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3D GEO-INFORMATION METHODS AND APPLICATIONS IN MEASURING AND REPRESENTING TREE ROOT SYSTEMS IN URBAN ENVIRONMENTS: A REVIEW

Xiaxia Gao

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3D geo-information methods and applications in measuring and representing tree root systems in urban environments: a review

Xiaxia Gao

Registration number 89 09 19 250 130

Supervisor:

Dr. Ir. Ron van Lammeren

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Foreword

In the courses of Master of Geo-information Science in Wageningen University, we learned some knowledge and applications of LiDAR and trees, and I am curious to know more about the applications of 3D geo-information technologies. 3D geo-information technologies are developing fast and have great potential in wide application field. This was one of main factors which attracted me to do this study. On the other hand, urban environment is important in our life and especially I have some different experiences of living in urban and rural environments. The urban setting topic is also interesting for me. Trees are beneficial to the urban ecosystem and people are more and more aware of it. There is also a trend in China that people are willing and like to have more trees in urban environment. However urban tree root systems are still unknown in a large extent. Thus combining research needs and my interests I chose this topic, which is exploring the potential role of 3D geo-information methods in measuring and representing tree root systems in urban environments.

This research reviewed literature of applying 3D geo-information methods in studying above ground urban tree structure and investigated the potential role of above ground 3D geo-information methods and techniques in measuring and representing spatial distribution of tree root systems in the urban environments. Even though this is just a first small step, I think this study provides some new possibilities and helpful recommendations for future researches.

Finally, I would like to give my gratefulness to my supervisor Ron van Lammeren, counsellor Miranda van der Slikke, study advisor Willy ten Haff, and Professor Arnold Bregt who gave me lot of encouragement and guidance. I would like to thank Ineke and Esther who gave me confidence. I would like to thank Joost van der Gun and Harm Bartholomeus who answered my questions for tree roots. Thanks Alvaro for answering my questions and offered me some useful literature. Thanks my classmates Gvantsa, Viki, Benjamin, and Yan. Special thanks to Keyang who helped me a lot and always encourages me. Last but not least, thanks my parents for supporting me all the time.

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Abstract

3D geo-information techniques have shown its great advantages and become popular. There are already many 3D city models created from 3D geo-information technique. There are also increasing research interest for applying 3D geo-information for urban trees because trees in the urban environment, play a very important role. All the valuable effects trees offered are based on healthy root system. However studies for urban tree root systems are limited. The study applying 3D geo-information in urban tree root system measuring and modelling is quite new and waits for people to uncover. Researchers of Wageningen University plan to study the subsurface component of a tree (tree root system) based on the above surface lessons. Thus it is necessary to conduct a review focusing on investigating the potential of above ground 3D geo-information methods in measuring and representing the structure and patterns of tree root systems in urban environments. In this study, firstly small scale literature review was done for knowing the successful or useful methods and lessons from applying 3D geo-information techniques in urban tree measuring or modeling. The review also contained some articles for other environment like forest. Then secondly, the aim, which are the research priorities and unknown parameters of urban tree root systems were investigated from literature review of urban tree root system study. Some articles showing tree root system measuring methods and properties were also reviewed. Thirdly, the current progress (trials) of applying above ground 3D geo-information technique in measuring tree root system were reviewed and new possibilities applying 3D geo-information techniques in estimating urban tree root system parameters were summed. Finally, the future research directions of applying efficient above ground 3D laser scan technique and related processing methods in measuring and modelling urban tree root system parameters were pointed out. If fully excavation of the tree root system is possible, or occasionally a storm uproots trees, laser scan could be applied in creating robust and valuable 3D measurements of the exposed urban tree root systems and providing data for reconstructing high detail level tree root system model. Creating different detail-level urban tree root system models considering species, ages, environment conditions, and estimations of root system parameters from accurate above ground tree parameters, rules of thumb and some allometry equations of specific tree species could be another one future research path.

Keywords: tree root system parameters, laser scanning, urban, measuring, 3D geo-information

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Chapter 1 Introduction

1.1 3D geo-information and tree representation

Geographic information techniques like Geographical Information System (GIS) and Remote Sensing are powerful for capturing, modeling, representing, and analysing geographic data. They have been widely used by multi-discipline professionals, such as civil engineers, urban and rural planners, surveyors, ecologists, etc. They use GISs and remote sensing for analysing, interpreting and representing the real world and understanding spatial phenomena with their different background and knowledge (Abdul-Rahman & Pilouk, 2007). Specifically, representing our real three-dimensional (3D) world need 3D techniques and 3D visualizations which are assumed easier to be understood by people than two-dimensional data and visualisations. Thus during the past few years, 3D geo-information techniques have shown its great advantages and is becoming a trend (Zlatanova & Penninga, 2008; Abdul-Rahman & Pilouk, 2007; Chen, 2013).

In the last twenty years, more and more 3D city models which combined geo-information techniques came out. They used GIS environment for consolidating spatial data, satellite images and aerial images for 3D (re)construction of building objects, and close-up images (e.g. laser scans) for providing more detailed information of objects.

Compared to building objects, trees are more difficult to be represented in 3D. Because they have complex structures, their physical forms are diverse (Muhar, 2001). Many researchers have studied simulating or representing trees. From a visual perception point of view, two main representing scales have been set for trees: the first is landscape scale, representing trees as texture from distance; the second is the object scale, stimulating each tree model individually (Muhar, 2001). In urban settings tree representation of object scale is more appropriate (Chen, 2013). This study also would focus on object scale.

A single 3D tree representation (only the above ground part) can be created by different means (e.g. measuring, modeling, visualising) based on various kinds of data (for example, 2D images and 3D LiDAR data). This can be explained by Table 1.1.

Table 1.1. Means of creating single 3D tree representation (Creating based on Figure 5 of Nijhuis, Van Lammeren, and Van der Hoeven, 2011)

	Measuring	Modeling	Visualising
Single 3D tree representation	LiDAR (Omasa et al., 2008); ...	AMAP system (Jaeger & De Reffye, 1992); L-system (Lindenmayer & Prusinkiewicz, 1988);	Virtual Reality Modelling Language (Lim and Honjo, 2003);

		TREE system (Bosanac, 1990) …	Texture-mapping (Muhar, 2001); …

Related computer simulation algorithms like AMAP system, L-system, TREE system are often based on botanical models, expert knowledge and massive inventory data (Lim and Honjo, 2003). Compared to them, the direct and active 3D geo-information method LiDAR technique, is relatively simple. Having these advantages, during the recent years, LiDAR has been applied in the field of 3D tree modeling.

1.2 Urban tree root systems

Trees, in the urban environment, play a very important role. They contribute to purifying air, balancing temperature and humidity level, and filtering noise (Müderrisoğlu et al., 2006). Trees in the living environment also has stress reducing influences (Ulrich et al., 1991). Then the base of all these valuable effects is the root system. The capacity and health status of tree roots directly influence these functions performing. However in urban areas, the underground environment is restrictive to the growth of tree root systems. Thus it has been quite meaningful to understand how tree root systems develop and respond in this urban environment.

In addition, some tree roots are surficial or brittle which means they have higher risks to fall aside when storms come. In cities, it is easy to cause accidents, like hurt people or damage property. We can see the reports about such accidents from the media (Figure 1.1.).

Figure 1.1. Photos showing accidents caused by roots in an urban context (CNN, 2012; BBC, 2013).

Besides, large tree roots can be dangerous to the underground infrastructure. Randrup et al. (2001) did a research reviewing numerous intrusions by roots into unsealed pipes. Such conflict between tree roots and urban infrastructure can be a multimillion dollar problem (Mcpherson & Peper, 1996).

This makes it important to study and understand tree root structures in urban settings.

Researchers of Centre of Geo-information Wageningen UR did lot of studies about measuring, modeling and visualising the above-ground tree structure. Together with other organisations they established a website (http://www.boomregister.nl/) providing reliable information of trees (tree height, crown diameter, etc.) in whole Netherlands. Based on these experiences and knowledge, the researchers of Wageningen University intends to study the subsurface component of a tree (tree root system) based on the above surface lessons (R.J.A. van, Lammeren, personal communication, July 10, 2014). So it is necessary to conclude and review the past studies to prepare for future research.

We can conclude from previous mentioned points that there are established 3D models for the above ground part of trees, and there are quite some powerful 3D geo-information techniques have been utilized in urban planning and city visualisation, but for urban tree roots measuring and representing, the topic is still quite new and waits for people to uncover. So it's valid to critically look at the past researches and study the newest progress about 3D geo-information techniques and applications to find effectible and efficient ways to measure, model and visualize urban tree root structure.

1.3 Problem definition

The study of urban tree root systems and GIS seems limited so far. In Web of Science, the search word (urban tree root system AND GIS) led a 1 article result which is not about the tree root and GIS. The review for urban tree root system study is also few. Earlier review about urban tree root (Gilman, 1990a) is published more than 20 years. Day et al. (2010) did a review of past literature relevant to urban tree root systems and have pointed out that terminology used to describe tree roots is very diverse and not standardized. She worked on the contemporary concepts of urban tree roots from an arboriculture’s view and summarised several important properties of urban tree roots. Urban tree root systems face more complex situation, and due to species and site conditions, the considerable variation can be expected.

Thus we could say there are limited researches about GIS and urban tree root system, and existed reviews worked on important properties of urban tree root system. There is a need for a good review that summarises and synthesises what researches of urban tree root system is addressed and what parameters are pointed out to be studied. These parameters can be used later as study focus for applying different geo-information techniques, for examples as used in above-surface studies, to measure and model urban tree root systems.

In terms of measuring and modeling urban tree root systems, through an ordinary literature search in Web of Science, few reviews can be found. Tobin et al. (2007) published a review summarising and evaluating root systems modeling. This review has placed more weight on biochemical and ecological models of woody root systems not restricted to urban settings. For the topology and geometry measurements part, it concluded four ways doing the measurements namely manually operation, computer program based on manually working, semi-automatically digitising combined with

AMAPmod software, and non-invasive techniques like by X-radiography. It did not mention the site, precision, calibration, and validation aspects of measurements. Danjon and Reubens (2008) have done a detailed overview of techniques for 3D root system architecture measurement and analysis. They worked out general process steps studying 3D root system architecture, i.e. getting to the roots, sampling, measuring, coding and analysing. But this review did not show clear comparisons of methods and techniques and it has indicated that improving and standardizing methods is one of the future needs.

The papers of measuring and modeling urban tree roots are sparse.

Ground-penetrating radar (GPR) was the often used geophysical method in the studies (Čermák et al., 2000; Nadezhdina and Čermák, 2003; Ow and Sim, 2012). Čermák et al. (2000) studied the root systems of two mature field maple trees in an urban environment using GPR, light microscope and sap flow techniques but they did not present any GPR survey images and the GPR survey procedure were not clear explained. In the study of Nadezhdina and Čermák (2003), they applied the GPR method to provide 3D images of coarse roots from the soil surface to several meters deep in undisturbed materials (e.g. concrete and asphalt), but the GPR survey executive process and 3D result images are hard to find. Ow and Sim (2012) did another detailed research using the 400 MHz antenna on clay laden soils to detect urban tree roots. They have showed clear process of GPR survey and 3D result images but only one excavated root digital image which was used for validation has been provided and explained in several words.

In the earlier stage, 3D-digitizer was successfully used to get the geometry and topology of the roots to acquire exposed root systems' structure (Danjon et al., 1999a). They helped measuring single roots. However, they have not represented the surface structure in a realistic way due to cylindrical or cone-shaped root representations simplified approximations (Wagner et al., 2010). Then Wagner et al. (2010) used a laser scan arm to re-product realistic tree root architecture and incorporated ring-width measurements manually on sampled cross sections using computer program. This research aimed at root segment and had a special research procedure which need more effort on coding step.

Leucci (2010) conducted another study tested the reliability of the GPR, electrical-resistivity tomography (ERT) and seismic methods on eucalyptus trees in an urban environment. He found the three geophysical methods are capable of detecting, independently of each other, the distribution of the tree roots in the subsoil. Radar technique was able to resolve the root-zone (in 2D/3D), but it was not able to resolve (in the 3D slices) the single root. In his study, the field survey procedure was not clearly compared, and statistical processing information was rarely mentioned.

We can summarise that there are quite few reviews paying close attention to 3D techniques and methods in measuring and modeling urban tree root systems, especially lacking review from geo-information science's point of view. In addition, the published papers are sparse in different research subject (e.g. diverse tree species, root types, root zone, root segments, root growing site environment), methods, survey procedure, data processing tool, outcome type, consuming time, etc. Moreover, the quite new field calls for improving and standardizing methods. Besides, the 3D geo-information technology including measuring, modeling and visualising methods has been developing fast in recent years. Researchers of Centre of Geo-information Wageningen UR have conduct lot of studies about measuring and modelling the above-ground tree structure and intend to study the subsurface component of a tree (tree root system) based on the above surface lessons. Thus it is necessary to conduct a review focusing on investigating the potential of above ground 3D geo-information methods in measuring and representing the structure and patterns of tree root systems in urban environments and studying recent progress for shedding light on improving methodology to map tree root systems in urban environments.

1.4 Research objective and research questions

Hence the main research objective of this study is to investigate the potential role of above ground 3D geo-information methods and techniques in measuring spatial distribution of tree root systems in the urban environments.

This objective has then derived the following 4 questions:

1. What 3D geo-information (including technology) is available to measure the above ground urban tree structure?
2. What research on tree root systems, especially in urban environments, is addressed and what tree root system parameters are found to be known?
3. Could the above ground approaches be applied to measure and model the parameters of the urban tree root system?
4. What possibilities and research directions could be thought of to measure and model urban tree root system parameters by above ground 3D geo-information methods and techniques?

Here the focus of this literature review is measuring. The study scope and focus of this literature review are explained in Figure 1.2.

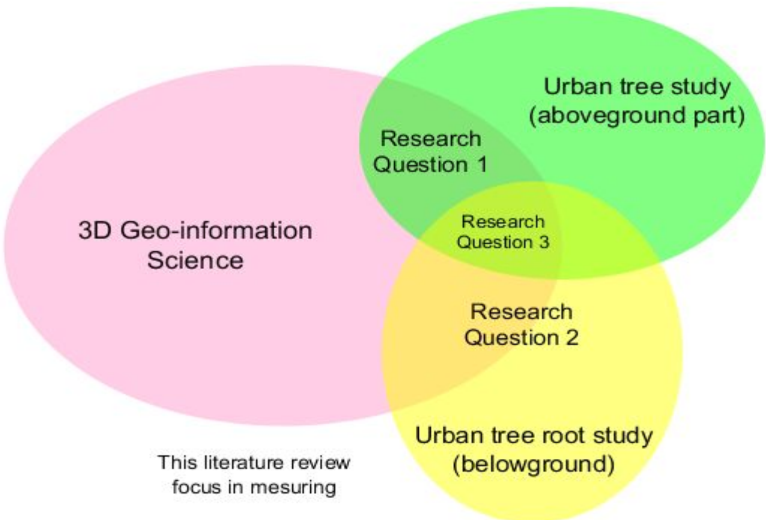


Figure 1.2. The study scope and focus of this literature review

1.5 The structure of this minor thesis

The minor thesis is composed by 6 chapters.

Chapter one states the background, problems definition and research objective as what have been presented above.

Chapter two explains the whole methodology and study procedure including the general review process, review process of research question 1, 2 and 3, and the integration of research question 4.

Chapter three shows the results of 3D geo-information which was used in literature to measure the above ground urban tree structure.

Chapter four illustrates the outcome found in literature about known properties and unknown tree root system parameters of urban tree root system study.

Chapter five gives answer about the above ground approaches can be applied to measure and model the parameters of the tree root system.

Chapter six provides the recommendation about possibilities and research directions to measure and model tree root system parameters by above ground 3D geo-information approaches, then gives discussion about the whole study, and finally gives conclusions.

Chapter 2 Methodology

Firstly 2.1 introduces the whole framework of methodology and next, 2.2 explains the general review process I applied in this minor thesis. Following 2.3 illustrates the specific review process of research question 1 3D geo-information for above ground urban tree structure. Then 2.4 explains the specific review process of research question 2 urban tree root system research and parameters. 2.5 nextly shows the specific review process of research question 3 about the above-ground approaches whether could be applied to urban tree root system. 2.6 lastly shows how to answering research question 4 about possibilities and future directions.

2.1 Framework of methodology

A schematic representation of the whole study procedure is depicted in Figure 2.1.

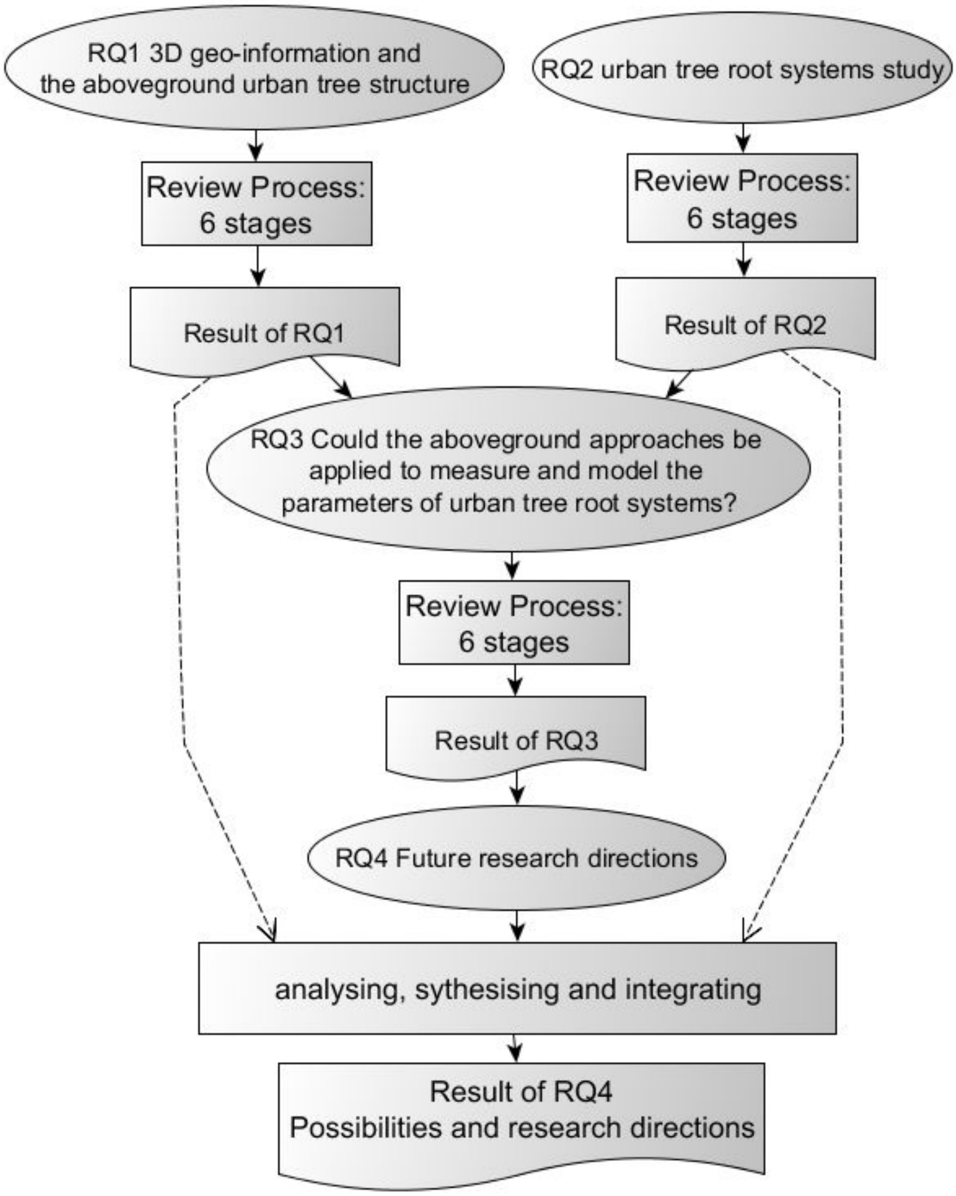


Figure 2.1. The whole procedure of this study

Firstly, research question 1 and 2 will give a lead to research question 3. The outcome of research question 3 then give directions to research question 4, by which the main research objective finally can be addressed.

To be specific, research question (RQ) 1, 2, and 3, will have the general review process separately. The review process would contain 6 main stages (scoping, searching, selecting, analysing, synthesising and reporting) (Rickinson & May, 2009). As the next big step, analysing and synthesising will be done based on the results of RQ 1, 2, and 3, and the outcome of RQ 4 will be produced.

The general six main stages of review process are simply explained in Figure 2.2.

Six main stages:

— *scoping* – clarifying the focus and scope of the review
— *searching* – identifying potentially relevant literature sources
— *selecting* – deciding which items to include or focus on in more depth
— *analysing* – analysing and appraising the included literature
— *synthesising* – drawing together data/findings from the analysis of included studies
— *reporting* – structuring and creating review outputs.

Figure 2.2. The six main stages of review process (Rickinson & May, 2009)

2.2 Specific review process for research question 1

As for RQ 1, the research steps are:
(a). Scoping
Based on this research question, through personal thinking and discussion with experts, the study scope would be made precise and clear: "urban tree study" and "3D geo-information (techniques)".

(b). and (c). Searching and selecting
According to the scope set in the previous step, I would find or define the basic scope of "urban tree" which need to be applied in the whole searching process, e.g. "Urban tree" refers to trees growing among buildings or other structures for human use regardless of overall land use (Day et al., 2010). Then several searching strategies have been set for following databases, journals or search engine:

bc1. Global Search of Wageningen UR Library
Key search words and several key words combinations would be set combining urban tree study and 3D geo-information, like *(urban tree) AND (3D geo-information)*, or *(urban tree) AND (3D Remote sensing or 3D GIS)*. Then the titles and keywords of first 10 related articles and first 10 newest published articles will be checked. Among the results of each search-word-group, the authors who published most articles will be recorded and searched again. Then the summary or abstract of his/her publications (3 to 5 newest) would be read.
bc2. Frequently used databases--Scopus, Web of Science, Google Scholar

Key words groups would be searched and in each database the first 10 related articles' titles and keywords will be carefully read. After the general search, if applicable, publications search through specific subject or research fields like "urban forestry", "urban ecology", "remote sensing", "GIS" would be done.

bc3. Databases have more publications related to geo-information science and urban tree-- Geographic Information Systems (USGS Publications Warehouse), CiteSeer.IST: scientific literature digital library (from Penn State's School of Information Sciences and Technology), Forestry library, urban forestry (from University of Minnesota), Dryade, using trees in urban landscapes (from Wageningen UR Library)

Key words groups would be set and tried. The first 10 related publications' titles, and keywords would be checked. Then through personal judgment, the highly related publications will be picked up and abstracts or summaries will be carefully read.

bc4. Important journals of urban tree and geo-information science--*Arboricultural Journal: The International Journal of Urban Forestry, Arboriculture & Urban Forestry, Remote Sensing of Environment, International Journal of Geographical Information Science, International Journal of Applied Earth Observation and Geoinformation*

Key words focusing on urban tree and 3D geo-information would be tried. The titles, and keywords of first 10 related publications and another 10 newest articles would be checked. Then selected highly fitted publications' abstracts or summaries will be carefully read.

bc5. Google

Several groups of search-word having little bit difference (e.g. urban tree and 3D geo-information, 3D urban tree structure, or urban tree and 3D remote sensing) would be worked out. These groups of search-word would be used for searching target documents (papers, articles, presentation documents, conference proceedings, project introduction, etc.) showing newest progress in study of applying 3D geo-information to urban tree structure. The first 20 items of the results will be checked.

bc6. Master theses and PhD dissertations from Wageningen UR Centre of Geo-information

Search-word will be same as stated previously.

From the various documents of above 6 ways, through carefully checking titles, keywords, abstracts and quickly full text scanning, combined with critically thinking, 5 to 8 articles or documents would be chosen as the target documents showing showing performance of 3D geo-information methods in measuring urban tree structure (the aboveground part) and be intensively studied.

The whole searching and selecting process is depicted in Figure 2.3.

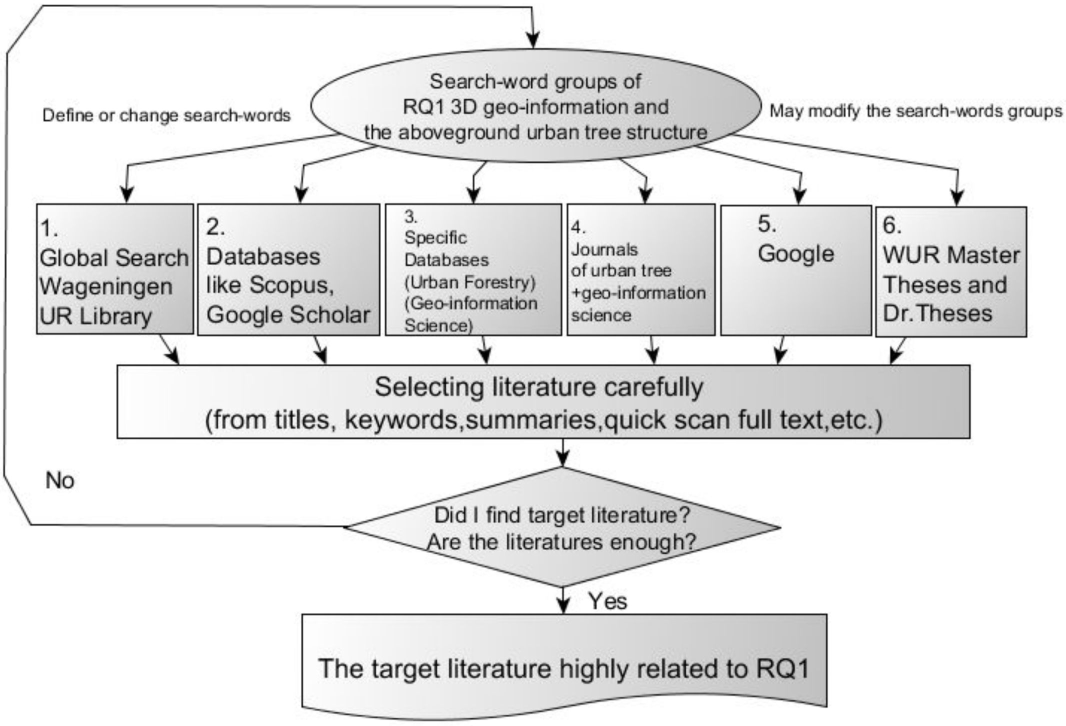


Figure 2.3. The searching and selecting stages of RQ1.

(d). and (e). Analysing and synthesising

For analysing and synthesising, I would conduct the intensively study from following aspects:

- Which 3D geo-information techniques are successfully applied, and why?
- How the researchers applied 3D geo-information techniques?
- What are the useful points, successful part, strengths, limitations?
- What are the future research priorities?

(f). Reporting

For this last step of research question 1, I would use tables and diagrams, as well as try to make my own conceptual maps connecting the literature.

2.3 Specific review process for research question 2

As for research question 2, the basic steps are the same with research question 1.

(a).Scoping

This time the scope will be "urban tree root system".

(b). and (c). Searching and selecting

The searching strategies are very similar with strategies of research question 1. The search-word groups would be set only about urban tree root, like "urban tree root", or "tree root system AND urban". The bc3 and bc4 step will also differ and there is no bc6 step:

bc3. Databases have more publications related to urban tree root study- Forestry library, urban forestry (from University of Minnesota); Dryade, using trees in urban landscapes (from Wageningen UR Library) bc4. Important journals of urban tree root study--*Arboricultural Journal: The International Journal of Urban Forestry, Arboriculture & Urban Forestry, Plant and Soil*

From the various documents of above ways, after carefully examining, 3 to 6 articles (reviews preferred) would be set as target files showing current progress of urban tree root system study.

(d). and (e). Analysing and synthesising

I would conduct the intensively study like the analysis in research question 1. The aspects need more attention would be:

- What are the hot spots of urban tree root system study?
- What are the important parameters of urban tree root architecture?
- What parameters have been studied and to what extent?
- What parameters are pointed out to be studied?
- What are the future study priorities?

(f). Reporting

This step would use the same way as in research question 1.

2.4 Review process for research question 3 and literature from RQ1 and 2

Firstly, the scoping and searching in review steps are similar with research question 1.

(a). Scoping

The scope would be narrowed down based on the results of research question 1 and 2.

(b). and (c). Searching and selecting

The basic searching strategies are the same with strategies of research question 1. The search-words groups would be defined about the 3D geo-information approaches in result of RQ1 and urban tree root systems. The bc3 and bc4 step will have some differences:

bc3. Databases more related to geo-information science and urban tree root study -- Forestry library, urban forestry (from University of Minnesota); Dryade, using trees in urban landscapes (from Wageningen UR Library), Geographic Information Systems (USGS Publications Warehouse), CiteSeer.IST: scientific literature digital library (from Penn State's School of Information Sciences and Technology)

bc4. Important journals of urban tree root study and geo-information science--*Arboricultural Journal: The International Journal of Urban Forestry, Arboriculture & Urban Forestry, Plant and Soil, International Journal of Remote Sensing, Remote Sensing of Environment, International Journal of Geographical Information Science, International Journal of Applied Earth Observation and Geoinformation*

Then from the search results in literature databases, through examining, 3 to 6 articles would be set as target literature showing the current progress of above ground 3D geo-information methods in measuring urban tree root structure.

(d) literature from results of research question 1 and 2

Besides, there are some literature from results of research question 1 and 2 in the scope of this research question 3. These literature would also be examined and then selected as aim literature or not.

(e). and (f). Analysing and synthesising

The intensively study is like the analysis in research question 1. But the following aspects need more attention:

- Have the above ground approaches (3D geo-information techniques) been applied?
- How did the researchers apply (research subject, survey procedure, data processing, calibration or validation, outcome type, consuming time, etc.)?
- How about the research results?
- What are the useful points, strengths, limitations, and weaknesses of these studies?
- What are the differences and similarities of these studies?
- What are limits of these 3D geo-information techniques in urban tree root system study;
- What are the future research priorities?

(g). Reporting

This step would use the same way as in research question 1.

2.5 Synthesising results and answering research question 4

In terms of this question, we can sum that result of RQ1 would provide successful or useful methods and lessons from applying 3D geo-information techniques in urban tree measuring or modeling; result of RQ2 will set the aims-research priorities and hot spots of urban tree root systems; result of RQ3 would show the trials, and new possibilities applying 3D geo-information techniques in study of urban tree root. Through analysing, synthesising and integrating these results, research question 4 the possible research directions would be finally pointed out.

Chapter 3 3D geo-information for above-ground urban tree structure

In this chapter, simple result of literature search strategy is present in 3.1 section. Then 3.2 reviews important articles of applying multi-kind laser scanning for detecting and measuring single urban tree parameters like tree height, tree location and canopy dimension. The coming 3.3 focus on mobile laser scanning for detecting and modeling single urban tree and crown shape. Next 3.4 tells something about airborne laser scanning and portable LiDAR for modeling urban trees and extracting tree parameters. 3.5 shows the strong power of terrestrial LiDAR for modeling detailed tree structure in other sites. Following 3.6 gives a short summary (overview of tree parameters and related 3D geo-information methods in articles) about important points from whole chapter.

3.1 Results of literature search strategy

3.1.1 Significant key words, development in time of articles about urban tree and 3D geo-information

In Web of Science, I input the (urban tree and 3D geo-information) and there was no result for this search item. I used the input search-word of (urban tree AND (3D Remote sensing or 3D GIS)), and the result number was 20. After checking, no highly related articles found in the 20 files. They were about LiDAR and building models, terrain models, urban area environment and so on. Then (urban tree and 3D remote sensing) this search word gave 17 result records and no highly related articles found in 17 records.

Then (urban trees AND three dimensional remote sensing) gave 13 result records which 1 article (Omasa et al., 2008) was in the records and chose as target literature. Other articles were about urban vegetation and LiDAR, laser scan and urban building models, and so on. I tried (tree AND 3d remote sensing AND urban) and in the resulting 17 files no highly related articles found. Among 17 files, 11 articles were about LiDAR (laser scan). I input (urban tree AND 3D GIS) and in the 5 result files, 3 articles were about LiDAR and urban forest and vegetation. Another one was about thermal tool and 3D CAD. No highly related articles found.

Based on the fact that previous resulting records contained lots of articles about laser scan (LiDAR), I decided to change the search word into (laser scanning AND urban tree). This search word gave 51 resulting records, and in first 20 items, three highly related articles (Holopainen et al., 2013; Saarinen et al., 2014; Rutzinger et al., 2011) were found and selected. Some highly related cited articles in the chosen literature were also found and studied. Other records of the 51 resulting files were mostly about laser scanning and urban forest, then laser scan and urban vegetation, and also some articles were about laser scan and urban road, building, and floods.

In terms of development in time of published articles of (laser scanning AND urban tree) this input search word, there is a summary Figure 3.1. created by Web of Science citation report tool.

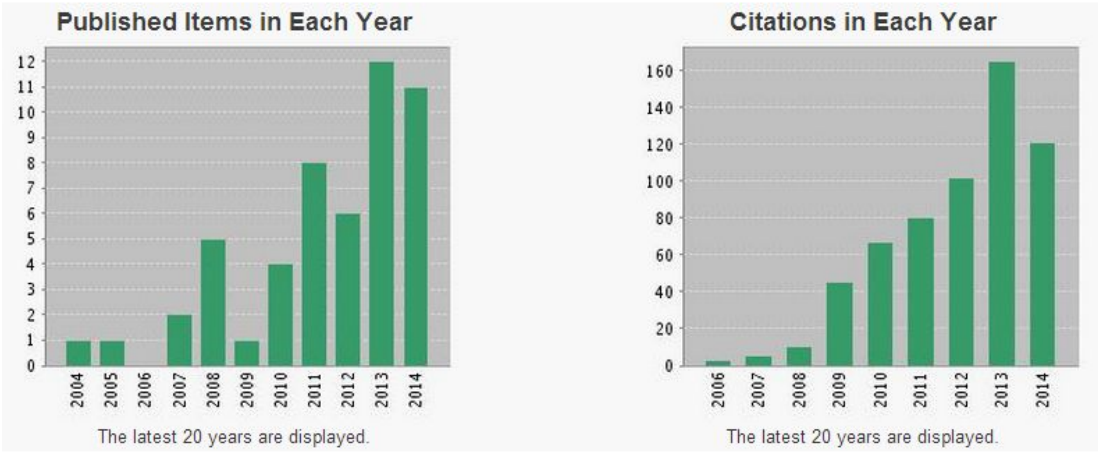


Figure 3.1. Published item numbers (left) and citation times (right) of <laser scanning AND urban tree> this literature search result in Web of Science

From Figure 3.1., we could see there are more and more published papers about "laser scanning AND urban tree", and the total number of published papers from 2004 is small (51) which shows this topic is developing. However, this topic has a obvious trend that researchers are more and more interested in it from right graph-the citation times figure.

All above points showed laser scanning was the often used 3D geo-information technique in urban tree study. This topic is new and the resulting literature number is small.

3.1.2 Significant key-words, development in time of articles about laser scanning and tree in other sites

Then I decided to search in a broader scope, about laser scanning and tree structure study. I used the search word (laser scanning AND tree), and 755 result records were showed. In the first 10 items, one highly related article (Raumonen et al., 2013) was found. In the first 40 items, another article (Dassot et al., 2012) was found. In the first 40 items of 755 records, there were articles about laser scan and forest monitoring, forest fires, standing level estimation, and so on. These studies mostly were in forest settings.

Then Figure 3.2 could explain something about development of article numbers of "laser scanning and tree" this topic in time.

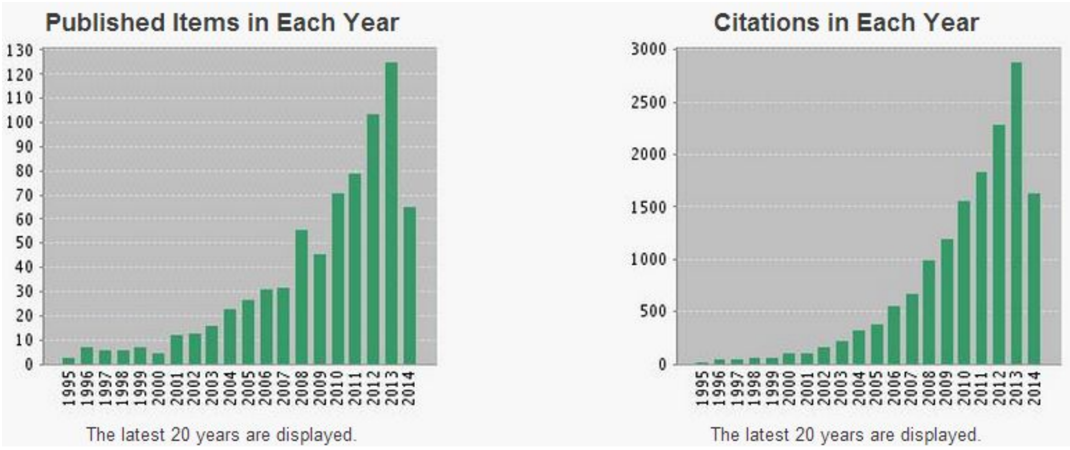


Figure 3.2. Published items(left) and citation times(right) of <laser scanning AND tree> this literature search result in Web of Science

We could see clearly from left graph in Figure 3.2., articles about laser scanning and tree in every year were more than articles of laser scanning and urban tree (left graph in Figure 3.1.). The trend in left graph showed that researchers have a increasing interest in laser scanning and tree this topic.

3.1.3 Short summary

The above paragraphs showed literature search result in Web of Science this database. Similar literature search result about "urban tree AND 3D geo-information", "laser scanning AND urban tree" and "tree AND laser scanning" were found in Google Scholar, and Global Search of Wageningen UR library. These literature search result showed a status that study about urban tree and 3D laser scanning is developing and the published literature about this topic is limited.

3.2 Multi-kind laser scanning for measuring tree height and crown volume

Airborne laser scanning (ALS) has been tried to detect individual tree in an earlier time (Hyyppä and Inkinen, 1999) and by increasing the number of laser pulses per m^2, individual trees can be recognized (Holopainen et al., 2013).

Recently, Finnish researchers showed more interest in comparing and combining ALS, TLS and mobile laser scanning for measuring and mapping urban trees.

Holopainen et al. (2013) examined and evaluated the accuracy and efficiency of airborne, terrestrial, and mobile laser scanning for measuring and mapping urban trees. They firstly created reference tree map manually from TLS data and later evaluated the tree detecting rate and location accuracy using automatic or semiautomatic ALS individual tree detection, and manual or automatic measurements of TLS and MLS (TLS_{auto}, MLS_{auto}, MLS_{manual}, MLS_{semi}). The main tree parameter they studied was the tree location. After getting the ALS, TLS, MLS data, they applied specific approaches (Yu et al., 2011; Liang et al., 2012;

Hyyppä and Lin, 2012) from other Finland researchers' previous study for ALS data classification and individual tree detecting, TLS_{auto} and TLS_{manual} points cloud processing and tree extracting, and MLS data cleaning and tree modeling, respectively. Then they took manual measurements from TLS data as references for tree location accuracy. The accuracy results were an average location error of 15cm with TLS_{manual} and 20cm with TLS_{auto} and RMSE (unit: m) were TLS_{auto} 0.45, MLS_{auto} 0.50, MLS_{semi} 0.44, MLS_{manual} 0.49, and $ALS_{ITDauto}$ 1.55 (Holopainen et al., 2013). In conclusion, they summed that ALS individual tree detecting with some fieldwork would be the most cost-efficient approach for only tree mapping, due to the rapid speed for large area and relatively small amounts of data processing (Holopainen et al., 2013). TLS provided more accurate data and MLS offered a mean of monitoring trees growing near roads or paths (Holopainen et al., 2013). This research was new in testing and evaluating several laser scanning approaches, as well as in detecting and measuring over 100 urban heterogeneous trees. It proved that TLS and MLS can be applied for producing accurate tree maps in urban forests. In terms of limits, this whole research used data from different departments, and need more labor, money and time to do the comparison and apply various approaches. They also pointed out the need of further analysing the effect of target distance, from the scanner, to tree detection. For the ALS individual tree detecting methods, the location accuracy was poorer, because the location of a tree was selected from the highest point of the canopy. The unique "Y" shape of the trunk in urban park area also affects the tree location accuracy (Holopainen et al., 2013).

Saarinen et al. (2014) carried out another study of a multisource single-tree inventory where ALS and TLS data were combined for mapping trees and measuring tree variables in part of Helsinki urban area. They used the terrestrial laser scanning tree map as input information in addition to airborne laser-scanning (ALS) data. Tree height and crown dimensions were measured from ALS and stem diameter-at-breast height (DBH) were predicted by using metrics extracted from ALS data, and compared to the field measures. In terms of accuracy assessment, they calculated the bias and RMSE. They did not compare the crown-size data because of lacking historical data. Compared with other similar literature, they found their tree-height measurement accuracy from the ALS data expected to be ±1 m was close to the accuracy of clinometer measurements in the field (Saarinen et al., 2014). The RMSE of their DBH measurements were varied (3.97cm to 7.09cm for park area and from 6.85cm to 7.58cm for forest area) and they found the influence came from stem form (Saarinen et al., 2014). Because tree stem form is not fully circular and especially stem forms of urban trees can differ greatly (Saarinen et al., 2014). They checked similar literature, compared the RMSE and proved their DBH measurements were acceptable. For conclusion, they summed multisource single-tree inventory is applicable for urban tree-attribute updates (Saarinen et al., 2014).

This research was a relatively new attempt combing ALS and TLS data for urban trees and they showed a clear study procedure in accuracy assessment. They applied several statistical methods to check the accuracy and examine the results and showed enough images of statistical calculation consequences. For discussion part, they also gave acceptable explanations from comparable articles. But the authors did not present enough images of their ALS and TLS data. The multisource single-tree inventory method needs to be examined in different areas and the accuracy needs more attention.

From the above new articles, we can sum that airborne laser scanning is quite important tool for urban trees inventory and relatively large number of tree investigation. It also has advantages in measuring urban tree height and tree location for acceptable accuracy. Combing different laser scanning methods could be a good attempt especially when there already existed different laser scan data for urban area. About studying the detailed structure of a single tree, ALS seems not that suitable while TLS and MLS have more advantages and potential. No matter researchers or practitioners want to employ which laser scan method, the data processing and accuracy steps need more attention.

3.3 Mobile laser scanning for detecting and modeling single tree and crown shape

Mobile Laser Scanning (MLS) data-sets are collected in many city areas for cadaster and 3d city modeling. So far little attention has been paid on realistic tree modeling from MLS in urban areas (Rutzinger et al., 2010).

Rutzinger et al. (2010) have developed a workflow of detecting and modeling 3D urban trees from MLS data. They firstly did tree detection from MLS point cloud data, then simplified the tree shape for data reduction, extracted key tree parameters (tree height, crown width, stem height, stem width, and crown shape) from point cloud, and finally generated the tree models. In the tree detection step, they used segmentation method from Vosselman et al. (2004), and classification methods from Rutzinger et al. (2007) and Höfle et al. (2009). Later they applied a 3D alpha shape approach (Edelsbrunner and Mücke, 1992; Da and Yvinec, 2010) for reducing data and keeping the outside shape of tree crowns. From the extracted single tree point clouds, parameter values are derived, and were used to create tree model in OpenAlea (Pradal et al., 2008) with the modeling approach of Weber and Penn (1995). For the results, they calculated completeness (86%), correctness (90%) and quality (78%) of the tree detection, tested different alpha values for knowing the quality and robustness of model parameters, and checked the realistic appearance of the final model through comparison with photographs and the original point cloud (Rutzinger et al., 2010). They found the general crown shape types matched the original tree shape very well but real asymmetric tree crowns were changed in the models due to branch angles which are fixed values for each crown shape type (Rutzinger et al., 2010).

The authors later applied whole workflow for 38 trees (Rutzinger et al., 2011). The 86% completeness and 93% correctness have been reached and the generated tree models have been directly integrated into 3D city models (Rutzinger et al., 2011).

The above studies can be seen as meaningful exploration for using MLS data modeling urban trees. It may improve the use efficiency of existed data and help for the delineation and parameter estimation of urban forestry. Besides, they did reduce the amount of massive point clouds which can be applied in later automated working process. The created tree models also can directly be used in city models and have realistic appearance. The limitation is that the inner structure of tree such as branching of the crown was parameterised (Rutzinger et al., 2011). In addition, the angle between subsequent branches is constant for each crown shape type which can be improved.

What we can conclude is MLS can be efficient tool for detecting and modeling tree in urban area when there are more trees. Compared to ALS, MLS has an advantage that the tree trunks are clearly visible in most cases (Rutzinger et al., 2010). But it may be need more effort that MLS has more amount of point clouds than ALS.

3.4 ALS and Portable LiDAR for modeling urban tree and extracting tree parameters

Omasa et al. (2008) confirmed the utility of airborne and portable on-ground scanning LiDARs for 3D visualization of an urban park and quantification of biophysical variables of trees in the park. Firstly digital canopy height model and digital terrain model were derived from ALS data using their own softwares, and the height of 166 trees were estimated from the canopy height model manually. Then portable on-ground scanning LIDAR provided point clouds of individual trees from different measurement positions. In this step, specific noise removing as well as merging algorithm and transformation were applied. Lastly a complete 3D model of three standing trees were created from combining airborne and on-ground LIDAR data overcoming blind regions. Delaunay triangulation, smoothing filter and ball-pivoting algorithm were used in the last combing step. Then the 3D model was sliced at different heights to compute the trunk diameter, maximum canopy, diameter, and canopy cross-sectional area.

In their result, the tree height from ALS were slightly underestimated (mean error=.0.14 m, RMSE=0.30 m) compared with trigonometrically measured ground-truth data (Omasa et al., 2008). Tree height errors ranged from 0.13 to 0.31m for the on-ground LIDAR data and from 0.05 to 0.73 m for the final merged model (Omasa et al., 2008). The error of the trunk diameter was within 1 cm for both the on-ground LIDAR image and 3D model. The canopy volume, trunk volume, and canopy cross-sectional areas were calculated without ground-truth data.

This research confirmed the capability of airborne and ground LiDARs for 3D visualization of an urban park and quantification of tree variables. This kind of research was hard to find for urban trees, to the best of my knowledge. Besides, the blind area of ALS (understructure) and blind area of ground LIDAR (overlapping some canopies parts) were tried to be complemented by merging data. A complete 3D model of three standing trees was created in 2006 and the authors paid more effort in merging data and dealing with massive point clouds. The weakness were in deriving tree parameters from the final 3D model and accuracy assessment. Final 3D model was actually 3 trees standing near each other and the lower part of canopies were overlapping which can be observed from figures in the paper. In addition, because the parameters like canopy volume are difficult to measure, in this paper, there were no ground-truth data for these parameter. So how well they did the slice and computing the canopy volume remains unknown. The model is also weak in terms of inner structure like branching because it only showed the outside smoothing outline of 3 trees.

Chen (2013) from Wageningen UR did another study about comparing extracted tree parameters between two types of 3D tree models raster based model (canopy height model) and point cloud model generated from airborne LiDAR data. The single trees were selected in Wageningen University campus and tree parameters like tree location, tree height, crown base height, crown width, diameter at breast height were compared. He pointed out the crown blocking effect reduced the accuracy and DBH could only be extracted from point cloud based model, but the low amount of points on the stem made the results coarse (Chen, 2013). An ideal way to solve this problem is by adding the terrestrial lidar technique (Dassot et al., 2011).

We can see the ground LIDAR have showed its power in capturing and measuring trees especially for lower part of the tree (e.g. stem) and combining techniques would be promising. But the methods of extracting trees from the point cloud and estimating the accurate tree parameters would need more care.

3.5 Terrestrial LiDAR for modeling detailed tree structure in other sites

Terrestrial LiDAR discrete return point cloud datasets (sequence of x, y, z coordinate combinations) was mostly base method for existing 3D reconstruction methods for trees, as it is shown in literature (Wu et al., 2013). Further, most of the research on T-LiDAR in forestry (during the last decade) has been concentrated on developing automated algorithms for plot-scaled forest inventories (Dassot et al., 2012). There are few to no related studies for individual trees in urban landscapes (Shrestha & Wynne, 2012; Holopainen et al., 2013). Thus here I focus on T-LiDAR based single tree detailed structure research not only restricted to urban environment.

There are specific T-LiDAR based researches for extracting (1) DBH and stem profile (Bienert et al., 2006, 2007; Maas et al., 2008); (2) cross sections of branches and stem (Pfeifer & Winterhalder, 2004; Thies et al., 2004); (3) wood volume and tree branches (Gorte & Pfeifer, 2004; Gorte & Winterhalder, 2004); (4) branch location, length, and patterns (Binney, 2009); (5) total and partial above-ground volume, branch size and distribution (Åkerblom et al., 2012; Raumonen et al., 2013, 2011). These kinds were classified according to Dassot et al. (2012), Wu et al. (2013), and Lau Sarmiento (2014).

(1) DBH and stem profile

Bienert and the team (Bienert et al., 2007; Bienert, Scheller, et al., 2006) generated an automatic point cloud processing scheme to extract stems from point cloud data. They mainly used the circle fitting approach. After segmentation based on point cluster search, a circle is fitted into each cluster at 1.3 m height using a circle fitting method for getting tree diameters (Bienert, Scheller, et al., 2006). They improved the quality of this process by adding a classification method detecting the underrate and overstate diameters (Bienert et al., 2007).

Then tree height was the difference between the highest point and the terrain model lowest point (based of the DBH) inside of the cut cylinder (Bienert, Maas, et al., 2006; Bienert, Scheller, et al., 2006). DBH was defined by cutting a slice at 1.30 m above the terrain model. Tree position was the coordinates of the centre point of the DBH in the right-handed system (Bienert, Maas, et al., 2006). Stem profile at different height intervals could be computed as well (Bienert et al., 2007; Maas et al., 2008).

They used measured data as validation data. For accuracy, their method had a detection rate of 97.4% in multiple tree detection (Bienert, Scheller, et al., 2006). DBH measurements by circle fitting showed an average RMSE of 1.8 cm and a RMSE of 4.7 cm for the stem profiles (Bienert, Scheller, et al., 2006). These were high accuracy ratios. But for tree height, they got a low accuracy, between 2.07 and 4.55m (Maas et al., 2008).

(2) cross sections of branches and stem

Pfeifer & Winterhalder (2004) and Thies et al. (2004) worked in this direction. They applied cylinder fitting method for extracting diameter and growing direction of the stem of its parts (Thies et al., 2004). Firstly the point cloud was separated into a grid of variable grid size for deriving digital terrain model (DTM). The lowest z-coordinate was selected for each cell. Then DTM was subtracted from the point cloud and the tree reconstruction was built from the remaining points. They used a cylindrical model fitting into the given point cloud in a limited height area of points (Thies et al., 2004). The two parameters radius and axis direction of cylinder were directly related to diameter and growing direction of the stem. The iterative process simulated growing pattern. When a RMSE of a set threshold was reached, the algorithm stopped automatically (Thies et al., 2004).

They used RMSE to decide the quality of fitting. The RMSE was the residual of the difference between the 3D points to the approximated cylinder surface (Thies et al., 2004). The comparison with measured data got RMSE for stems of 1.7 mm, an average deviation between -1.3 up to 0.6 cm for DBH, and accuracy of -11.5 cm in terms of tree height parameter (Thies et al., 2004).

(3) wood volume, stem and tree branches

Gorte and co-workers (Gorte & Pfeifer, 2004; Gorte & Winterhalder, 2004) used voxel-based algorithm to identify the structure of a tree in terms of stem and branches. They created a 3D raster space using 3D small cubes cells called voxels (volume element) at first. The size of the voxels decided the space resolution and they used a spatial resolution between 2 and 5 cm. Later using coarser spatial resolution they reduced details and using finer resolution, they could increased computation time (Gorte & Pfeifer, 2004). After whole point cloud was transferred to the 3D raster, they used neighbour-hood operators which removed isolated voxels and filled small holes and gaps between voxels.

Next they applied line-skeletonization of the tree. It reduced the thickness of tree trunk and branches to a single voxel wide linear structure (Gorte & Pfeifer, 2004). They did this for identifying branches and revealing topological relations. Then segmentation based on Dijkstra's algorithm was used to find the shortest route from the tip to the destination node and by this the whole structure of the tree was found (Gorte & Pfeifer, 2004). They established a logical model for a tree and they did not mention the accuracy assessment.

(4) branch location, length, and patterns

Binney (2009) developed a probabilistic method for reconstructing trees from laser data. It can extract branch location, angles, radii and lengths of branches these parameters. This method used a generative statistical model to fit likely hypothesis, and then used a sensor model to evaluate the likelihood of each hypothesis (Lau Sarmiento, 2014). It firstly created the base of the trunk and after reconstructing trunk, it reconstructed each branch. After each branch was finished, the same process continued to find sub-branches. The result was validated firstly with simulated data. The outcome segments were less than 1 cm from where should be (Binney & Sukhatme, 2009). Then 0.4 cm overestimation of stem radius was found with measured data, compared to millimetre errors with simulated data (Binney & Sukhatme, 2009).

(5) total and partial above-ground volume, branch size and distribution

Åkerblom et al. (2012) and Raumonen et al. (2011, 2013) worked out the quantitative structure model automatically approximating above-ground volume, branch size and distribution of trees from point cloud. They assumed that the point cloud is a sample of a surface in 3D space and that this surface is locally like a cylinder (Lau Sarmiento, 2014). Each point cloud must describe one single tree (Lau Sarmiento, 2014). Then the point cloud was covered with small patches, creating a surface. Next, patches were characterized geometrically (size, shape and orientation) into their neighbour, leading into a classification of these patches into a tree component (trunk, ground, branches, sub-branches) (Lau Sarmiento, 2014). The components which were not part of the tree (e.g. ground) were deleted. Trunk base was defined. Later tree components were segmented. Each segment was reconstructed with successive cylinders which locally approaching the radius and orientation of segments. They used small branches to do the validation. Result showed less than 1 cm error. Then it was tested with artificial trees, visual inspection proved that the branching structure was well defined (Raumonen et al., 2013).

Lau Sarmiento (2014) from Wageningen UR did a study analysing the performance of T-LiDAR in tropical forest with quantitative structure model to derive tree parameters and tested the parameters in the WBE plant-scaling model (Bentley et al., 2013). His result supported the use of T-LiDAR for assessing tropical trees structure. He summed T-LiDAR can deliver a reliable 3D point cloud, which can be used for tree modelling (Lau Sarmiento, 2014). The branches resulting from the quantitative structure model approach were very accurate with a low RMSE (up to 1.26 cm for radius parameter) for the first branches level (Lau Sarmiento, 2014).

From above articles, we can find T-LiDAR has really good ability (high accuracy, direct, active) in capturing 3D information about the tree structure (e.g. stem, DBH) and thus there are more and more researches of applying T-LiDAR studying tree structures. But at this moment, these studies are focusing on forest environment. Besides, after conducting the T-LiDAR measurements, the approaches of processing point clouds and extracting tree parameters are still in fast developing. Especially detecting and modeling the inner structure of trees like branching are the hot-spot. The modeling methods of trees are also flourishing out (circle fitting, cylinder fitting, voxel based algorithm, etc). There is also an important point that the existing literature have paid special attention to the accuracy assessment part (statistic methods, validation data, simulation data test, etc.) and often have good discussion and reflection.

The limits of T-LiDAR related tree structure study maybe are: firstly T-LiDAR is expensive, especially when extrapolating it to larger areas. Secondly there are massive point cloud data, which need more effort and time. Thirdly the hard and core steps are in processing and extracting tree parameters from point clouds which may require other related subject knowledge and skills (e.g. computer science, mathematics, topology).

Lastly, T-LiDAR is promising and have the potential that more tree parameters can be computed with high accuracy from its scans because the methodology research is still developing.

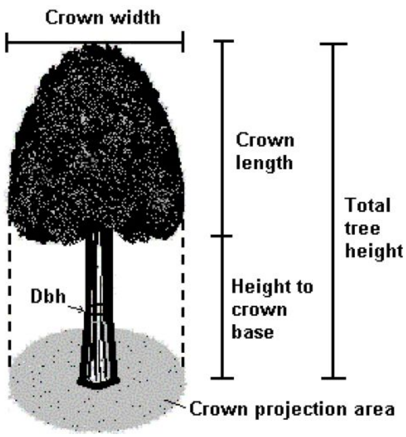
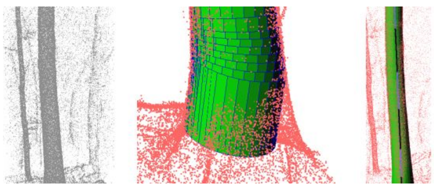
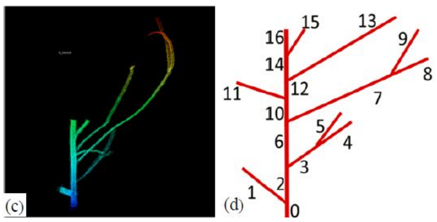
3.6 Short summary

3.6.1 Tree parameters and 3D geo-information methods

In order to understand tree and tree structure better, researchers defined some tree parameters. These tree parameters are important targets when we using 3D geo-information to measure and model urban trees. The important parameters used in literature was summed in following Table 3.1.

The tree parameters could be employed by researchers for different research objectives in different fields, such as tree inventory, forestry, plant ecology, remote sensing, 3D city modeling.

Table 3.1. Tree parameters and 3D geo-information methods summary

Figures	**Parameters**	**3D geo-information methods (capturing information)**	**Reference**
 Source: US Forest Service Remote Sensing Applications Center	Tree location, coordinates;	Airborne Laser Scanning (ALS); Terrestrial Laser Scanning (TLS); Mobile Laser Scanning (MLS); Multi-kinds Laser Scanning;	Holopainen et al., 2013; Saarinen et al., 2014
	Tree height,	ALS, TLS, MLS	
	Crown dimension (volume, size), Crown Base Height (CBH), crown width, crown density;	ALS; While TLS and MLS can get more details	Chen, 2013; Rutzinger et al., 2010, 2011; Omasa et al., 2008;
	Diameter at Breast Height (DBH)	Terrestrial Laser Scanning (LiDAR), MLS	Rutzinger et al., 2010; Omasa et al., 2008; Bienert et al., 2007
 Source: Pfeifer & Winterhalder, 2004	Cross sections of tree branches and stems	Terrestrial Laser Scanning (LiDAR)	Pfeifer & Winterhalder, 2004; Thies et al., 2004
 Source: Lau Sarmiento, 2014	Branch location, angles, radii, number of branches, branch length	Terrestrial Laser Scanning (LiDAR)	Binney & Sukhatme, 2009; Lau Sarmiento, 2014
Reference data from literature or local database	Tree Species	ALS; T-LiDAR; (Trials)	Chen, 2013; Saarinen et al., 2014; Omasa et al., 2008;

3.6.2 Strength and limits of laser scanning for tree structure measurements

Airborne laser scanning can really support urban trees inventory and relatively large number of tree investigation and it also has advantages in measuring urban tree height, tree location for acceptable accuracy as well as the relatively small amount of data. About studying the detailed structure of a single tree, ALS seems not that suitable due to the canopy obscuring other structure and understory.

Mobile laser scanning is also strongly helpful and efficient in detecting and modeling tree in urban area when there are more trees. Especially some cities already have the MLS data for other purpose. MLS is more powerful capturing tree trunks. But it has more amount of point clouds. Rutzinger et al. (2011) their attempt of reducing the amount of data can be improved and may used in later automated working process. Modeling the inner structure of tree such as branching from MLS data can be future research direction.

Terrestrial LiDAR has features of high accuracy, direct, active and has been popular applied in detecting and modeling detailed structure of trees in forest environment. Meanwhile there are quite few studies about extracting these parameters from T-LiDAR data in urban area. From existing researches, we can find T-LiDAR shows excellent in capturing information of tree structure (e.g. stem, DBH, branching, inner canopy structure). Accuracy could reach RMSE (up to 1.26 cm for radius parameter) for the first branches level in (Lau Sarmiento, 2014).

The approaches of processing point clouds and extracting tree parameters are still in fast developing (circle fitting, cylinder fitting, voxel based algorithm, quantitative structure model, etc). In addition, researchers have paid special attention to the accuracy assessment part (statistic methods, validation data, simulation data test, etc.) and often have good discussion and reflection. There will be more accurate tree parameters extracted from T-LiDAR scan data in the future.

Combing different laser scanning methods (composite 3D imaging techniques) could be a good attempt especially when there already existed different laser scan data for urban area. Besides, airborne laser scans, mobile laser scans and terrestrial LiDAR scans could be combined together to overcome each other's shortcomings which we can see light from the work of Finnish researchers (Holopainen et al., 2013) and Omasa et al. (2008).

No matter researchers or practitioners want to employ which laser scan method, the data processing and accuracy steps need more attention.

Chapter 4 Urban tree root systems research and parameters

In this chapter, firstly 4.1 section showed results of literature search strategy (significant key words, development in time of articles) in Web of Science this database as a represent and a summary of some other databases or search engine. 4.2 section showed known properties or concepts as well as unsolved questions about urban tree root system study according to literature I found. Next, 4.3 section reviewed important articles studying urban tree root system architecture from measuring methods this view and summed some limitations. 4.4 explored a little bit wider scope of literature about methods of measuring and modelling, and parameters of woody root systems. Finally 4.5 gave a summary about the parameters which need to known, and limitations of measuring methods in urban tree root systems study.

4.1 Results of literature search strategy

4.1.1 Significant key words, development in time of articles about urban tree root system research

In Web of Science, I used the search-word (root system of urban trees) in topic search, and the literature result number from all databases was 43. By checking titles, key-words and abstracts, I found 6 articles which are really about urban tree root system structure, and they are (Pierret et al., 1999; Čermák et al., 2000; Leucci, 2010; Ow and Sim, 2012; Ghani, Stokes, & Fourcaud, 2008; Jim, 2003). There are more articles about water sources of urban trees, water relation and growth of trees, nitrogen retention, root conflict with pipes, etc. which are not really related to the topic urban tree root system structure.

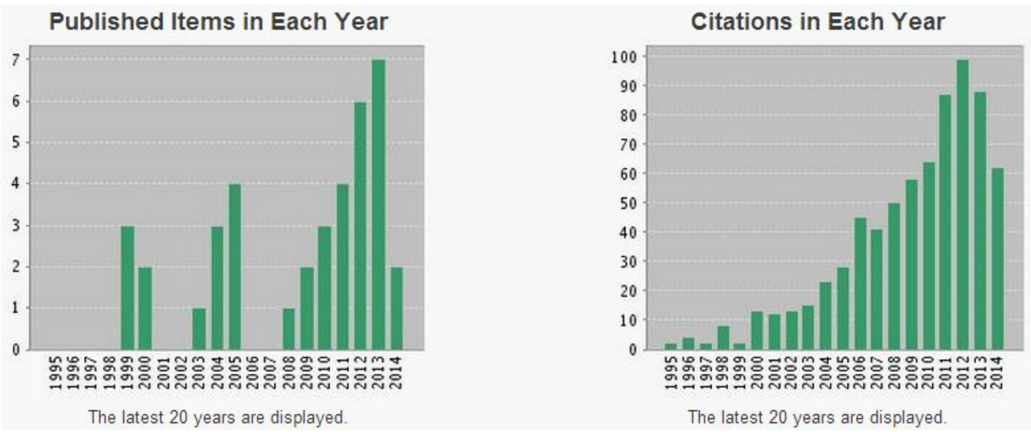


Figure 4.1. Published items(left) and citation times(right) of <root system of urban trees> this literature search result in Web of Science

In terms of development in time of published articles, there is a summary Figure 4.1. created from Web of Science citation report tool. From Figure 4.1., we could see there are more published papers about urban tree root systems from 2008, and the total number of published papers is small which shows this topic is developing in a first stage. However, this topic has a obvious trend that attracting more scientific research interests from the citation times figure.

I also tried several different input-search-word, but the result number became smaller and did not contain many target literature (see the Table 4.1.).

Table 4.1. Different search-word and result about urban tree root system in Web of Science

Input search-word	Literature result number	Notes in selecting process
(Urban tree "Root system")	10	Papers about "shrubs, transplant establishment" in the result
(Urban tree root system architecture)	6	Some papers about ground penetrating radar, water relations of specific species of trees
(Mapping urban tree root system)	4	1 paper about ground penetrating radar application
(detect* urban tree root)	21	Many papers about urban vegetation, urban building, metal and ecology study
(detect* urban tree root system architecture)	1	A review of using GPR in root detection not restricted to urban environment
(Mapping root system architecture of urban tree)	1	A review of using GPR in root detection, the same one

4.1.2 Significant key-words, development in time of articles about tree root systems study

Then I decided to search in a broader scope, on tree root systems study. I used the following search-words (tree root system architecture), and the results were 404. In the results, there were quite different directions like slope stability, soil condition and tree species, tree-soil-crop interactions, RNA, etc. By carefully checking, the important reviews (Tobin et al., 2007; Danjon & Reubens, 2008) about analysing woody root systems were finally found.

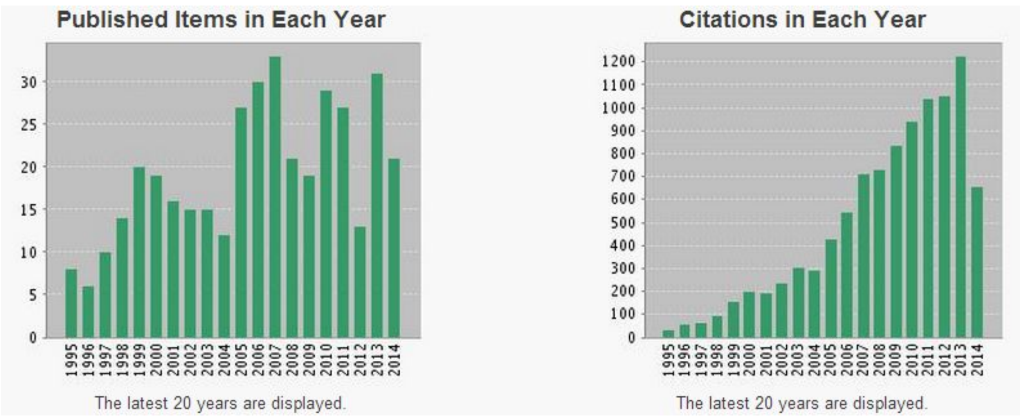


Figure 4.2. Published items (left) and citation times (right) of <tree root system architecture> this literature search result in Web of Science

In terms of tree root system articles development in time, Figure 4.2 could explain something. From Figure 4.2 (left), we see that there are of course more published papers than urban tree root system this topic; from 2005 to 2014, the approximately numbers of literature in each year are more than 20 except in the period 2009 and 2012. The research interest about this tree root system architecture topic has been increasing steadily and quickly from citation times (right graph of Figure 4.2.) in each year.

Later I used the search-word (detect tree root), and the result number increased sharply to 1231. I roughly scanned the article titles and found more papers from different study directions (RNA, DNA, and so on). When typing in <mapping tree root system architecture>, the result number was 16 and more articles studying effects of roots or tree growth on different sites appeared in the result.

4.1.3 Short conclusion

The above contents explained literature search result in Web of Science this database and there are similar search result about "urban tree root system study" and "tree root system study" in Scope, Google Scholar, Global Search of Wageningen UR library. All the literature search result showed a current situation that urban tree root system research is under development and the published literature on this topic is limited.

4.2 Urban tree root system: known properties and unsolved questions

4.2.1 Common category and function of tree roots

From literature, we can find terminology used to describe tree roots is very diverse and not standardized (Day et al., 2010; Tobin et al., 2007).

The quite often used term "tap root (primary root)", the first root to emerge from a tree seed (Sutton & Tinus, 1983), does not continue to develop on every tree (Gilman, 1990a). Gilman (1990a) stated that a tap root occurs when soil conditions permitting, most frequently on trees in a naturally regenerated forest and many trees do not develop tap roots. In shallow, or poor soils typical of urban areas, the tap root often branches into several roots and people cannot distinguish it from other roots (Gilman, 1990a).

Day et al. (2010) summed roots can be fundamentally classified as woody or non-woody anatomically (Lyford & Wilson, 1964) and woody roots are those that have undergone secondary growth, resulting in rigid structure and perennial lifespan. They also stated that functionally, woody roots are often called structural roots, anchoring the tree and creating a framework for the root system (Day et al., 2010).

Day et al. also pointed out from their knowledge and experience, typically, a tree has 5-15 (or more) primary structural roots that grow from the root collar and descend obliquely into the soil before becoming horizontal within a short distance of the trunk, although the whole pattern of root development can vary considerably (Day et al., 2010). The area within 1-2m of the trunk on larger trees is usually referred to as the zone of rapid taper where structural roots often found considerable secondary thickening generally believed helpful for stabilization (Day et al., 2010).

On the other hand, extensive "non-woody" roots, having not undergone secondary growth, proliferating from the structural root framework, are often called fine or absorbing roots, which have primary function in water and nutrient uptake (Day et al., 2010). These roots are generally small in diameter (<2 mm) and can live for a few days to weeks (Black et al., 1998; Pregitzer et al., 1998; Pregitzer et al., 2002).

Another team Tobin and the co-workers found in the related literature, the most common division of roots is the one distinguishing coarse from fine roots showing difference in diameter as well as in function (Tobin et al., 2007). Coarse roots play a more mechanical role in plant anchorage and transport and fine roots works in water and nutrient absorption (Tobin et al., 2007). But they did not mention the diameter difference in numbers. They also stated that it could be possible to introduce other sub-categories again based on morphological and physiological differences that could be measured but at the same time lack of a general agreement on definitions makes the inclusion of categorisation in modelling a difficult task (Tobin et al., 2007).

We can conclude that the most common category, or root system components, described by research articles consists of coarse roots (woody, structural roots) and fine roots (non-woody, absorbing roots) which can be measured by the difference in diameter. However the definition of an exact boundary is not clear. From my point of view, it is better for researchers to record the number of diameter of studied roots and explain the definition in their articles. In poor soil condition urban areas, trees often donnot have tap root (Gilman, 1990a). Besides, a primary work need to be done is general agreement on categorization of roots (Tobin et al., 2007). This is not easy because firstly the relationship bewteen coarse and fine roots is still not completely understood, and then so far researchers are not sure about how long a fine root could remain as fine root (Majdi et al., 2005; Tobin et al., 2007). That means some fine roots eventually grow into woody, structural roots (coarse roots) but most perish and are replaced (Fahey & Hughes, 1994).

4.2.2 Tree root system depth and spread estimation

Day et al.stated that although advanced remote detection technologies, such as ground-penetrating radar (e.g., Nadezhdina & Cermak, 2003; Hirano et al., 2009), may accurately detect root location in the future, rules of thumb are typically relied upon for estimating root extent and depth (Day et al., 2010). They summed typical rules in texts and educational materials estimating root spread as up to 3 × canopy spread (e.g., Elmendorf et al., 2005) or 1-1.5 × tree height (e.g., Marrotte, undated.); tree protection zones for sensitive older specimens are defined as a ground radius of 0.18 m per cm of trunk diameter (Harris et al. 2004); depth, described less consistently, is sometimes vaguely described as being primarily or mainly distributed in the upper 0.3 m of soil (Gilman, 2003; Day et al., 2010).

Jim (2003) also did a similar but slightly different summary from literature (Gilman, 1990a, b; Harris et al., 1999; Hruska et al., 1999; Perry, 1992, 1994) about the tree root system depth and spread: most roots are found in the upper 1 m of the soil; most roots extend laterally and in unconfined soils they can spread up to 3 times the diameter of the tree crown; the main framework roots are composed of lateral roots that are rope-like and spread horizontally beneath the soil, mainly in the upper 50 cm of soils; very few tree species develop roots that penetrate the soil deeply; most feeder or absorption roots branch off from the lateral roots and divide many times to grow in different directions, including upwards (Jim, 2003). Further, in urban sites commonly having many constraints, a soil disk with a diameter similar to the crown is acceptable (Jim, 2003).

Jim (2003) used "root envelope" to describe a tree root system (Figure 4.3.), which contains the bulk of a tree's root system, is a disc-like soil volume with a curved bottom and a flat top.

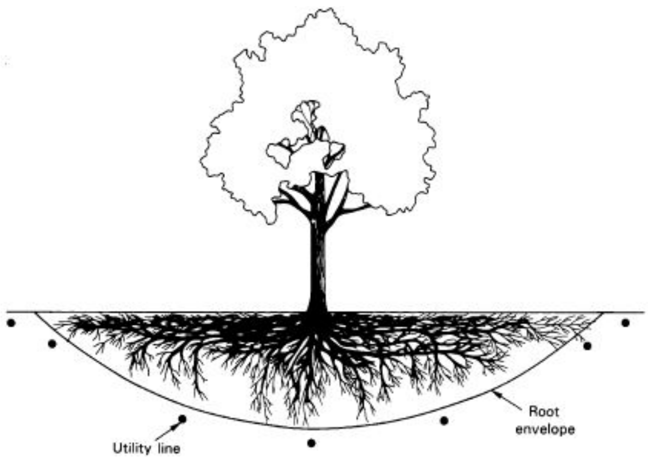


Figure 4.3. Root envelop, a disc-like soil volume contains most tree roots (Jim, 2003)

Recently, Chung and Berry stated that the surface 1-3.5 ft (30.48 cm to 106.68 cm) provide best conditions for growth and typically 80% of the root system is in this zone (Chung & Berry, 2012). They also stated that tree roots in many soil conditions grow horizontally more than vertically and the tree root architecture can be combinations of 3 or 4 major woody systems, i.e. structural roots, horizontal roots, tap root (not always have) and sinker roots (Chung & Berry, 2012). In terms of tree root branching pattern, they summed three general patterns of tree root systems (Chung & Berry, 2012): plate, heart, and tap (Figure 4.4.).

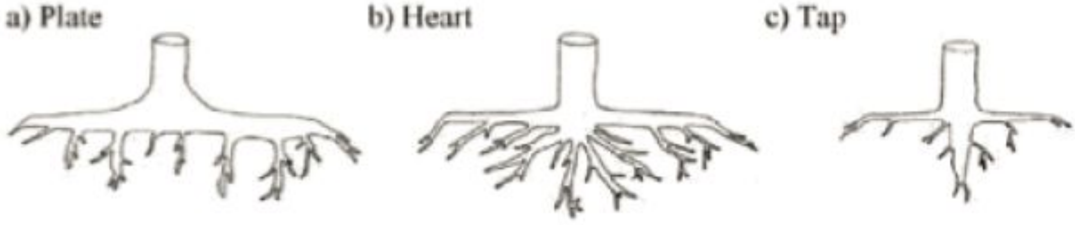


Figure 4.4. Three general patterns of tree root systems (Chung & Berry, 2012)

In other literature I found, there were few information about the tree root branching pattern. Further work could be done to search more literature about tree branching patterns.

In addition, Day and co-workers did regression analysis to available published data, and result showed tree height is a poor predictor of root spread in urban and landscape setting (Day et al., 2010). Because the regression analysis clearly showed almost none of the data points fall within the 95% confidence interval, Day et al.'s conclusion about tree height is convincing. They also examined related articles, found quite different instances, and summed that canopy spread is not likely to be a successful predictor of root spread unless a relationship is established for a particular species (these relationships may not hold for older trees) and it is clearly recognized that root distribution may not correspond to canopy distribution (Day et al., 2010). Their summary for canopy spread as predictor was conflicted with Jim (2003), and with some literature of more than ten years ago. Because some articles used canopy spread as predictor just based on partial excavation or literature study while some articles (e.g. Gilman 1988) did full excavation as well as Day et al. showed clear comparison, it seems that views of Day et al. are more reliable. For short summary, the point canopy spread is not likely to be a successful predictor of root spread still needs further study. Day et al. also applied nonlinear regression to investigate the relationship between trunk diameter and maximum root spread using available published data and summed, trunk diameter can provide a reasonable estimate of tree root spread to certain extent (Day et al., 2010). This point seems quite reliable based on the regression result. Besides, Čermák et al. (2013) found there seems some links between DBH and active absorptive root area, which also confirmed Day et al.'s view to some extent.

4.2.3 Key growth conditions and deciding factors

The real tree root architectural pattern depends on key growth conditions: soil moisture, aeration, and mechanical impedance (soil compaction) and in the upper part of the soil profile conditions are usually best (Chung & Berry, 2012). Soil (type, moisture, etc.), water (underground water level, rainfall, etc.), gravity factor (topography or terrain contains slope direction etc.), wind (wind strength, direction, etc.), etc. all influence the tree root growth and distribution (Čermák et al., 2013; Ghani et al., 2008; Tobin et al., 2007; Danjon & Reubens, 2008). As the soil environment plays a decisive role in root system development, variation in environmental conditions often results in a highly heterogeneous distribution of coarse roots (Nicoll et al., 1997). If there are hard pan, bedrock or seasonal waterlogging, root growth seems would be restricted vertically (Ghani et al., 2008).

Except the outside factors (environment factors), another very important factor is tree species, that is actually the genetic control (inside factor). Day et al. summed roots are opportunistic and will grow wherever environmental conditions permit from some instances limiting root development from below and from above (Day et al., 2010). But they also pointed out the species may differ in their foraging strategies, growing upward or downward or far way to find nutrient-rich soil patch (Day et al., 2010) and Tobin et al. agreed with this view by stating every tree species has its own mode of root branching and elongation rates, specific root activity and response to moisture, aeration and temperature conditions (Tobin et al., 2007).

Thus we could say the environmental factors of tree growing site and species (genetic control) together decide the root distribution. Tobin et al. had similar summary that root distribution is a product of the interaction between the tree species and the rooting volume characteristics (Tobin et al., 2007).

4.2.4 Unsolved questions for urban tree roots

The factors deciding tree root distribution are summed but the contributing percentages (how much power of deciding) of each factor, and in what condition which factor would be the main decider are not that clear in the literature I read. Day et al. also indicated that independent of species' environmental tolerances is not that clear (Day et al., 2010).

Day et al. checked existing reviews of documenting tree root depth and found that the reviews did not categorize forest versus urban growing sites; most of the horticultural examples were in orchards or agriculture settings; many researches used partial sampling or excavations (Day et al., 2010). Thus there seems no clear answers of how deep are tree roots of urban and landscape trees. Besides, root depth and distribution research on larger trees must be interpreted with caution, as it is generally impossible to follow every tree root to its tip (Day et al., 2010).

What is clear is that it is common to find some horizontal tree roots relatively near the surface (Day et al., 2010). Some studies (Jackson, 1999; Stone & Kalisz, 1991; Wong et al., 1997) indicated that some tree species commonly used in urban settings have the potential for rapid development of deep root systems (Root depths greater than 2 m documented) and Day et al. stated it is need further confirmation that whether these species realized this genetic potential for deeper roots or not when grew in urban and landscape settings (Day et al., 2010).

Notably, Day et al. stressed limited information can be found about how urbanized sites affect root anchorage (Day et al., 2010). That means the density of coarse roots, root length distribution, direction distribution of different kinds of roots etc. parameters of urban site tree root systems comparison with other sites same species tree root systems need further research. Day et al. also found another two future research directions: systematically study of the ecology of root foraging in urban sites; whether the tendency toward shallower root systems persists in mature urban trees. Actually, there are quite few studies systematically measured and quantitatively analysed the whole or almost the whole root systems of urban trees according to the literature I found.

4.3 Urban tree root system: measuring methods and limitations

From the literature I found about urban tree root systems, some general things can be summed: the objectives of these studies are diverse and thus their methodology, applied techniques, measured tree root system parameters are quite different. Researchers applied approaches like X-ray, ground penetrating radar (GPR), excavation and manually measuring, etc. for detecting and measuring urban tree root systems and these methods have different strength and weakness.

4.3.1 Sampling and X-ray

Pierret and co-workers tried X-ray computed tomography to quantify tree rooting spatial distributions by scanning some core soil samples extracted from specimens collected around the base of trees (Pierret et al., 1999). They regarded X-ray CT images as regularly-spaced sections through the soil, used them to create horizontal root contact maps, reconstructed roots from 3D cylindrical objects, and derived indices (e.g. Root length distribution) of the spatial organization of roots (Pierret et al., 1999).

Their results were 3D skeletons of root segments in sampled soil and analysis of these skeletons. The results showed on average, approximately 5% of the segments are >20 mm in length, 15% are >10 mm, 25% are >8 mm and 50%>4 mm of all samples; a significant part of the tree root systems of both species in both soil types grow at angles < 45 degrees to the horizontal; chestnuts could develop more oblique roots than maples (Pierret et al., 1999).

This study actually was a meaningful attempt for developing methods using nondestructive technique from sampling to generation of indices of tree root organization. X-ray CT images contained vertical direction information about quite small root segments. The shortcoming are: the X-ray technique and data process require professional skills and instruments, not practical for field; they did not assess the accuracy of the analysis done to root segments; from the result images of root segments we can only see some lines and pieces and the cylinder soil samples were only collected from 0 to 0.5m under the ground, thus the results were not that convincing.

4.3.2 Ground penetrating radar (before excavation)

Čermák and co-workers (2000) used ground penetrating radar (GPR), light microscope and sap flow techniques analysing root systems of two mature field maple trees growing in shaded and non-shaded sites, on clay soil in an urban environment. They performed 450 MHz GPR measurement along specified grid lines from the tree stems to the walls of the nearest houses (only one side due to expense). Root distribution of the other side was assessed through 2 m trenches cut in the road during roadworks. Microscopic measurements were performed on thin woody roots and associated fine roots sampled from a depth of 0.5 m and of 1.2 m (Čermák et al., 2000). The volume of fine roots was estimated using a pycnometer and their total projected area by a planimeter (Čermák et al., 2000). Root systems spatial distribution (coarse roots) were then drawn by hand directly from the evaluated data of GPR measurements and coarse root depth were taken from radar images.

Their results showed roots of the shaded tree were close to the house wall at a distance of 3 m, but roots terminated near the edge and did not appear to grow into the building foundations; during excavations, few living roots were found beneath the asphalt of the road and all roots were dead at a distance of 1 m from the stem (Čermák et al., 2000). Deeper roots were rare, and the maximum rooting depth was found to be 1.4 m (Čermák et al., 2000). Roots of another exposed tree grew to a distance of 8 m, thus reaching the nearby building and radially around the trunk up to a depth of about 0.7 m (Čermák et al., 2000). However, some roots reached a depth of 1.3–1.7 m near the fence with the neighboring garden. Two root branches were seen growing into the house wall. Below the asphalt surface of the road, roots only grew to a length of approximately 1 m (Čermák et al., 2000). Fine roots (mostly around 0.7 mm in diameter) were also found very dense at the house wall (Čermák et al., 2000).

From the study of Čermák et al. (2000), we can find the whole study procedure combined several approaches. Their measurement data for roots (1999) and aboveground tree part (1997) were in different year, and the GPR measurements were done only for one side. The other side root assessment was checked during roadwork but no information about date. They sampled part of woody roots and fine roots near the house but they seems not sample roots from other area. Hand-drawn spatial distribution of coarse roots were given but there were two kinds of units (ft and meter) respectively in X and Y axes-quite difficult to read, use and compare, and no GPR survey result images were given (GPR raw data seems not that easy to use from their discussion). The accuracy and validation information also were hard to find. Since they did not excavate the two tree roots, their result root depth and extent numbers need be carefully used.

Stokes et al. (2002) including Čermák later tested GPR to map root systems of three urban trees *in situ* (Stokes et al., 2002). After GPR measurements, root systems were excavated with an air spade and photographs were taken of root system transects for comparison with GPR images. Next two-dimensional image of the root system was reconstructed using AMAPmod software (Stokes et al., 2002).

Their measured result, the GPR images, drawn by hand from the raw data, suggested that the pine tree root system extent was more than 6m X 6m and the trunk was positioned centrally within the circular shape root system (Stokes et al., 2002). As for root depth of the pine tree, they only excavated to 1 m due to limited time but images showed the depth of the pine tree was more than 1 m. Another two mountain ash trees root systems were also mapped from GPR data but the hand-drawn result image contained two root systems near each other and the scale bar was quite rough. Thus I only can estimate the two root system extent could be 3 m to 4 m horizontally around the trunks and they did not show depth information of the two ash trees. Age, DBH, tree height etc. were not shown in the article. In terms of root density, they found, for pine tree, lateral roots were abundant in the top 20 cm of soil, and then again at a depth of 80 cm; between these two distances, no lateral roots were found; however, vertical roots were present (Stokes et al., 2002).

The highlight part of their research is that they compared actual roots with images hand drawn from the GPR data, showing GPR is reliable for mapping large roots in the horizontal plane only (Stokes et al., 2002). GPR could not identify smaller roots < 20 mm in diameter, nor distinguish between root branching and two roots crossing over each other (Stokes et al., 2002). They also called for creating software or approaches reconstructing root system architecture from GPR raw data as hand-drawn map contains inevitable errors and takes long time (Stokes et al., 2002).

In the recent study of Leucci (2010), 500MHz GPR, electrical-resistivity tomography (ERT) and seismic methods were tested on four closely standing eucalyptus trees (10 to 30 year-old) in an urban environment to produce 3D images of total root volume in the subsoil. He first did a test survey to study the heterogeneity of the site and examine physical parameters of the 3 approaches, and later conducted the main survey for tree root-zone. In terms of results, he found that the three geophysical methods are capable of detecting, independently of each other, the tree root-zone in 2D/3D, but cannot resolve the ring structures; GPR data was not able to resolve the single root in the 3D slices (Leucci, 2010). Actually his GPR data images showed 4 trees root-zone were about located at 0-0.65m in depth and there were bedrock at 0.78-1.04m; horizontally 4 trees root-zone were about 10m X 8m, in irregular polygon shape at 0–0.13 m depth.

His research supported the point geophysical approaches could be useful in root investigation as well as the need to have a standard field procedure of geophysical surveys. Besides, since he solved the research objective creating images of root volume, he did not do further analysis of the result data of 3 methods. He also stated there is a future work for developing a statistical processing tool to relate total below ground biomass to geophysical parameters (Leucci, 2010). In addition, the accuracy assessment information of 3 methods were hard to find.

Ow and Sim (2012) tested the 400 MHz GPR on two trees *Khaya senegalensis* (Desr.) A. Juss. and *Swietenia macrophylla* King in the urban environment and a controlled study involving roots that were pruned and buried at known depths and orientations. Their results indicated GPR system, under controlled conditions have the capability to accurate detect the presence of buried roots (diameter >= 0.05 m) positioned at various orientations and at depths of 0.15 and 0.3 m; three coarser lateral roots with diameters between 0.05 and 0.09 m at a depth of 0.10 m from the surface were also clearly detected by the GPR system while the mass of finer roots were absent from the GPR image (Ow and Sim, 2012).

The strength of their study is that they confirmed 400 MHz GPR was only capable of identifying larger roots (diameter >= 0.05 m) in clay loam soil and the GPR was also not able to distinguish between roots that were crossing over each other from those that were simply branching away. They also summed the RADAN software is a useful tool allowing for interpretation of recovered field data and has a 3D capability but still need improvement for image quality (Ow and Sim, 2012). In terms of validation of mapping root system, it seems can be improved that they visually checked the accuracy by comparing one digital image of excavated root system and GPR result. The spread, max depth, and distribution features of the root system were not mentioned.

4.3.3 Excavation and manually measuring

Ghani, Stokes, and Fourcaud carried out a a rigorous investigation of the influence of root loss through trenching on tree mechanical stability of 20 year-old *Eugenia grandis* (Wight) trees on sandy clay soil in an urban park (Ghani et al., 2008). They set 4 groups of total 28 trees, dug trenches at different distances (1.5, 1.0 and 0.5 m) from the trunk on the tension side of groups of trees, measured the force necessary to winch trees 0.2 m from the vertical, and lastly extracted root systems for architectural analysis and mechanical stability analysis (Ghani et al., 2008). They manually using callipers and a compass measured the shape, size and orientation of all structural roots (defined as any woody root with a diameter > 10 mm) based on the approaches in Mickovski and Ennos (2003) (Ghani et al., 2008).

In their study results, no taproots were found; large lateral roots emerged from the stem base and sinker roots descended vertically from the lateral roots and beneath the tree trunk; most of the first order lateral roots (97%) were found at a depth<0.3 m beneath the soil surface and only 3% were found at a depth of 0.3-0.6 m (Ghani et al., 2008). Mean rooting depth for all trees was 0.7 ± 0.3 m, with sinker roots usually located beneath or close to the stem base (Ghani et al., 2008). The maximum horizontal spread of most major first order lateral roots was 1.5 m from the trunk, with few roots growing beyond this limit (Ghani et al., 2008). Their results indicated that there is an increased allocation of root biomass on the northern side of the tree, which may due to usually northerly wind direction in monsoon season as well as tree growing on a slight slope of 7-10° (Ghani et al., 2008).

The most successful part of their study lies in quantitative analysis: they established relatively complete definition of a set of rigid measuring working approach containing setting the coordinate system, azimuth measuring, root cross-sectional area calculating, root eccentricity calculating, group comparison etc. and then did stepwise regression analysis. Even through whole root system morphology was examined by eyes and photographs, but quite large partial the first order lateral roots and vertical roots were measured, recorded and used for statistical analysis. The accuracy control was done by setting control group of trees, calculating standard error and significant level, and discussing with related literature. The pity was that trenching and manually measuring took long time thus they only can record some parameters from vertical sections (profiles) of whole 3D root system structure, and of course these key data were stored in tables.

4.3.4 Summary

Based on above studies, we can find the measuring work of whole urban tree root system is just in the first stage, or more exactly, quantitative analysis of whole urban tree root systems is in developing. GPR this 3D remote sensing technique is already applied in urban tree root systems study while there seems none application of laser scanning or LiDAR in urban tree root system researches (according to literature I found). The 3D modelling approaches for urban tree root systems seem few, in the studies of urban tree root systems I found, except little description in X-ray detecting (Pierret et al., 1999). Manually measuring and 2D data storing is still the main working approach and statistical analysis of whole urban tree root system distribution is few in the literature.

It is generally accepted that quantitative measurements of whole tree root systems are difficult (Nadezhdina and Čermák, 2003; Čermák et al., 2013). A tree root system is hard to measure because it is three dimension complex object which has vertical structure under the ground (which cannot be seen) as well as it has complex organisation. Within this organisation, the smaller roots-fine roots can be really small in diameter (generally < 2mm in Day et al., 2010). These all makes detecting or excavation work quite hard especially in urban environment. Researchers often combined different methods for studying urban tree roots.

Researchers due to technique reasons, limited time (or labor), and different research objectives, did not measure whole root system architecture, and instead, they only measured part of tree root system, and showed only some parameters. The parameters are various and hard to compare. They used qualitative description as well. Thus the summary or comparison work can be challenge.

The previous studies also need improvements in standard measuring procedure, data recording, accuracy control and assessment. For instance, from one article we can see one hand-drawn root distribution result map in two different units. Sometimes researchers even did not do any accuracy control work. Besides, the excavation work also contains some uncertainty, i.e. sometimes researchers excavated the root system only for 1 m or < 1 m depth and they did not clearly state they dig the roots to their tips or not.

We also could sum some limitations of existed measuring methods for urban tree root systems: X-ray CT images contained vertical direction information about quite small root segments but the X-ray technique and data process require professional skills and instruments, not practical for field. GPR is reliable for mapping large roots in the horizontal plane but GPR could not identify smaller roots < 20 mm in diameter, nor distinguish between root branching and two roots crossing over each other (Stokes et al., 2002). GPR raw data also needs specific software to process and further link geophysical parameters to tree root system parameters (Leucci, 2010). RADAN software could be a choice which still needs improvement in image quality (Ow and Sim, 2012). Hand-drawn map of excavated roots contains inevitable errors (Stokes et al., 2002). Excavation and manually measuring contains some uncertainty and measured data storing can be more systematic. The statistical analysis of measured data should be applied in more studies.

4.4 Measuring and modelling methods of woody root systems

Let us move to a wider world of tree root system study and related woody root system study. There are more kinds of quickly developing and widely applied methods for measuring and modelling root system and more parameters describing roots.

4.4.1 Concepts

Corcoran et al. explained the terms in root study in a simple and clear way: "Root biomass" is morphologically characterized separately from the root growth medium (soil matrix) while the combination of the growth medium intertwined with the roots is often defined as "root ball" or "root wad" (Corcoran et al., 2011). The root biomass structure is explicitly described in terms of "root architecture", which is the spatial configuration, sizes, and forms of the roots while the soil matrix is not included in an analysis of root architecture (Corcoran et al., 2011). Root architecture (size, shape, depth) of woody vegetation actually varies significantly with respect to species, soil, slope, depth to groundwater, competition, and many other parameters (Danjon & Reubens, 2008). The word "root system" usually refers to the roots proper but sometimes include the growth medium, depending on the purpose of the study (Corcoran et al., 2011).

4.4.2 Mapping techniques of root architecture

Danjon and Reubens (2008) reviewed lots of literature of woody root system and worked out common process steps of studying 3D root system architecture, i.e. getting to the roots, primarily root architecture coding, sampling of measured roots, actually performing measurements, reconstructing 3D architecture, and analysing. Specifically, the mapping techniques of tree root architecture could be roughly grouped into following categories mainly based on (Danjon & Reubens, 2008; Reubens, 2010; Corcoran et al., 2011):

1. <u>Sub-sampling approaches</u> contain measuring parts of the root system and interpolating or extrapolating conditions to the left parts of the system. Examples are auger or core sampling (Retzlaff et al., 2001) and trenching (Millikin and Bledsoe, 1999).

2. <u>Noninvasive approaches</u> measure the root systems with instruments that do not need destroying or unearthing the tree. Examples are ground-penetrating radar (Butnor et al., 2003; Hirano et al., 2009), electrical conductivity (Nadezhdina & Cermak, 2003; Cermak et al., 2006a,b), electrical resistivity (Amato et al., 2008), and X-ray tomography (Pierret et al., 1999).

3. <u>Invasive approaches</u> require the tree to be excavated and measured in the field or laboratory. Excavating techniques are manual soil removal (Di Iorio et al., 2005), crane removal of the tree (Danjon et al., 1999b), compressed-air soil removal (Danjon et al., 2007), and hydraulic soil removal (Stoeckler & Kluender, 1938; Tharp & Muller, 1940). Measuring techniques are manually measuring coordinates (Henderson et al., 1983), semi-automated digitization using electromagnetic or acoustic devices (Danjon et al., 2007), and laser scanning (Gartner & Denier, 2006; Teobaldelli et al., 2007).

4. <u>Simulation models</u> modelling root architecture or interaction between root systems and

their environment. Examples are 3D root architecture modeling (Pagès, 2000; Vercambre et al., 2003) and functional-structural growth models connecting growth-driven processes with plant morphogenesis (Drouet and Pagès, 2007; Fourcaud et al., 2008).

Every single one of the above techniques has distinct strength and weakness (Reubens et al., 2007; Danjon & Reubens, 2008), and researchers need wisely to select techniques or combine techniques depending on the required resolution of the results, the application environment of interest, and the resource or time constraints (Danjon & Reubens, 2008).

Danjon and Reubens also noticed that previous studies examined a low number of root systems and produced qualitative results, and they thought improvements in characterization of root properties were due to the recent advances in 3-D root architecture studies, especially digitizing tools and software programs precisely and rapidly measuring the full 3D architecture of excavated coarse root systems (Danjon & Reubens, 2008). In addition, they found that noninvasive methods were not as reliable as actually mapping an exposed root system, e.g. GPR was found useful only for single root segments (Stokes, 1999; Butnor et al., 2001; Butnor et al., 2003; Barton & Montagu, 2004). They also stressed one of the future need is improving and standardizing methods.

4.4.3 Modelling root systems architecture

In terms of modelling root systems architecture, Tobin et al. summed that two main types of models were generally used to model root system growth, (1) static fractal branching models which were based on fractal properties of the root parameters and (2) dynamic 3D developmental models, based on the developmental rules of the apices and incorporating soil effects on root growth (Tobin et al., 2007). Then they further grouped existing studies as fractal branching models, developmental models, functional structural plant models, and density based models (Tobin et al., 2007).

4.4.4 Parameters of root system architecture

Reubens reviewed the literature and did a overview of the most commonly used root architectural characteristics (Reubens, 2010). He stated root architecture could be regarded as totality of variables characterizing the 3D structure of a root system including both its topology (branching pattern or physical connections between plant components) and geometry (shape, size, orientation and spatial location of the components) (Reubens, 2010). Some variables can be assessed at different levels, i.e. root system level, individual root level or root segment level while they can also be grouped in other means like size and branching property, or density characteristic (Reubens, 2010). The following Table 4.2. showed some common measured parameters (geometry and topology) from Reubens (2010) and more detailed parameters like fractal branching variables could be found in (Reubens, 2010).

Table 4.2. Part of most commonly parameters for describing root architecture (Reubens, 2010)

Size characteristics	Definition	Calculation
Root system level (also for sub-sections)		
root volume (cm^3) Vol_R	Space occupied by the root system. Can also be calculated for an individual root	Frequently calculated from mean root diameter and length
root length (m) L_R	Length of all root members present. Can also be calculated for an individual root	
horizontal spread (m) HS	Maximal horizontal distance between the two horizontally furthest reaching roots on a plant root system	
rooting depth (cm)	Depth of the deepest root found on a plant root system	
Individual root level		
root external surface area (cm^2)	Area measure of the outside surface of an entire individual root	Frequently calculated from root length and diameter measurements
root taper ($cm\ cm^{-1}$)	Longitudinal variation of root diameter	
root diameter (mm)	The diameter of an average individual root; usually assumed to be a plain cylinder	Frequently calculated from Vol_R and L_R or Fresh Weight
Root segment level		
root cross-sectional area (cm^2) CSA (Figure 4.7.)	Area measure of the cross-section of a root segment, usually assumed to be a plain cylinder	Frequently calculated from root diameter measurements
Branching and topology		
branching angle (°)	Angle between a root descendant and its parent root	
inclination (°)	Angle of the measured root towards the horizontal plane	
root or link order (Figure 4.6.)	Branching order of a root or root segment	
root fork number	Total number of root bifurcations	
altitude	Number of links in the (topologically) longest directed path. Also known as maximal topological depth	

4.5 Summary

We could see the tree root system studies in urban settings are quite scattered in research objective and have used different parameters describing tree root systems (detailed parameters summary in following Table 4.3.). Some parameters could be explained by Figure 4.5., Figure 4.6., and Figure 4.7.

The parameters are not clearly defined and not consistent.
Some article recorded length, angle, density of root segments (Pierret et al., 1999), and some carefully noted length, vertical angle, diameter and azimuth of large lateral roots and calculated distribution of parameters, individual, and mean root system characters (Ghani et al., 2008). Some only test the techniques (Ow and Sim, 2012). It is not easy to find the

definition of parameters in articles and how they actually calculated these parameters. Even for one parameter, there could be some uncertainty in literature. For example, root system depth, in earlier study (Cermak et al., 2000; Stokes et al., 2002) researchers just excavated some part of the whole root system and noted the max depth; in later study (Ghani et al., 2008) used mean root depth but they did not tell the definition. Thus it could be necessary firstly telling the clear definition of used parameters in future studies. Standard definitions or agreements of parameters need to be given.

Secondly, some parameters need background knowledge to understand. Some given definition of root density and branching order are quite confusing. Without professional knowledge about root systems, it is hard to read, compare, and use the parameters.

Table 4.3. Parameters used in urban tree root systems study

Parameters	Methods	Reference
Root system level (section level)		
Maximum rooting depth (see Figure 4.5.)	GPR; partly excavation; visual check; partly trenching; light microscope; sap flow; pycnometer;	Cermak et al., 2000;
Coarse roots horizontal max extent; Coarse root length		
Fine root volume		
Root system spread; Root depth; Root spatial distribution;	GPR; Excavation to 1m; manually measuring; hand-drawn map; photographs; AMAPmod software;	Stokes et al., 2002;
Root system horizontal plane shape		
lateral roots density in depth; vertical roots density in depth; root density in diameter;		
Root-volume approximate depth	GPR; electrical-resistivity tomography ; seismic methods	Leucci, 2010;
Coarse roots distribution in approximate depth	GPR; Excavation to 1m; manually measuring; photographs;	Ow and Sim, 2012;
Taproot yes or no (see Figure 4.5.)	Trenching; comparable groups and control group trees; excavation all roots diameter >1 cm; manually measuring using callipers and compass; statistical software	Ghani et al., 2008;
Mean rooting depth		
Mean total root cross-sectional area; eccentricity		
Lateral root number; first order lateral root number		
Mean azimuth of first order lateral roots		
Maximum depth of sinker roots		
Lateral roots distribution depth and percentage		
The maximum horizontal spread of first order lateral roots		
Root segment level		
Root length distribution	Sampling core soil; X-ray imaging; reconstructing; statistical software	Pierret et al., 1999;
Root length density		
Root growth angle distribution		

Site details		
Soil condition	Previous study; sampling; lab analysis	All articles listed here
Climate information (wind, rainfall, temperature)	Data from local related organization	Ghani et al., 2008;
Topography	Previous study; measuring	Leucci, 2010; Ghani et al., 2008;
Tree details		
Species	Data from local related organization; previous study	All articles listed here
Age	Data from local related organization;	Ghani et al., 2008; Leucci, 2010;
DBH	Previous study	Ghani et al., 2008; Cermak et al., 2000;
Tree height		Ghani et al., 2008;
Crown spread		

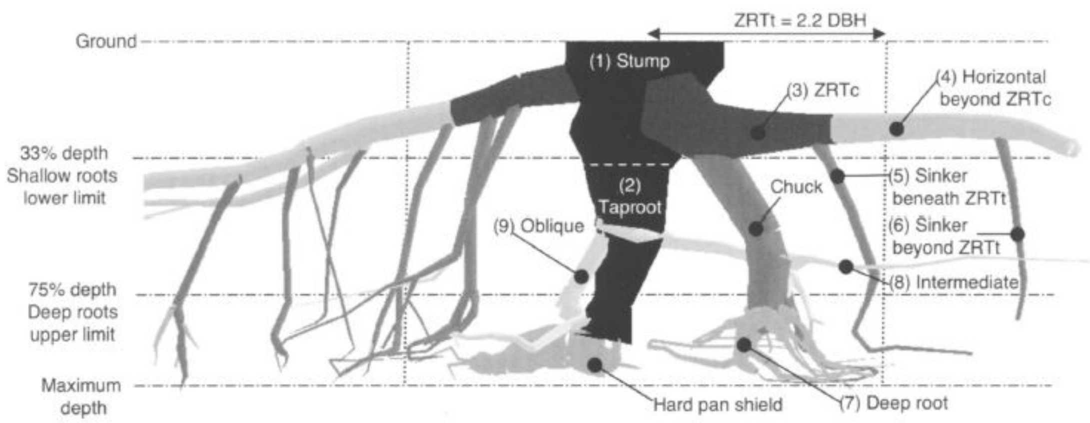
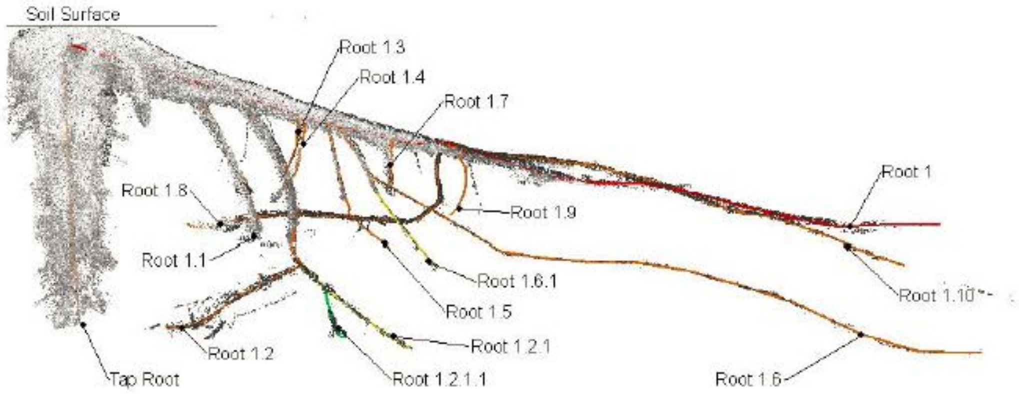


Figure 4.5. Max rooting depth and tap root from reconstructed measurement data (Danjon et al., 2005)



Data sheet for root vector model

Root ID	Root order	Azimuth angle	Vertical angle	Branching angle	Root length	Branching point	Root Type
n	n	Degree (°)	Degree (°)	Degree (°)	m	m	H, V, O

Figure 4.6. Branching parameters of tree root system based on laser scan data (Chung & Berry, 2012)

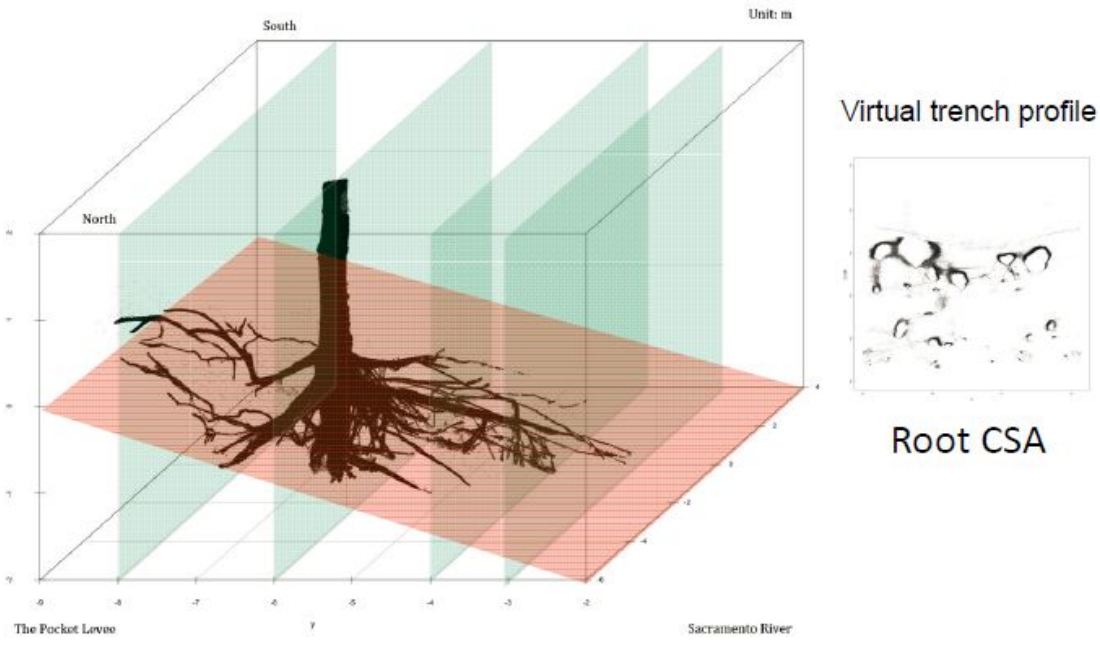


Figure 4.7. Root cross sectional area parameter from laser scan data (Chung & Berry, 2012)

We also can conclude some current study progress in urban tree root system research based on literature we found: quantitive analysis of 3D tree root system architecture at urban sites is missing; manually measuring and some statistical analysis in two dimensions approaches have been reported; no research on recording coordinates of tree root systems; no agreements on standard measuring procedure, data recording, accuracy control and assessment; no studies did model urban tree root systems in the articles I studied.

Besides, some limitations of existed measuring methods for urban tree root systems could be concluded: X-ray was tested in small root segments but no large urban tree root systems, and it is not practical. Secondly GPR is reliable for mapping large roots in the horizontal plane but GPR could not identify smaller roots < 20 mm in diameter, nor distinguish between root branching (Stokes et al., 2002). The software for processing GPR raw data also need improvement. Manually measuring in the related literature needs to be more systematic. Relatively systematic and rigid measurements (setted sections according to angle, and distance to the stem centre, marked growing order of roots, etc.) and statistic analysis of urban tree root systems could be found in (Ghani et al., 2008).

The study about tree root system in other environments like forest stand seems developing faster in quantitive analysis and 3D root system architecture modelling but still not-standard in measuring methods and parameters. Some researchers stated that there is a need for logical, systematic, and rigid measurements (Ghani et al., 2008; Danjon & Reubens, 2008). Measurement procedures can be more or less "robust" (used for more times) (Danjon & Reubens, 2008). The example of robust measurement method is (Danjon, Fourcaud, & Bert, 2005) which providing a comprehensive overview of quite all aspects of coarse root architecture (Danjon & Reubens, 2008). Under many circumstances, at least partly quantitative measurement, or a coarse root distribution (of e.g. root volume, length and diameter) in compartments defined from their function, location or potential contribution to mechanical resistance, may provide a more valuable dataset than a simple profile of root density distribution with depth (Danjon et al., 2005; Reubens, 2010).

Chapter 5 Could the above ground approaches be applied to measure and model the parameters of the tree root system?

In this chapter, firstly 5.1 section illustrates search scope of literature based on the results of chapter 3 and 4 and the result of literature search strategies. Next 5.2 shows the above ground often used laser scanning technique and related reconstruction methods could be applied in tree root system measuring and modelling. Following 5.3 shows the relations between above ground tree parameters and root system parameters (root system spread and root volume) and the above ground accurate data could be used in assuming and estimating tree root system parameters. Lastly 5.4 section sums important points and gives conclusion.

5.1 Scope from previous chapters and result of literature search strategies

5.1.1 Scope from chapter 3 and 4

From chapter 3, we know that laser scanning (LiDAR) is the 3D geo-information technique which can efficiently and precisely measure the above ground urban tree structure, and its point cloud data could be used to build quite real tree models. During different kinds of laser scanning, ground LiDAR has showed its power in capturing and measuring trees especially for lower part of the tree (e.g. stem). But according to the literature I read, at the moment, there is a limitation of applying LiDAR in capturing the inner structure of urban trees such as branching of the crown. Meanwhile terrestrial LiDAR has features of high accuracy, direct, active and has been popular applied in detecting and modeling detailed structure of trees in forest environment. There are different researches about deriving tree parameters like DBH, cross sections of branches, branch location and length, branch size, etc. from LiDAR point clouds and using the parameters to build tree models. These articles agreed that laser scanning (LiDAR) has good ability in capturing 3D information about the above ground tree structure.

From chapter 4, we could find there seems no 3D urban tree root system architecture quantitive analysis based on literature I found; there are manually measuring urban tree roots and some statistical analysis in two dimensions; there are seems no research recording 3D coordinates of urban tree root systems based on literature I found; there are seems quite few study modelling urban tree root systems. The researches about tree root system in other environments call for more valuable datasets such as quantitative measurement for coarse root spatial distribution as well (Danjon et al., 2005; Reubens, 2010).

In sum, there is necessity of quantitative analysis about root system spatial distribution in root systems study of urban trees as well as trees in other environments, while above-ground tree researches applied more quantitative analysis including measuring and modelling. Thus naturally we have a question, could the above ground approaches be applied to measure and model the parameters of urban tree root systems?

For answering this question, here I firstly consider "the above ground approaches" as the efficient and accurate 3D geo-information technique laser scanning (LiDAR) based on result in chapter 3. Secondly from chapter 3, the above ground approaches could contain the following or related laser data reconstruction (modelling) methods. Thirdly, from chapter 3 (maybe not that obvious) the above ground approaches could contain the resulting accurate DBH, tree canopy, etc. data. Thus the question changes into several questions and the first question is "could the laser scanning technique be applied to measure and model the parameters of urban tree root systems ?"

Actually laser scanning can't penetrate into soil, so there are would be 2 ways if one wants to use laser scanning for root system study: after excavation, directly measuring roots or just using laser scanning for above ground tree part and then indirectly modelling root systems. The latter one approach is based on assuming that there are quantitative relationships between above ground tree part parameters and underground root systems parameters.

Based on above analysis, I searched literature about two topics: first laser scan and (urban) tree root systems, and then quantitative relationship between aboveground (urban) tree parameters and underground (urban) tree root systems parameters. Another important literature source was from literature I found in chapter 3 and 4.

5.1.2 Result of literature search strategies

According to the scope set in previous section, I defined (laser scan AND root system of urban trees) as search-word. In Web of Science, there was no record from all databases for this search-word. I tried (laser scan AND urban tree root system), (laser AND urban tree root system), (LiDAR AND urban tree root system), and (laser scan AND urban "tree root") respectively and the result number all was 0. The search-word (laser scan AND urban tree root) lead to a result of 2 articles not related to tree roots (about 3D city models based on laser scanning).

I decided to search in a broader scope. Search-word was set about tree root and LiDAR. There were 141 result records for (LiDAR AND tree root) this search-word, and I checked the first 20 items having high relevance. They were about above ground part of tree. The search-word (LiDAR AND tree root system) had 32 result records almost all about above ground part of tree. The search word of (laser scan AND tree root) lead to a result number of 96 records and I examined first 30 items. Two articles about laser scan and coarse root segment were found (Wagner et al., 2010, 2011) and chose as target literature.

Another search-word (LiDAR AND "tree root") had 2 literature records. 1 article is about radar and root and the other is what I have found (Wagner et al., 2010). Then (Laser AND "tree root") this search word gave 2 records containing the same article (Wagner et al., 2010) and another paper about using open source software creating 3D models.

In other literature search databases like Google Scholar, there were similar results. There were many papers about LiDAR and above ground tree while quite few literature about LiDAR and tree root system (no articles found about urban tree root and LiDAR). The input search-word (LiDAR tree root) in Google gave me a target literature (Chung & Berry, 2012) (presentation file) about LiDAR and tree root system.

From literature in chapter 3 and 4, I found (Gartner & Denier, 2006; Teobaldelli et al., 2007; van der Heijden et al., 2007) these 3 articles. In total, there were 6 literature (Wagner et al., 2010, 2011; Chung & Berry, 2012; Gartner & Denier, 2006; Teobaldelli et al., 2007; van der Heijden et al., 2007) studying applying laser/LiDAR in measuring and modelling tree root systems and no literature found about laser/LiDAR and urban tree root system.

As for quantitative relationship between aboveground tree parameters and underground root systems parameters, there are already some literature in chapter 3 and 4 containing contents about this relationship. Considering time limitation as well, I decided to only search literature in Web of Science and Google.

Because in (Danjon & Reubens, 2008), when discussing the relationship, the above ground part of tree could be called as "shoot", and the below ground root system part could be simply called "root". Then I set search word using "shoot" and "root".

The search word (tree shoot volume and root volume) was input in Web of Science, and the result number was 151. In first 20 items I found 1 article (Mugasha et al., 2013) studying about quantitative relationship between root and shoot. When I scanning the text of (Mugasha et al., 2013), I found the article used a specific term "root to shoot ratio". Thus I used search word (Tree root to shoot ratio european) in Web of Science, and it gave a result of 27 literature. First 20 items were checked and (Pretzsch, Biber, Uhl, & Hense, 2012) and (Bolte et al., 2004) were found.

When I input (urban tree root to shoot ratio), the result were 10 literature and no highly related articles were found. I used (tree root shape and shoot shape) and 63 files were given. No highly related articles found in them. Here I only used Web of Science for explaining the literature search result and Google gave more or less similar result. Because of limited time, I did not do further literature search.

5.2 Applying above-ground approaches in tree root system measuring and following data processing

The often used above ground technique laser scanning could be applied to measure and model the tree root systems. Actually there are five researches which have applied laser scanning in measuring and modelling tree root systems.

5.2.1 Researches already applied laser scanning technique

Gartner and Denier (2006) from Swiss Federal Research Institute WSL did a pilot study applying ground-based 3D laser scanner to acquire the structure of a large uprooted tree root system. They used a Cyrax ® HDS2500 scan device and the resulting file data contained 1.000.000 data points (xyz-coordinates) representing the surface of the roots visible from the position of the scanner (Gartner & Denier, 2006). They did the scanning from 4 directions to minimize the shadowing effects, set 4 stages with fixed points to guarantee correct orientation of single scan, set 2 mm point-to-point measurement spacing to simplify data processing and combined scenes into a scatter-plot of whole root system (Gartner & Denier, 2006). They found coarse root structure is clearly visible from scatter-plot and single roots bigger than 5 mm in diameter can be distinguished (Gartner & Denier, 2006). Later they conducted a basic modelling by cutting 10 cm horizontal layers, combining lowermost data points girdling the surface texture to closed contour lines, and adding the height information of the layers using the CAD/CAE-software Bentley MicroStation (Gartner & Denier, 2006). However the basic modelling need more manually data corrections to accurately represent smaller roots in the structure (Gartner & Denier, 2006). They summed that a more detailed modelling technique is required to fully used the potential of the high resolution scatter-plot (Gartner & Denier, 2006).

As a successful attempt, Gartner and Denier found the laser scanning could be able to map the coarse root structure and single root > 5 mm in diameter and pointed out future research needs in detailed modelling technique. But except setting 4 stages for correctly merging different direction scanning, this research lacking more accuracy control and assessment steps.

Teobaldelli et al. (2007) used the Spot laser measurement system LARA53500 to measure above- and belowground structures of three 14-year-old poplar trees in a poplar plantation. After completely excavated by an air-spade, the root systems were scanned from ten different points of view (Teobaldelli et al., 2007). Then they used software JRC-3D Reconstructor ® to filter, register, and sub-sampled (due to hardware limits) the laser scanning data (Teobaldelli et al., 2007). They also manually measured, dried and weighted root systems and calculated the volume by multiplying those values with wood density. Then they used the software WGROGRA and AMAPmod to create geometric models based on the structural information from laser scanning and manually measurements; next compared with the laser scan point clouds using the inspection tool of JRC-3D Reconstructor ®, and the tool showed an error of about 10 cm for the stem and from 10 to 40 cm for the branches; lastly these error information were used in an iterative process to modify and improve their geometric models (Teobaldelli et al., 2007).

Their research did not build models only based on laser scanning point clouds and instead they used laser scanned data combining with WGROGRA, AMAPmod to validate geometric models of tree root systems. We could also find that they manually extracted the topology information of root systems using JRC-3D Reconstructor ®. Thus the methods of extracting topology information and modelling whole root system based on laser scanning point clouds need further study.

Wagner et al. (2010) from Swiss Federal Research Institute used a Faro Platinum Scan Arm (FARO, 2009) with a reverse measuring principle to acquire the 3D structure of a tree root segment. After scanning, they used Geomagic software (Geomagic, 2007) to reduce noise, generate root surface models, and test different interpolation algorithms filling holes created by noise (Wagner et al., 2010). Then they used WinDENDRO manually measured ring-width on sampled cross sections, calculated correct orientation of the measured radii within the model and intersection point based on trigonometric formulas, computed ring boundaries coordinates, and applied a MATLAB program optimizing the coordinates position (Wagner et al., 2010). The incorporating 2D tree-ring data in 3D laser scans was successfully achieved and reached deviations between 5% and 7% in volume calculations from the actual volume (Wagner et al., 2010).

Later Wagner et al. (2011) did a further study in which they first scanned 12 year-old pine tree root systems (root diameter > 0.5 cm) with a FARO Laser ScanArm (resolution ±50 μm), then created 3D surface model with Geomagic, measured cross section ring-width with WinDENDRO, integrated the ring-width measurements into the 3D model with a MATLAB program, and finally computed cross sections at any point within the model to obtain growth layers with a weighted interpolation algorithm. They got a quite good result an annual basis 3D tree root development MATLAB sector model whose total volume computations deviated by 3.5–6.6% from the scanner reference model (Wagner et al., 2011).

Chung and Berry (2012) applied ground-base T-LiDAR to map and analyse tree root systems on leeves from projects of California Levee Vegetation Research Program. After air spade excavation, they used T-LiDAR to scan root systems of 15 Valley Oaks and 5 Cottonwoods *in-situ* including aboveground (stem), slope, and belowground compartments and they also did manually measurements (Chung & Berry, 2012). Then they did conversion of point clouds in two ways respectively: they did tomographic slicing, reconstructed hierarchical nested datasets, and created biomass models; in another way they did vectorization of polylines, made topological datasets, and created vector models (Chung & Berry, 2012). During the analysis of tomographic slicing, they used R software to analyse 2D plot of root cross sectional area, ArcGIS software to do some spatial analysis, and Fragstat software to make spatial metrics analysis (Chung & Berry, 2012). While during the vector model construction, they used azimuth angle, zenith angle, root length, and root order as the critical variables to analyse branching pattern and directionality (Chung & Berry, 2012). In their results, average maximum rooting depth of 17 trees equals 1.58m (± 0.47 SD), and they found every tree on levee has a taproot. Besides, they used root topological index (Oppelt et al., 2001) to quantitatively illustrating the branching pattern of root systems and found small trees are tend to be more herringbone branching (Chung & Berry, 2012). Because this literature is a presentation file in a symposium, not all of their results were in the file, and no information were found about the resolution of their

LiDAR device and minimum diameter of root they measured. But according to their data images, the minimum diameter of measured root could be smaller than 1 cm.

5.2.2 Applying aboveground technique and related laser data reconstruction methods

From the above five studies, we could see laser scanning can provide rigid, quick, efficient and high accuracy measurements for tree root systems. This technique could make robust and valuable quantitative measurement for whole tree root systems which was called for in (Danjon & Reubens, 2008). This is also agreed with the view laser scanning is rather robust in architecture measuring methods of plants (van der Heijden et al., 2007). Besides, laser scanning is the best technique available so far to describe the surface and shape of roots for root-modeling applications (Danjon & Reubens, 2008). No other device used for root studies was able to depicture big root systems in such an accurate way (Wagner et al., 2010). Hence, the often used above-ground technique laser scanning is a quite important technique which could be applied for further coarse-root studies.

At the same time, we could also find that the minimum measured root diameters in (Gartner & Denier, 2006; Wagner et al., 2010, 2011; Chung & Berry, 2012) are all smaller than 1 cm. While the above-ground approaches (laser scan measuring and following reconstruction methods) in previous chapter 3 can reach a level of accuracy about several centimeters, e.g. DBH measurements by circle fitting showed an average RMSE of 1.8 cm and a RMSE of 4.7 cm for the stem profiles (Bienert, Scheller, et al., 2006) ; the branches resulting from the QSM approach were very accurate with a low RMSE (up to 1.26 cm for radius parameter) for the first branches level (Lau Sarmiento, 2014). Thus the accuracy level difference is not that far and instead, it is acceptable and possible to get smaller. Besides, there are needs for quantitative measurements and analysis of tree root systems and it seems in the coarse root study the centimeter accuracy level is acceptable and still necessary based on different research objectives, which were mentioned in chapter 4. Hence, we could say, from accuracy level this point of view, the above-ground approaches (laser scan measuring and following reconstruction methods) could be applied in tree root system measuring and following data reconstruction.

In terms of laser data processing methods, there are already quite some above-ground approaches (details in chapter 3) for reconstructing stems, branches, branch orientations, wood volume, cross sections of branches and stem, etc. While so far there are only 5 researches about laser scanning in tree root system measuring and of course the following data processing methods of extracting coarse root volume, orientations, cross sectional area and other parameters are lacking. In addition, in chapter 4, we find that the cross sectional area this parameter, and architecture analysis of whole tree root systems are hot spot in tree root studies. The above ground leaf-off branches and single tree roots also seem to have similarities. Thus, the above ground approaches (laser scan measuring and following reconstruction methods) could give some hints and clues for measuring and modelling tree root system parameters of cross sectional area, woody volume, branching location and pattern, etc. We could say, in regards of existing relatively rich reconstruction methods and similar wood volume and structure, the aboveground approaches (laser scan measuring and following reconstruction methods) could be applied in tree root system parameters measuring and following data reconstruction.

5.3 Applying above-ground accurate data in tree root system assuming and estimating

In the previous section 5.2, the five researches all applied laser scanning after excavation. The professional excavation of tree roots is not easy and needs time, labor, specific device (e.g. air spade) and money. If the research objectives don't have requirements in very high accuracy, one could think about using accurate above ground tree parameters to assume and estimate tree root system parameters. Is it possible ?

5.3.1 Arboriculture view and rules of thumb about root system spread estimation

From literature in chapter 3 and 4, there are some articles discussing about the relationships between above ground tree part parameters and below ground tree root systems parameters.

Ghani et al. (2008) summed that arborists often use above-ground tree features to specify the dimensions within which root systems should not be damaged and simple calculations involving branch spread, trunk diameter, and tree height are commonly used. They seem to support the calculation by trunk diameter more than the other two above ground tree parameters due to they only gave some examples of calculation of this parameter. They gave the instances as first two lines in below Table 5.1. :

Table 5.1. Calculating tree root horizontal radius using trunk diameter
(Sources: Ghani et al., 2008; Day et al., 2010)

Description	Reference	Summary in numbers
Suggest a minimum distance for trenching along one side of the tree of 0.15 m for each 0.025 m diameter at breast height (DBH)	British Standard Institute (1989); Watson (1990);	Root system dimension (volume) horizontal radius least about 0.15 m × (DBH/0.025 m) = 6 × DBH from the trunk
Recommend 0.30 m for each 0.025 m DBH	American Society of Consulting Arborists (1989); Miller and Neely (1993); Harris et al. (2004);	Root system dimension (volume) horizontal radius about 0.30 m × (DBH/0.025 m) = 12 × DBH from the trunk
Suggest suitable tree protection zones have a ratio anywhere from 6:1 (radius of TPZ:trunk diameter) for young or tolerant trees, to 18:1 for old trees of sensitive species (note these ratios are unit-less)	Harris et al. (2004)	Radius of Tree protection zones (unit-less) about 6 × trunk diameter (young tree or tolerant trees); 18 × trunk diameter (old trees of sensitive species)
Average ratio of predicted tree	Day et al. (2010)	Tree root system radius about 38×

root system radius to trunk diameter is 38:1 (0-20 cm trunk diameter range)		trunk diameter (when trunk diameter <= 20 cm)

Day et al. (2010) also reviewed related articles and supported the view trunk diameter can provide a reasonable estimate of tree root spread. They stated trunk diameter is often used to estimate tree root spread; municipal ordinances frequently specify this method for determining tree protection zones (TPZs) and ensuring adequate soil resources for preserved trees (Day et al., 2010). They gave examples (in Table 5.1.) as well. More importantly, they employed nonlinear regression to investigate the relationship between trunk diameter and maximum root spread using available published data (Day et al., 2010). A much stronger relationship (R^2 = 0.89) was found when relating root spread to trunk diameter rather than tree height (Day et al., 2010). They explained the regression as analysis of the linear portion of the regression (0-20 cm trunk diameter range) decided the average ratio of predicted tree root system radius to trunk diameter is 38:1 which means on young trees, root system radius may increase by 38 cm for every cm of trunk diameter (Day et al., 2010). However, on older trees, this relationship changes, and root extent increases very slowly relative to trunk diameter (Day et al., 2010).

It seems that from literature trunk diameter or DBH is reasonable predictor of tree root spread meanwhile the exact number of ratio is differently in literature what I read.

For canopy diameter this parameter, Day et al. (2010) also summed that the relationship between canopy and roots is highly species dependent (Tubbs, 1977; Gilman, 1988) and they pointed out (Gilman, 1988) did fully excavation while (Tubbs, 1977) seems did not mention this point. Root system diameter averaged 2.9 times the diameter of the canopy, but varied from 1.68 times the canopy for *Fraxinus pennsylvanica* (green ash) to 3.77 for *Magnolia grandiflora* (Southern magnolia) in (Gilman, 1988). In (Tubbs, 1977), *Acer saccharum* (sugar maple) mean root spread (not the maximum) was found to equal canopy spread (Day et al., 2010). In addition to species variation, Day et al. (2010) indicated root spread may not be symmetrically situated beneath the canopy from (Tubbs, 1977; Di Iorio et al., 2005) and the researches all used young trees (diameter < 18 cm). Thus canopy spread is not likely to be a successful predictor of root spread unless a relationship is established for a particular species and the relationship may change for old trees (Day et al., 2010).

Jim (2003) held a different view about the relationship from some literature in 1990s: most tree roots can spread up to three times the diameter of the tree crown. Due to there are no detail proof about the exact "three times" number in Jim (2003), I think the view from Day et al. (2010) is relatively reliable.

Canopy diameter is not that strong predictor of tree root system spread and there are conflict about the relationship between canopy diameter and root system diameter. More investigation need to be done in studying relationship between canopy diameter and tree root system spread of specific tree species and different ages.

Tree height parameter also seems not reliable from Day et al. (2010) who did regression analysis to available published data and found no significant relationship.

Some limits need to be considered when we use above estimations. The above 3 tree root system spread predictors in literature were described from arboriculture view. These arboriculture guidelines have been developed based on observations of trees and site characteristics after failure occurred and lack sound experimental procedures (Ghani et al., 2008). Estimates of root spread (many rules of thumb) also generally assume there are few physical impediments to root extent while this is rarely the case in very urbanized environment (Day et al., 2010). Besides, Day et al. (2010) indicated that individual trees perhaps considerably vary from the estimate; root spread may be irregular and not uniformly distributed around the trunk, especially when trees are leaning or located on a slope; and physical constraints, e.g. confined urban planting pits, or other structures may limit root growth in certain dimensions.

Besides, according to what I found and read, there seems few information about the relationship (symmetrical or not) between above ground tree shape (or volume shape) and below ground root system shape. Only Day et al. (2010) summed it is clearly recognized that root distribution may not correspond to canopy distribution. However, due to time and labor limitation, I only searched limited literature, and there are certainly some researches studying about root system shape which could be in specific root simulation models and fractal analysis of tree root system.

Hence, we could say there are some relationships between above ground tree parameters and below ground tree root system parameters from literature I found, which mainly from from arboriculture view and rules of thumb. Trunk diameter or DBH is reasonable predictor of tree root spread meanwhile the exact number of ratio is differently (6:1 to 38:1) in literature what I read. Canopy diameter is not that strong predictor of tree root system spread and there are conflict about the relationship between canopy diameter and root system diameter. Thus when we have accurate laser scan measurements of above ground tree parameters like DBH and canopy diameter, it is possible to estimate the tree root system spread.

5.3.2 Allometry view about the root volume estimation

In (Tobin et al., 2007), there are some simple allometry equations and figures showing relationships of root system biomass and DBH. Tobin et al. (2007) stated relatively simple allometric equations could be used as integrals of more complex whole-tree, ecosystem or architectural models (modelling of root architecture section). Allometric models are species specific but other parameters e.g. soil type, geographic location, climate, site quality and stand stocking must also be considered (Tobin et al., 2007).

Obviously, allometry studies offer another view to describe relationship between above ground tree parameters and below ground root parameters which could be used to model tree root architecture with DBH.

Allometry is all about studying the relative sizes of plant parts (Siccama, 1998). Allometry studies often establish some equations about biomass and DBH, as we could find in (Tobin et al., 2007). Root Biomass is the weight of root system or root sections, which could be calculated by root volume multiply wood or root density (as this calculation used in Teobaldelli et al., 2007). The allometry equations showed quantitative relationships between root biomass and DBH. Thus one maybe uses DBH (the current study measuring data) combining specific allometry equations of some tree species (from previous study) to get the tree root system biomass (the current study new tree), then divide new tree root biomass by wood density or root density (from previous study), and get the result root volume of current study new tree. This is just my thoughts when I read the allometry equation, which needs further study and confirmation.

In (Mugasha et al., 2013), belowground biomass models were developed from 80 sample trees. They also present basic statistics on the root-shoot ratio which was calculated by below-ground root biomass divided by above-ground tree part biomass. They found the root-shoot-ratio was significantly different between DBH classes ($p < 0.001$) (Mugasha et al., 2013). This means there are quantitative relationship between root-shoot ratio and DBH. Pretzsch et al. (2012) also analysed and modelled the coarse root–shoot dynamics of *Pinus radiata* tree in South Africa by methods of allometric research and they stated the allometric equation offers an appropriate approach to describe the size development of a plant and the relationship of one plant dimension to another as, for example, root versus shoot diameter. (Bolte et al., 2004) did another study in which coarse roots of 42 spruce and 27 beech trees were sampled by excavating the entire root system and they built a linear model with logarithmic transformation of the variables to describe the relationship between the coarse root biomass (CRB, dry weight) and the corresponding tree diameter at breast height (DBH). They got the coefficients of determination (R^2) attained values between 0.92 for spruce and 0.94 for beech (Bolte et al., 2004).

The three articles all proved that in allometry study, there are quantitative relationships between tree root system biomass and DBH for different species of trees. How much this could contribute to estimating or calculating tree root system volume, and how to use these relationships correctly, need further work and confirmation.

5.4 Conclusion

The commonly used above ground technique laser scanning can be applied to measure and model the tree root systems. Five researches I found already applied laser scanning in measuring and modelling tree root systems. Excellent in depicture big root systems in an accurate way, laser scanning could be applied for further coarse-root studies (Wagner et al., 2010).

No matter from accuracy level this point of view, or in regards of existing relatively rich point clouds reconstruction methods and similar wood volume and structure, the above-ground approaches (tree stem and canopy laser scan measuring and following data reconstruction methods) could be applied in tree root system parameters measuring and following data reconstruction after excavating the tree root systems.

Besides, there are some relationships between above ground tree parameters and below ground tree root system parameters from literature I found, which mainly from arboriculture view and rules of thumb. Trunk diameter or DBH is reasonable predictor of tree root spread meanwhile the exact number of ratio is differently (6:1 to 38:1) in literature what I read. Canopy diameter is not that strong predictor of tree root system spread and there are conflicts about the relationship between canopy diameter and root system diameter. Thus when we have accurate laser scan measurements of above ground tree parameters like DBH and canopy diameter, it is possible to estimate the tree root system spread. Especially when one could not do the excavation, these estimation based on above ground accurate measurements could be important.

In allometry study, there are quantitative relationships between tree root system biomass and DBH for different species of trees. It seems possible to use DBH, specific tree specie allometry equations, and wood density number from previous study to work out the tree root system volume. Thus when we have accurate laser scan measurements of above ground tree parameter DBH, the root volume has the possibility to be estimated in terms of allometry study.

In sum, the often used above ground technique laser scanning could be applied to measure and model the parameters of the tree root system after excavation and has high accuracy level (less than 1 cm). The aboveground approaches tree stem, canopy, branches laser scan measuring and following data reconstruction methods also could be applied in measuring and modelling tree roots after excavation. But due to root structure complexity, the accuracy level and modelling result maybe not as good as applying in above tree part. For different research objectives of coarse root study, it is acceptable and still required. The above ground laser scanned tree DBH, and canopy diameter data could also be applied in estimating tree root system spread and volume (before excavation) from arboriculture and allometry. These estimation are less accurate and need carefully used. All these could be conducted in tree root system study in urban settings, because quantitative analysis of urban tree root system architecture including measuring and modelling are quite limited and need more investigation.

Chapter 6 Recommendations, discussion, and conclusions

In this chapter 6, recommendations about possible future research directions are explained in 6.1 section. Following 6.2 puts forward some discussion points when conducting the review. 6.3 gives conclusions for whole study.

6.1 Recommendations

For urban tree root system study, from chapter 4 we know the literature number is small, and according to articles I found, the quantitative measuring and analysis are in developing and quite few. The rigorous investigation of urban tree root system architecture I found so far is (Ghani et al., 2008) this one article. The modelling work of whole urban tree root system architecture is also quite few to almost none in the literature I found. Thus, there are several possible future research directions of applying 3D geo-information methods and techniques in measuring and modelling urban tree root system parameters.

6.1.1 Robust 3D measurements of urban tree root system architecture

If fully excavation of the tree root system is possible, or occasionally a storm uproots trees, laser scan could be applied in creating robust (could be used many times for different level of research objectives) 3D measurements of the exposed urban tree root systems. According to (Ghani et al., 2008; Danjon & Reubens, 2008), firstly measuring threshold of root diameter could be set based on research objectives. In (Ghani et al., 2008), they measured any woody root with a diameter >10 mm. The resolution of laser scan device also needs to take into account. If possible, the measuring work also needs suggestion from experts because the complex structure like small sinker roots, small fine roots and overlapping of several roots could be problems especially when trees older than 20 year-old. Then laser scanning could be done in different positions due to shadowing effects. Partly scanning of urban tree root systems is also lacking and required. Clear measuring procedure, data recording, and accuracy control and assessment part could also be achieved. In addition, there are also demands for robust 3D measurements of tree root system architecture in forest or other different sites.

6.1.2 Testing and improving above ground laser data reconstruction methods for tree roots

After laser scanning, the tree root system data reconstruction work would be similar but maybe more difficult than data reconstruction work of above ground part of leaf-off tree (Wagner et al., 2011). However, there are relatively rich laser data reconstruction methods and modelling methods of above ground tree structure (tree stem, tree branches, cross section area, wood volume, branch pattern, etc.) in literature, and the large woody roots (coarse root) are similar in shape and volume with branches of above ground part. Thus the quantitative structure model of branches (Raumonen et al., 2011, 2013; Lau Sarmiento, 2014), probabilistic 3D branch reconstruction (Binney & Sukhatme, 2009), voxel-based processing of wood volume (Gorte & Pfeifer, 2004), cylinder fitting of cross sections (Thies et al., 2004), and circle fitting of stem (Bienert et al., 2007; Maas et al., 2008) would be helpful in reconstructing large coarse root from laser scanning data. Exploring or testing, and then modifying or improving these reconstruction methods for tree roots in urban settings or other sites could be one future direction.

6.1.3 Quantitive analysis of 3D tree root system architecture

In (Ghani et al., 2008), they manually using callipers and a compass measured the shape, size and orientation of all structural roots and then did statistical analysis. While in (Chung & Berry, 2012), they applied T-LiDAR and then did two ways of analysis of 3D point clouds data of tree root systems: virtual tomographic slicing, creating hierarchical nested datasets, and root biomass models; in another way they did vectorization of "polylines", made topological datasets and vector models. The 3D data obviously saved time and labor and it is relatively easy to do analysis to 3D data. During the analysis of 3D tree root system architecture in (Chung & Berry, 2012), they set a methodology of applying R and ArcGIS the software as well as related geo-information to analyse the geometry and topology of tree root systems. Applying the quantitive analysis and methodology of (Chung & Berry, 2012) or similar quantitive analysis and methods to study tree root systems in various settings like urban or forest could be one future direction.

6.1.4 Urban tree root system models in different detail levels

Centre of Geo-information Wageningen (CGI) is building 3D tree models based on Level Of Tree-detail (LOT) theory and it has four levels, ranging from zero to three (Figure 6.1.).

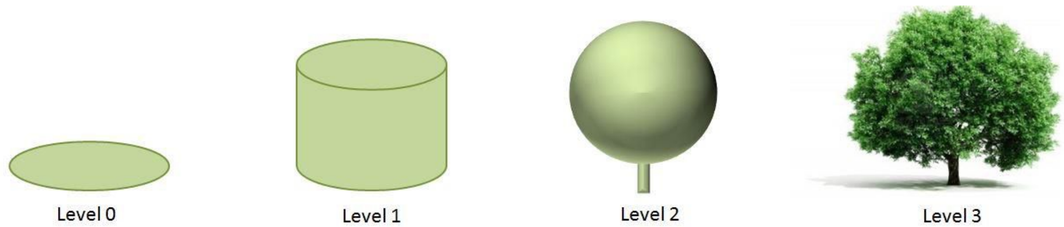


Figure 6.1. Example of Level Of Tree-detail (Source: Chen, 2013)

Similarly, this LOT theory could be used in building models of urban tree root systems.

One point needs special attention that modelling tree root system is more difficult than modelling above ground part (Danjon & Reubens, 2008; Wagner et al., 2011). Roots have a more irregular, opportunistic growth than aboveground part of plants (Danjon & Reubens, 2008). The tree root system architecture and distribution is apparently at least as much dependent on the environment as on the tree's genetic makeup (Reubens, 2010; Tobin et al., 2007; Stokes et al., 2009). Hence, it is better to focus on species-related phenotypes, expressed in response to certain environmental conditions (Stearns, 1989;Reubens, 2010).

Thus, the different detail-level urban tree root system models need consider different tree species, ages and environment conditions.

The one possible very simple (level 1) represent of tree root system could be "root envelope" in (Jim, 2003). Researchers also use "radiated" these kind of words for describing root system shape. Other simple basic shapes of tree root systems need more investigation in literature, based on different tree species, age, and site conditions. For level 2, I did not find clear volumetric description of tree root system in literature I selected, and "root ball" or "root wad" was used for describing root and soil matrix (Corcoran et al., 2011). Further work would be directly searching volumetric description (level 2) of root systems of different tree species in literature. The further work would also contain investigating and confirming another two ways to estimate the volume and root system spread: the arboriculture view (rules of thumb) could be used combining accurate aboveground tree parameters like DBH, canopy diameter to estimate the tree root system spread; specific tree specie allometry equations seems possible to be combined with accurate DBH, and wood density number from previous study to work out the tree root system volume. The rules of thumb and allometry equations are highly different in different tree species and ages. The tree root system depth in literature I found is often 1 m (Jim, 2003; Chung & Berry, 2012). However, root depth and extent can be severely limited and highly irregular in urban settings (Day et al., 2010) and Day et al. found root depths greater than 2 m have been documented for several urban species.

The more detailed level (level 3) model of tree root system could be built on several common distribution patterns of large coarse root system of young trees in flat ground firstly and later further enrich the distribution patterns from different species and ages after wide literature investigation or excavation measurements. Even higher detailed level (level 4) could be achieved by containing almost all coarse root (diameter > 5 mm) from high accuracy laser scanning data (like data in Wagner et al., 2011). The common distribution patterns of large coarse root system of young trees (level 3) could use summary from (Chung & Berry, 2012; Day et al., 2010). Chung and Berry (2012) summed that tree roots in many soil conditions grow horizontally more than vertically and the tree root architecture can be combinations of 3 or 4 major woody systems, i.e. structural roots, horizontal roots, tap root (not always have) and sinker roots. Day et al. (2010) stated typically, a tree has 5-15 (or more) primary structural roots that grow from the root collar and descend obliquely into the soil before becoming horizontal within a short distance of the trunk, although the whole pattern of root development can vary considerably. Considering a general agreement on definitions of roots categories is lacking (Tobin et al., 2007), more literature investigation and confirmation from experts are necessary.

The level 3 tree root system model could also be created considering root diameter classes, circular sectors and compartments, which were suggested for analysis of coarse root systems in (Danjon & Reubens, 2008).

Besides, the environmental conditions could contain soil condition, rainfall, temperature, wind, topography, ground water level, etc. Different environmental conditions could really cause the irregular structure and distribution of tree root system (Danjon & Reubens, 2008;

Tobin et al., 2007; Gartner & Denier, 2006). Due to limited time, in this study I did not do much investigation in literature about tree root system growth models. One possible future research direction could be growth models for urban tree root systems, which consider both the genetic control (species, inside factor) and the environment conditions (outside factors). These factors could have a deciding index and the environment conditions could set in different urbanized levels.

The common urban tree species also need investigation which could be based on literature or cooperating with related local municipal department (from their database). One article (Östberg, 2013) may be helpful which showed inventories about urban tree roots and their conflicts with pipes in several Sweden cities, as well as most common urban tree species in five Nordic cities.

The software AMAPmod could be very helpful in modelling tree structure including above ground part and root systems from literature I read. Now AMAPmod is one part of the OpenAlea open source project (Pradal et al., 2008; http://openalea.gforge.inria.fr).

6.1.5 Cooperation from different research fields

The final point for future work is cooperation between researchers from different fields. The tree root system study calls for quantitative analysis while researchers from geo-information and remote sensing are interested in applying advanced 3D techniques in tree root measurements. Besides, for people who did not study root systems before, the terminology in root studies is confusing. From researches which successfully applied laser scan in studying tree root systems (Chung & Berry, 2012; Wagner et al., 2011), we also could find they have a research group containing experts from tree root system study and researchers from technique field (remote sensing, computer science, etc).

6.2 Discussion

6.2.1 Search-words

In the literature search stage in chapter 3, the literature result numbers of 3D geo-information and urban tree study is quite less. In Web of Science, (urban tree AND (3D Remote sensing or 3D GIS) this search word leads to a 20 result records. Except the fact researches of urban sites are limited, there could be some reasons for the small literature search result. The search-word item like "urban tree" maybe is not used in titles, key words and abstracts of the aiming articles. Authors maybe think this site description not-that-important. Or researches maybe are conducted for one specific tree specie. Or authors maybe used similar word like "city" or "town". Due to limited time and labor, I did not set search-word including "city" and "town". This limitation could be improved by group work and well preparation in defining search-word.

The search item "3D Remote sensing or 3D GIS" also contains some uncertainty contributing to limited search result number. The researchers maybe used one 3D remote sensing technique like radar, and they did not put the "3D remote sensing" in title, key words, and abstract. Search engine in literature database also maybe could not recognise radar is one of 3D remote sensing technique. Thus this article maybe did not present in my search result records. Besides, there are many remote sensing techniques and search engine in literature database could not identify all the 3D geo-information techniques.

Better literature search result could be got from deeply thinking about 3D geo-information, and deciding to focus on one aspect of 3D geo-information. When defining search-word, putting all kinds of 3D geo-information technique in search word and connect them with "OR" maybe can increase result number. Another possible way is using citations in one aiming article and checking the cited articles, which I also used to some extent in chapter 3 and 4. Group work also can increase resulting literature number because one person can search for one specific 3D geo-information technique and people can think of and use more synonyms in search-word.

6.2.2 Searching and selecting process

Due to limited time, I read the title, key words, and abstract of articles quickly. It is possible that I missed some literature which is what I want. In the methodology part of this study, the selecting criteria has not been clearly defined and consequently, my criteria of target literature maybe changed a little bit in selecting process. This may lead to the situation that I maybe missed some articles applying other 3D geo-information techniques like 3D ultrasonic sensors and X-ray CT imaging in urban tree (above ground) structure study in chapter 3. Improvements could be realised from setting clear selecting criteria about data acquisition method and processing method in articles.

The searching strategies for this time limited review based on my own experience is too ambitious. It is maybe better for group work. I have better user experience in the literature database Web of Science due to its redefining tools and citation report tools. Google Scholar gave large number of articles while lacking more redefining functions. Google the search engine performs well in search files of latest research progress (presentation documents, conference proceedings, etc.).

6.2.3 Analysing and synthesising

When conducting reading the literature of root system study, it was easily that too much time was spent for reading and understanding concepts in the literature. It seems in analysing and synthesising stage, criteria also need to be set in methodology for easier reporting and efficient time control.

6.2.4 The uncertainty in researches of tree root system

Firstly, the terminology are various and confusing. As in 4.2, definition of different kinds of root did not reach in agreement. Root structure concepts and terms used in one article may different from another article, and earlier literature (about before 2006) rarely mention definition of terms in numbers. Earlier researchers used qualitative analysis and description. Thus difficulties occurred when I read the articles, compared the results, and tried to sum. Recently, definition of terms (parameters) in numbers were applied in tree root system study, like (Ghani et al., 2008).

Secondly in literature root system depth and spread the two key parameter of tree root system could contain some uncertainty. In (Cermak et al., 2000; Stokes et al., 2002) researchers just excavated some part of the whole root system and recorded the max depth. Day et al. (2010) stated the root system depth and spread uncertainty was from two reasons: the fact it is generally impossible to follow every tree root to its tip when excavating roots; and the methodologically inconsistent in root researches (fully excavation, circle sector excavation, etc.). Thus when we use the root system depth and spread, we need pay more attention to the uncertainty. Researchers may need to explain their definition of the root system depth and spread in their article.

6.3 Conclusions

Based on the literature I selected and studied, we could make some conclusions:

The laser scanning (LiDAR) is the efficient and accurate 3D geo-information technique for measuring above ground urban tree structure. Airborne laser scanning can really support urban trees inventory and relatively large number of tree investigation and it also has advantages in measuring urban tree height, and tree location. Mobile laser scanning is also strongly helpful and efficient in detecting and modeling tree in urban area when there are more trees. Terrestrial LiDAR has features of high accuracy, direct, active and has been popular applied in detecting and modeling detailed structure of trees in forest environment. Meanwhile there are quite few studies about extracting these parameters from T-LiDAR data in urban area. There are also circle fitting, cylinder fitting, voxel-based processing, probabilistic 3D tree branch reconstruction, quantitative structure model, and so on data reconstruction methods in literature.

Some basic tree root function, category (coarse root and fine root), and properties (details in section 4.2) were known in research of tree root system. We could sum some current study progress in urban tree root system research based on literature I found: quantitive analysis of 3D tree root system architecture at urban sites is missing; manually measuring and some statistical analysis in two dimensions approaches have been reported; no research on recording coordinates of tree root systems; no agreements on standard measuring procedure, data recording, accuracy control and assessment; I found none studies did model urban tree root systems. Parameters of tree root systems could be grouped in root system level, individual root level or root segment level while they can also be grouped in other means like size and branching property, or density characteristic (Reubens, 2010). Detailed parameters summary is showed in Table 4.2. and Table 4.3. Quantitative measurement and robust measurement method are called for tree root study.

The often used above ground technique laser scanning has been applied to measure and model the parameters of the tree root system after excavation and has high accuracy level (less than 1 cm). The aboveground approaches tree stem, canopy, branches laser scan measuring and following data reconstruction methods also seems possible to be applied in measuring and modelling tree roots after excavation. For different research objectives of coarse root study, it is acceptable and still required. The above ground laser scanned tree DBH, and canopy diameter data could also be applied in estimating tree root system spread and volume according to rules of thumb and maybe some specie allometry equations.

If fully excavation of the tree root system is possible, or occasionally a storm uproots trees, laser scan could be applied in creating robust (could be used many times for different level of research objectives) 3D measurements of the exposed urban tree root systems. Clear measuring procedure, data recording, and accuracy control and assessment part could also be achieved. Exploring or testing, and then modifying or improving above ground stem, branches, cross section area, wood volume, and branch pattern reconstruction methods for tree roots in urban settings or other sites could be one future direction. Applying quantitive analysis of 3D tree root system architecture and methodology like (Chung & Berry, 2012) in various settings like urban or forest could be another one future direction. Creating different detail-level urban tree root system models considering tree species, ages, environment conditions, and estimation of root system parameters from accurate above ground tree parameters, rules of thumb and some allometry equations of specific tree species could be one future research path. Cooperation between researchers from root system study and technique fields is necessary.

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