.27	0.50	1.7
	S (n=15)	D (cm)	4.8	0.5	4.5	5.5
		L (m)	1.0	0.01	1.0	1.7
		S	0.37	0.08	0.20	0.4
<i>Ulmus procera</i>	L (n=77)	D (cm)	10.6	3.4	5.7	21.5
		L (m)	2.3	1.0	1.0	5.4
		S	0.46	0.22	0.10	1.3
	M (n=22)	D (cm)	7.2	1.9	4.00	11.0
		L (m)	2.2	1.03	0.70	4.8
		S	0.65	0.35	0.20	1.3
	S (n=17)	D (cm)	4.8	0.6	4.0	5.50
		L (m)	2.7	0.8	1.5	4.0
		S	1.18	0.38	0.60	1.8

Notes: L: large, M: medium and S: small. *D: diameter (cm), **L: length (m) and ***S: Slenderness.

B). 3rd order branches dimensions

Species	Size (# per tree)	Variable	Average	Standard deviation	Minimum	Maximum
<i>C. macualta</i>	L (n=419)	D (cm)*	5.5	1.8	1.5	15.8
		L (m)**	2.0	1.2	1.0	15.0
		S***	0.77	0.51	0.01	1.5
	M (n=36)	D (cm)	5.1	2.4	2.8	15.0
		L (m)	1.8	0.74	1.0	4.2
		S	0.76	0.28	0.4	1.8
	S (n=139)	D (cm)	4.8	0.9	2.8	9.0
		L (m)	2.0	2.6	1.0	27.0
		S	0.84	1.05	0.29	10.3
<i>P. x acerifolia</i>	L (n=478)	D (cm)	6.3	1.2	4.4	10.0
		L (m)	2.2	0.5	1.0	3.5
		S	0.72	0.16	0.33	1.2
	M (n=330)	D (cm)	4.8	1.1	3.2	10.0
		L (m)	2.3	1.5	1.0	2.9
		S	0.97	0.58	0.30	10.5
	S (n=89)	D (cm)	4.8	0.7	3.0	5.5
		L (m)	1.6	0.4	1.0	2.5
		S	0.79	0.17	0.53	1.4
<i>U. procera.</i>	L (n=492)	D (cm)	5.6	1.0	4.0	9.5
		L (m)	2.5	0.9	1.0	6.8
		S	0.89	0.27	0.31	2.0
	M (n=207)	D (cm)	5.0	1.0	3.0	8.9
		L (m)	2.7	0.8	1.0	5.2
		S	1.02	0.25	0.33	1.8
	S (n=108)	D (cm)	4.3	0.6	2.5	5.5
		L (m)	1.9	0.5	1.0	3.0
		S	0.91	0.27	0.44	1.6

Notes: L: large, M: medium and S: small. *D: diameter (cm), **L: length (m) and ***S: Slenderness.