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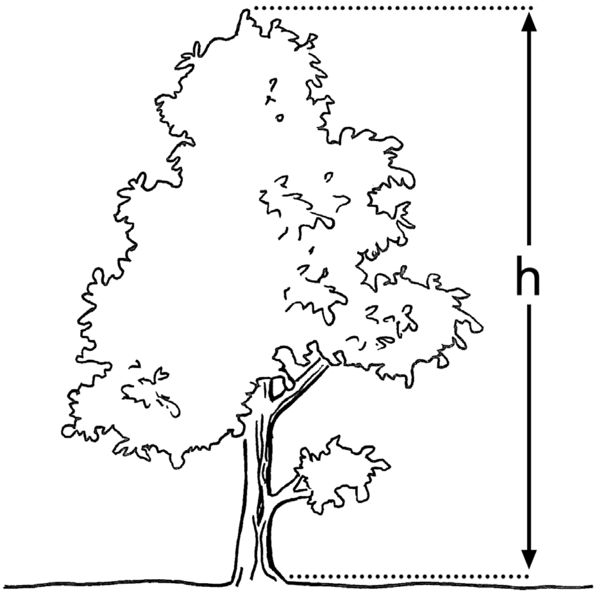
- Methodological development and new applications

Johan Östberg



Tree Inventories in the Urban Environment

Methodological Development and New Applications

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Tree Inventories in the Urban Environment. Methodological Development and New Applications

Abstract

Urban tree inventories are being employed to an increasing extent by a diverse group of users for a wide range of applications. This has resulted in large numbers of different parameters being recorded and a variety of methods being used by researchers and practitioners. Despite this, the potential of comparative studies has not been fully realised and there is a lack of understanding on how to link research objectives with choice of parameters and methods. This thesis therefore sought to support the development of a common framework that can facilitate synergies between different groups that use and/or collect data on individual urban trees.

The common framework was developed through comparative analyses linking objectives, choice of tree inventory methods, and parameters to collect at single tree level. Based on this a typology of contemporary urban tree inventory methods for data collection at single tree level is presented followed by a standard list of tree inventory parameters to include in urban tree inventories developed in a Delphi study with participation of academics, arborists, and city officials. The Delphi study revealed possible synergy effects between these stakeholder groups. Examination of the use of existing tree inventory databases resulted in a list of species that have caused root intrusion and a species distribution analysis of 10 major cities in the Nordic countries. These results can be used to make tree inventories comparable and to show how existing databases can be used to gain new knowledge, both for researchers and practitioners.

Keywords: Root intrusion, species distribution, Delphi study, tree inventory parameters, typology, native, exotic, street trees, urban forest, practitioners, urban forestry.

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To my friends,
without you I would be lost.

Contents

List of Publications

This thesis is based on the work contained in the following papers, which are referred to by their Roman numerals in the text:

I Nielsen, A., Östberg, J. & Delshammar, T. 201X. Urban tree inventory methods for collection of data at single tree level – a critical review and evaluation. (Submitted).

II Östberg, J., Delshammar, T., Wiström, B. & Nielsen, A. 2013. Grading of parameters for urban tree inventories by city officials, arborists and academics using the Delphi method. *Environmental Management* 51(3): 694-708.

III Sjöman, H., Östberg, J. & Bühler, O. 2012. Diversity and distribution of the urban tree population in ten major Nordic cities. *Urban Forestry & Urban Greening* 11(1): 31-39.

IV Östberg, J., Martinsson, M., Stål, Ö. & Fransson, A.M. 2012. Risk of root intrusion by tree and shrub species into sewer pipes in Swedish urban areas. *Urban Forestry & Urban Greening* 11(1): 65-71.

Papers II-IV are reproduced with the permission of the publishers.

The contribution of Johan Östberg to the papers included in this thesis was as follows:

I Carried out the literature search and, together with the other authors, analysed the collected data. Acted as co-writer of the article.

II Designed and carried out the survey and wrote the article with feedback and co-writing from the other authors.

III Together with the other authors, planned the research project and wrote the article. Was responsible for the data collection and, together with the other authors, analysed the collected data and acted as co-writer of the article.

IV Collected the data and together with the other authors analysed and structured the data. Wrote the article with feedback and co-writing from the other authors.

1 Introduction

As part of urban forestry, *i.e.* the planning and management of all woody and associated vegetation in and around urban environments (Konijnendijk *et al.*, 2006), tree inventories have been used for a long time as an important management tool (Tate, 1985; Brickmore & Hall, 1983; Bassett, 1976). Tree inventories are one of many approaches used by urban foresters and contain information gathered on individual trees or groups of trees during site visits or by other methods. Urban tree inventories are hence a method of gathering data, and the data are used by cities, researchers as well as other stakeholders within the field of urban forestry. According to Konijnendijk *et al.* (2006), although the scope of urban forestry includes all woody and associated vegetation in urban areas, ranging from small communities in rural settings to metropolitan areas, in the past it has traditionally focused on street trees.

Urban tree inventories are used for a wide range of purposes, *e.g.* mapping storm-damaged trees and determining the species and tree sizes most affected (Jim & Liu, 1997), risk management (Lonsdale, 1999; Mattheck & Breloer, 1994), charting the diversity of urban trees (Sjöman *et al.*, 2012a; Raupp *et al.*, 2006), modelling local climate (Nowak *et al.*, 2006; Dimoudi & Nikolopoulou, 2003; Nowak *et al.*, 2001a; Yokohari *et al.*, 2001) and reducing urban heat island effects (King & Davis, 2007). Urban tree inventories are also used to assist with choosing species able to capture particles that are a potential hazard to human health (Sæbø *et al.*, 2012; Gallagher *et al.*, 2011; McPherson *et al.*, 1997; Sæbø & Mortensen, 1996), for finding key places where trees contribute most in reducing energy costs, air pollution and decreasing runoff from stormwater (McPherson *et al.*, 1997), for calculating the overall economic benefits of urban trees (i-Tree, 2012a; Maco & McPherson, 2003) and for assessing the economic value of individual trees (Randrup, 2005; Cullen, 2002; CTLA, 2000).

Recent decades have seen an increase in the work conducted on urban forestry. According to Konijnendijk *et al.* (2006), this increase has arisen from the need to combat pests and diseases on urban trees in North America, and to search for more integrative approaches in Europe. As an example, the Swedish city of Malmö has cut down 45 000 elm trees since 1984, which is about 69% of the total tree population in street and park environments managed by the city's streets and parks department today (Arne Mattsson, Malmö City, pers. comm. 2013). Another reason for the increase in urban tree inventories is the digitalisation of tree inventory data (Bickmore & Hall, 1983), which has made it possible to process large amounts of data and also to get accurate positions on urban trees with the help of *e.g.* Global Positioning System (GPS). New uses of urban tree inventories have also been developed and became more widely used during the late 1990s (Gerhold & Frank, 2002), for example the use of species diversity and age structures (Jim, 2005; Adkins *et al.*, 1997), which is an important part of the maintenance and planning of the urban tree stock (Adkins *et al.*, 1997).

Tree inventories are an integral part of the urban forestry field, through *e.g.* their ability to provide an overview of the urban tree population for management purposes (Cheng *et al.*, 2000), comparisons of species distribution in different areas (Straigyte *et al.*, 2009) and hazard tree monitoring and management (Maruthaveeran & Yaman, 2010). The field of urban forestry emerged in North America during the 1960s and 1970s (Konijnendijk *et al.*, 2005), and has since seen a large increase in publications (Figure 1). Urban forestry is thus a young research field engaged in an on-going process driven by the elementary desire to "*obtain empirical regularities and to find out proper concepts and classifications by means of which those regularities can be formulated*" (Steinle, 1997, p. 70). The process described by Steinle (1997) fits well when looking back at the development of the research field of urban forestry, and more specifically the area of urban tree inventories. Here the process comprises first trying to facilitate easier mapping and inventories of trees (McBride & Nowak, 1989), which are then used to undertake more in-depth analysis (Sreetheran *et al.*, 2011), subsequently making it possible to carry out advanced calculations on *e.g.* uptake of VOC gases (Karlik & Winer, 2001), uptake of stormwater (Yang *et al.*, 2011), and the economic contribution of urban forest (Nowak *et al.*, 2008). These calculations would not have been possible if the basic resource data had not already been available.

The increased use of tree inventories has also led to an increase in both the methods and parameters used for urban tree inventories, which in turn has led to increased difficulty regarding comparability between the methods and parameters. In order to take the next step on this ladder of research development there is a need for standardisation; otherwise only simple comparisons can be conducted rather than in-depth analysis.

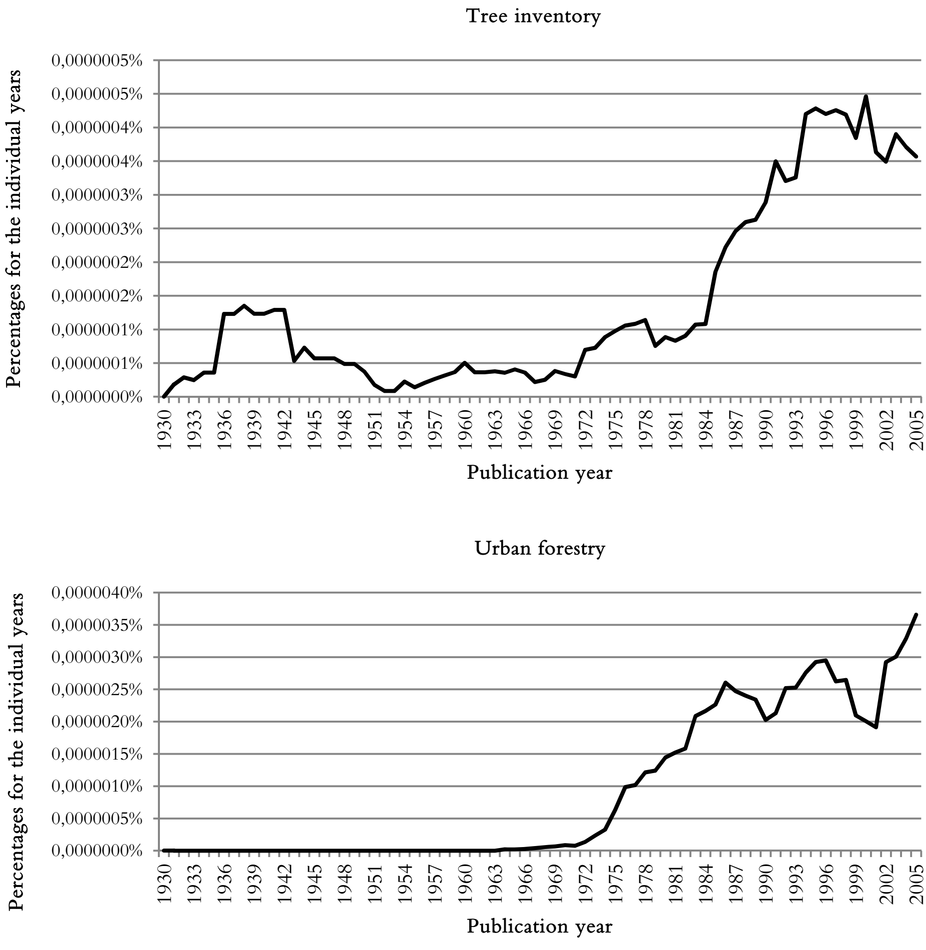

Figure 1. The development of urban forestry and tree inventories as seen in an *ngram* graph, where the occurrences of the terms '*tree inventory*' (above) and '*urban forestry*' (below) were calculated, as percentages for the individual years, from the 4% of all the world's books that have been digitalised by Google (Michel *et al.*, 2011).

With better standardisation, *i.e.* detailed tree inventory systems and common definitions of how to record inventory parameters, urban tree planners, researchers and arborists will obtain more, and better, data to manage urban trees and important synergy effects can also be activated. Today urban trees and forests are facing threats from pests and diseases, while also being pressured by a changing climate, which may compromise their resilience, future development and functions. For example, the Scandinavian region and other areas of northern Europe are currently experiencing serious damage to *e.g. Aesculus, Fraxinus* and *Ulmus* caused by different newly emerging diseases (described by *e.g.* Tubby & Webber, 2010; Garrett *et al.*, 2006). These tree families have long been a dominant feature in urban areas of northern Europe (Sæbø *et al.*, 2005), so their disappearance can be critical. However, there are many other problems facing the urban tree population too, such as restrictive soil volume (Grabosky *et al.*, 2009; Grabosky & Bassuk, 1996), air pollution and wind (Sæbø *et al.*, 2003), soil pollution (Gallagher *et al.*, 2008a; Gallagher *et al.*, 2008b; Sæbø *et al.*, 2003), damage from constructions (Glaeser, 2010), de-icing salt (Cekstere *et al.*, 2008; Sæbø *et al.*, 2003), climate change (Moore, 2012), the urban heat island effect (Armson *et al.*, 2012), and conflicts with urban infrastructure (Dahle *et al.*, 2006)

James *et al.* (2009, p.71) define one of the major questions for future research as "*What are appropriate indicators and typologies for the comparative assessment, monitoring and prediction of the state and trends of urban green space and their ecosystem services across Europe?*'. One of the key ways of monitoring the urban tree stock, which is an important part of the urban green space, is to use tree inventories. Nowak *et al.* (2001a) state that more research is needed on how urban forest structure and health change over time, and how structure is linked to important forest benefits. Dwyer *et al.* (2002) conclude that urban tree inventories can increase understanding of how the urban tree stock changes over time and also improve the management of the resource and resulting benefits. According to Schipperijn *et al.* (2005), scientists and practitioners (*e.g.* arborists, city officials) can jointly improve the situation for urban trees by developing and using more integrated information systems. Urban tree inventories could greatly expand the contextual knowledge base on urban trees, which is currently unavailable in the literature, *e.g.* regarding how different tree species are developing in different cities (Sjöman & Nielsen, 2010). Tree inventories are also regarded as a necessity in urban forestry as a whole (Elmendorf *et al.*, 2003).

The question of which tree inventory parameters should be used in urban tree inventories is something that has gained little attention, except from recent international efforts to develop urban forestry standards (UNRI, 2010) and the development of the i-Tree software suite by the US Forest Service (i-Tree, 2012a; Cumming *et al.*, 2008; Simpson *et al.*, 2004). The work conducted within *e.g.* i-Tree has started to provide a baseline when it comes to tree inventory parameters that could be used by cities in the United States, but it does not describe satisfactorily how cities and other stakeholders engaged in urban tree inventories should navigate through the large quantity of tree inventory parameters available.

To encourage the maturation of the practice and research field of urban forestry, a framework with comparable methods and terminology would be beneficial. Through this stabilisation, future data collected would be comparable and it would be possible to *e.g.* monitor urban trees more accurately. This would allow cities to exchange experiences and use data from each other, creating a foundation for more fact-based decision making.

2 Objectives of the thesis

In response to a) the emerging demand for reliable tree data for research advancement and sustainable tree management and b) the diversity of contemporary urban tree inventory methods and applications, the overall aim of this thesis was to support the development of a common framework for urban tree inventories that can facilitate synergy between cities, researchers and other actors, irrespective of the focus of the individual inventory.

Derived from this, specific objectives were to:

- *Explore ways to qualify and standardise urban tree inventory methods.*
- *Demonstrate the possibilities in comparison of different city tree inventory databases, and in combining urban tree inventories with databases on other urban infrastructure.*

The work was guided by the following research questions:

- *What type of tree parameters can contemporary urban tree inventory methods collect and what does this mean for their use in research with different focus areas?*
- *How can urban tree inventory methods be further developed to minimise cost and maximise output?*
- *How can existing urban tree inventory data be combined with other data sources to generate new knowledge and insights?*

3 State of the art of urban tree inventories

This chapter provides an overview of tree inventories in urban areas, in particular their importance, development and use. This includes the problems that tree inventories face with the divided research field, the purpose of tree inventories, and methods and parameters used when conducting urban tree inventories.

3.1 Trends in the use of urban tree inventory data

The field of urban forestry and urban tree inventories has experienced a large increase in interest recently, as shown in the *ngram* graph in Figure 1. The amount of scientific publications concerning urban tree inventories has followed a similar trend, having increased substantially during recent years, with *e.g.* 68% of all publications having been published in the past 10 years (Figure 2).

There are many ways of describing different research projects and research fields, one being with a chain of research components that includes *basic research*, *strategic research*, *applied research* and *innovation* (Table 1 and Figure 3).

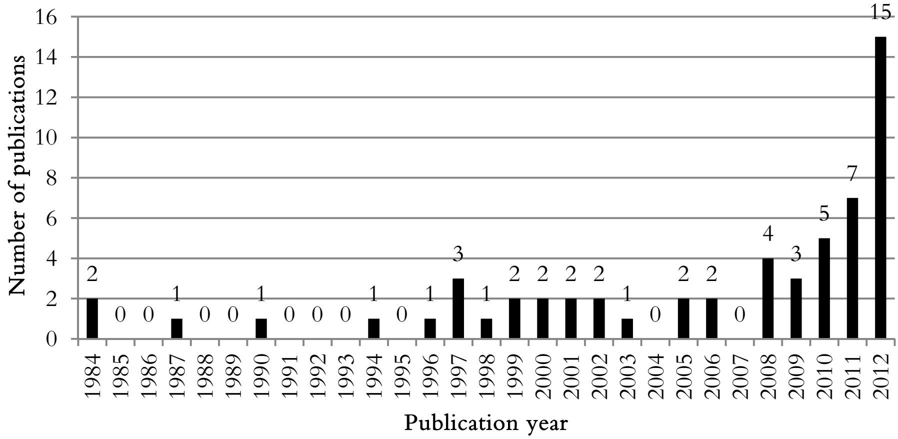

Figure 2. Number of scientific publications concerning urban tree inventories per publication year. The search terms *tree*; invent*; and urban** were considered among the categories 'Title, abstract, keywords' (Scopus) and 'Topic' (Web of Science). All publications had to meet the following requirements: 1) Published by 31 December 2012; 2) published in English; and 3) inventories conducted for single trees.

Table 1. Description of the different research components shown in Figure 3

Research component	Description
Basic research	*Experimental or theoretical work undertaken primarily to acquire new knowledge of the underlying foundations of phenomena and observable facts, without any particular application or use in view* (OECD, 1994, p. 7).
Strategic research	*Generally taken to mean research that a nation sees as a priority for the strategic development of its research base and ultimately its economy* (OECD, 1994, p. 7).
Applied research	*Original investigation undertaken in order to acquire new knowledge. It is, however, directed primarily towards a specific practical aim or objective* (OECD, 1994, p. 7).
Innovation	*Scientific and technological innovation may be considered as the transformation of an idea into a new or improved product introduced on the market, into a new or improved operational process used in industry and commerce, or into a new approach to a social service* (OECD, 1994, p. 4).

All these research components are of importance for a research field, but have different time frames and different certainties of application. The trend in urban forestry and urban tree inventories is towards more basic research after initial more applied research (Figure 3). One of the many examples of this is the problem of root intrusion into underground pipes. The first studies conducted in Scandinavia were rather simple and involved mapping the problem, which was intended to provide the industry with information on the extent of the problem (Stål, 1996). The information was also used to make recommendations to city planners and urban foresters, so that the problem could be reduced (Ridgers *et al.*, 2006). The Scandinavian research then developed into more in-depth studies, the results of which have changed some of the previous recommendations (Östberg, 2008). Although the problem of root intrusion still lies much within applied research, it has moved towards more strategic research by problematising the issue.

Konijnendijk *et al.* (2007) point out that generally speaking, universities have an obligation to carry out basic and strategic research. This can be compared with the more applied and sector-orientated research which is primarily done to acquire new knowledge with a specific application in view. The extension into experimental development activities is often in the hands of, and many times in close collaboration between, government research institutions and businesses. Regional governments also primarily take part in research with a specific application in view. Konijnendijk *et al.* (2007) concluded that it seems reasonable to expect that these differences in emphasis on basic understanding and certainty of application will lead to divergent scientific agendas across organisations and persons engaged in, or using, urban forest research. This divergence is a natural part of the difference between research and practice that does create some difficulties for urban forestry.

The same trend can be seen in the research concerning species distribution (Jansen *et al.*, 2006), urban ecosystem services (Hubacek & Kronenberg, 2013) and other areas related to urban forestry. In terms of species distribution, many articles have reported the species distributions of different areas, *e.g.* that of Shenyang, China (Ning *et al.*, 2008), Southern California (Lesser, 1996), Tokyo (Cheng *et al.*, 2000), an area in Utah (Adkins *et al.*, 1997), roadside trees in Maryland (Cumming *et al.*, 2001), street trees in Portland (Poracsky & Scott, 1999) and the Los Angeles Basin (Miller & Winer, 1984). With this information as a starting point, researchers were able to further improve the knowledge base with more basic research, such as on the amount of volatile organic compound (VOC) gases released by the urban tree population in different areas (Geron *et al.*, 1995). This is not basic research in the classical definition (Table 1), but shows a trend towards more strategic research.

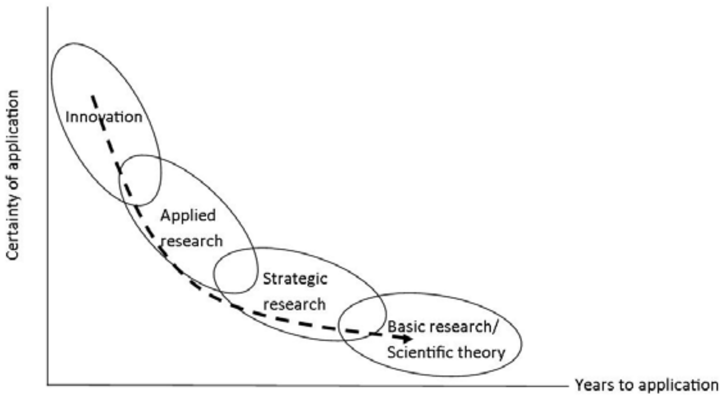

Figure 3. Differences in type of research and its certainty of application as a function of years to application. The arrow shows the development of urban forestry and urban tree inventories.

Tree inventories can be used for a large range of purposes, often for specific or general purposes that differ in their intended uses. When data collection has a specific purpose, the data are collected to serve this specific purpose. An example of such a specific purpose is hazard tree management (Terho & Hallaksela, 2004), where data are collected to identify and reduce the risk of specific hazard trees. One recent development in the area of hazard trees that is to a high degree reliant on urban tree inventories can be seen in Denmark, where several municipalities have begun to conduct tree inventories with the specific purpose of identifying hazard trees (Thomsen, 2012). Examples of general purposes for tree inventories are creating a model of air pollution (Diem & Comrie, 1998) and describing the urban forest of a city and discussing relevant management problems (Cheng *et al.*, 2000).

As mentioned, urban forestry as a young field of research and practice is constantly expanding the use of urban tree inventories. This expansion is being done jointly by researchers and practitioners and through it tree inventories are becoming more important, while at the same time losing their comparability.

The user groups researchers and practitioners differ in their use of urban tree inventories. The practitioners have for instance management issues on which they need data, which can be both specific and general, *e.g.* hazard tree management (Sreetheran *et al.*, 2011) as a specific issue, and species distribution (Lesser, 1996) as a more general question. The purpose of an inventory conducted by researchers can be *e.g.* finding new tree species to be planted in urban areas (Sjöman, 2012) as a specific purpose, and calculations on VOC gases (Drewitt *et al.*, 1998) as a more general purpose. Both researchers and practitioners are expanding the use of urban tree inventories for general and specific purposes.

This description of a diverse use of urban tree inventories where researchers and pratitioners, probably unknowingly, are diverging is rather categorical and does not provide a complete picture. However, it shows the general trend in development that, in a much simplified model, can be divided into: 1) knowledge building within research and 2) information to support decision making by practitioners. This does not mean, however, that researchers are only working with knowledge building and practitioners only with decision making. Both researchers and practitioners work with knowledge building, but the context often differs, from the local context for practitioners to researchers' desire for generalisations. Knowledge building is also a necessary and crucial part of decision making and is therefore used by researchers and practitioners, but the geographical scale differs from local to global.

One example of a study which uses urban tree inventories as knowledge building is that by Nowak *et al.* (2001b), where the effects of Asian longhorned beetle are calculated together with the economic effects these could have. The decision making conducted by practitioners is more about providing managers with data on which they can base their decisions. One example is a species distribution inventory which can be used in making decisions to increase the species diversity in a city or area. Although both examples deal with some form of knowledge building, there is a clear difference in the context.

3.2 The purposes of urban tree inventories

Without the basic resource information that the tree inventory offers, it is problematic for practitioners to develop a good management plan to steer decision making. An urban forest management plan can be used to protect the urban tree population when conflicts arise between stakeholders within a city, *e.g.* regarding infrastructure both above and below ground (Randrup *et al.*, 2001b; McPherson & Peper, 1996). Some recent usages of urban tree inventories occurred in New York, where a large-scale tree inventory was used together with the i-Tree programme to calculate the economic costs and gains of the urban tree population and thereby give the city a cost-benefit ratio in hard numbers (Hirabayashi *et al.*, 2012; Martin *et al.*, 2011; Peper *et al.*, 2007). These calculations led to the city's current One Million Tree programme, the aim of which is to plant one million trees around New York. This demonstrates the importance of both the knowledge building and decision making properties of urban tree inventories.

There are multiple purposes for urban tree inventories and it is almost impossible to list all of these. The list presented in Table 2 is therefore only meant as a source of inspiration and as a way of showing the diversity of uses locally, regionally, in research and as decision support.

Table 2. Purposes/use of urban tree inventories, together with an example of a study dealing with the stated purpose/use

Purpose of inventory	Example of study dealing with the subject
3D modelling trees with the use of Mobile Laser Scanning (MLS)	Rutzinger *et al.*, 2011
Assessing and analysing damage to trees by drought	Holopainen *et al.*, 2006
Calculating emissions of VOC gases from different species	Drewitt *et al.*, 1998
Calculating the economic value of individual trees	Cullen, 2007
Calculating the overall economic benefits of urban trees	Maco & McPherson, 2003
Calculating the effects of diseases that could infest the urban tree population	Nowak *et al.*, 2001b
Calculating the value of ecosystem services	Hubacek & Kronenberg, 2013
Calculating maintenance costs	Sudol & Zach, 1987
Choosing species that are able to capture particles posing a potential hazard to human health	Gallagher *et al.*, 2011; Sæbø & Mortensen, 1996
Determining species distribution in different areas	Straigyte *et al.*, 2009
Estimating the contribution of forests to reducing energy consumption, greenhouse gas emissions and other pollutants	Brack, 2002
Identifying management problems in urban forestry	Cheng *et al.*, 2000
Providing decision support on which tree species to plant in urban areas	Sjöman, 2012
Hazard tree monitoring and management	Maruthaveeran & Yaman, 2010
Mapping storm-damaged trees and the species and sizes most affected	Jim & Liu, 1997
Modelling local climate	Dimoudi & Nikolopoulou, 2003
Monitoring management strategies	Pauleit, 2003
Monitoring tree root conflicts with pavements, kerbs and roads	Randrup *et al.*, 2001a
Monitoring tree vitality	Pauleit, 2003
Providing guidelines for the protection of urban trees during construction	Glaeser, 2010
Reducing the urban heat island intensity	King & Davis, 2007
Showing the importance of urban trees, both financially and other services	Hubacek & Kronenberg, 2013; Randrup, 2005
Showing the spread of invasive species	Humble & Allen, 2006

3.3 Tree inventories as part of governance for urban trees

With carefully selected parameters, tree inventories can be an important foundation upon which the governance for the urban trees can be built (Gerhold & Frank, 2002) and there are large numbers of practical application of tree inventories (Table 2). Combining tree inventories with other databases increases the amount of information that can be obtained (Morani *et al.*, 2011; Östberg *et al.*, 2010a). This also increases the possibilities for cooperation between different stakeholders, which was the case for the sewage and water department and the parks department in Malmö. In this city, urban tree inventories were one of the starting points for a fruitful discussion between the departments that led to other positive side-effects, *e.g.* the development of open stormwater solutions (Stahre, 2008; Östberg, 2008; Stahre, 2006). The involvement of different stakeholders in the development and execution of tree inventories is also crucial for successful usage of the data obtained (Schipperijn *et al.*, 2005).

There are a large amount of inventories that have not been used to their full potential or unfortunately not used at all, even though considerable amounts of time and money were spent collecting the data (Keller & Konijnendijk, 2012; Thomsen, 2012). Conducting an inventory does not automatically mean that the management of the urban tree population will be based on this inventory. Thus urban tree inventories must become an integral part of the city governance of urban forestry, to be used to their full potential.

3.4 Methods and parameters used for urban tree inventories

Several tree inventory methods are available, for example *aerial photography* (*e.g.* Andarz *et al.*, 2009; Mausel *et al.*, 1992; Goldberg, 1981), *field surveys* (e.g. Martin *et al.*, 2011; Sreetheran *et al.*, 2011; Adkins *et al.*, 1997) and *satellite imaging* (*e.g.* Small & Lu, 2006; Cook & Iverson, 1991). At the same time, the amount of tree inventory parameters has increased, thanks to the increase in methods to measure the parameters, but also due to the expanding use of inventories for specific and general purposes by practitioners and researchers; e.g. in order to enable calculations of carbon squamation (Woodbury *et al.*, 2007), vegetation classification by airborne high spatial resolution remote sensing imagery (Yu *et al.*, 2006), and health and size calculation of urban trees with the help of the DISMUT model (Brack, 2006; DISMUT is a decision support system that has been used to assess Australian urban forest). Thus researchers and practitioners have a large variety of methods and parameters to choose from when an urban tree inventory is to be conducted.

The choices that the practitioners and researchers make concerning urban tree inventories are becoming increasingly important with the divergence in the use of urban tree inventories. If the comparability is lost, there is a risk that the possibilities to use the inventory will be limited to only one specific purpose. In contrast, if inventories are comparable other users can benefit from the results and the inventories can be used for several purposes, *e.g.* comparisons of tree vitality, growth and hazard ratings between different cities. This enhances both decision making and knowledge building purposes. This raises the question of how tree inventory method and parameters should be selected. On the one hand, tree inventory parameters should be selected for the specific purpose of the inventory (*e.g.* Östberg *et al.*, 2012b; Miller, 1997), but on the other hand this limits the possibility of comparisons between inventories.

4 Research methodology

4.1 Inductive and incremental research approach

The overall aim, to support the development of a common framework for urban tree inventories that can facilitate synergy between cities, researchers and other actors, irrespective of the focus of the individual inventory, was approached through an iterative process where new questions and realisations were obtained in a process that continued until the results had been archived (Nassauer, 2012; Iverson Nassauer & Corry, 2004). The studies described in Papers I-IV were therefore part of a workflow in which each offered valuable insights and revealed knowledge gaps within the research area that formed the basis for the next study. The workflow started with the research question: How can existing urban tree inventory data be combined with other data sources to generate new knowledge and insights? This question was addressed in Paper IV. The research project then proceeded upwards with the research questions dealt with in Papers III, II and I, from an intuitive understanding in Papers IV and III to addressing specific practical problems in the wider context in Papers II and Paper I.

The papers contributed to the thesis as follows: Paper IV started with a specific actual problem, while Paper III researched a concrete question and analysed the usability of the existing data. Paper II encompassed methodological development by trying to answer the question of how to increase the usability of data by strategic selection of which data to collect. Paper I then continued this methodological development by researching the methods used in urban tree inventories and evaluating the different tree inventory method for collection of data at single tree level. This essay connects the wider views presented in Paper I and II with the concrete problems dealt with in Papers III and IV.

Practical problems guided data collection and, during processing of open empirical data, other aims, questions and answers to the problems were discovered. The research questions were thereby open and allowed for discoveries throughout the data collection and analysis process. The overall method used was therefore inductive (Føllesdal *et al.*, 1999), with observational studies (Rosenbaum, 2002), but the individual studies used a slightly wider variety of methods. Paper I is an attempt to systematise inventory methods related to their specific purposes; Paper II is a development of existing systems for tree inventory based on a systematising and rating procedure; and Papers III and IV are empirical, with large data collections followed up by inductive analysis before clear aims and research questions were set. The inductive method is, in short, a process where research begins by collecting data that are later tested for correlation. The idea is that the data should support a law-like generalisation that in turn explains the data (Føllesdal *et al.*, 1999). The method chosen creates knowledge by analysing collections of data, rather than by disproving hypotheses (Kuhn, 1996; Hempel, 1966).

This method was chosen for three main reasons. Firstly, the close connection with practitioners revealed knowledge gaps in their work and in research. This overlap in gaps meant that the research conducted could be valuable for the research community and for practitioners. Secondly, there is a lack of baseline data within the research field. This made it difficult to use previous studies and articles, and the work associated with the development of each of Papers I-IV therefore utilised existing data provided by practitioners in an exploratory (Stebbins, 2001) and inductive (Føllesdal *et al.*, 1999) way. Thirdly, the iterative process made it possible to address research questions that emerged from one study to the next, thereby filling knowledge gaps as they were discovered.

4.2 An applied research approach

The work described in this thesis adopted an applied research approach, closely related to practical work and issues, where the problems dealt with originated from the intersections between researchers' and practitioners' problems, *e.g.* in municipalities, cities, consultancy work and cemetery maintenance. The research conducted thereby acquired new knowledge and had a high certainty of application in a short amount of time (Figure 4), conforming with the definition of applied research provided by OCDE (1994) (see Table 1).

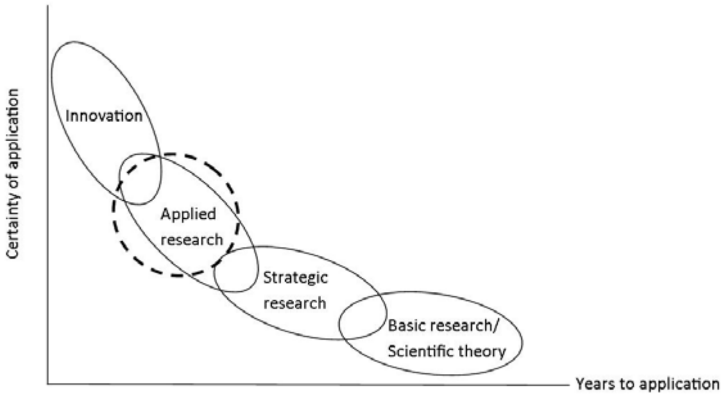

Figure 4. Differences in the type of research and its certainty of application as a function of years to application. The dotted circle shows the placement of Papers I-IV, which represented applied research and thereby have a high degree of certainty of being applied quite rapidly.

A question that could arise from the decision to base this thesis on direct, real-life problems is how this affected scientific quality. One could argue that the role of universities is to produce basic knowledge, and that the industry/organisations should then use this basic knowledge in their own applied research and development. However, problems arise if the gap between research and practice becomes too wide, as also concluded in a previous review in which a weak science-practice interface was rated as the third main weakness for urban forestry research in the Nordic and Baltic countries (Konijnendijk *et al.*, 2007). The research presented in this thesis sought to reduce the gap between researchers and practitioners and to support practitioners in their demand for up-to-date, high quality urban tree inventories.

5 Papers I-IV – methods and summary of results

In this chapter, the results of Papers I-IV are summarised and discussed. The key results from each paper are presented, but the reader is referred to the full papers (which are appended to this thesis) for a more in-depth description of the work. Novel results and information that did not fit within the scope of Papers I-IV are also included here.

5.1 Urban tree inventory methods (Paper I)

Paper I deals with the problem of which tree inventory method to choose when conducting urban tree inventories. It also addresses which tree inventory method has the broadest use. The objectives were to: 1) Provide a bibliographic overview of research where urban tree inventories at single tree level are used as the primary data source, 2) establish a typology of contemporary urban tree inventory methods and identify the type of data and the accuracy of measurements collected at single tree level by use of the different methods, and 3) evaluate the suitability of different urban tree inventory methods for data collection at single tree level.

In response to the growing and diversifying usage of data on single tree level from urban tree inventories, the variety of inventory methods has expanded rapidly (Schipperijn *et al.*, 2005; McBride & Nowak, 1989; Smiley & Baker, 1988). While field surveys offered the starting point, rapid technological development has meant that data on single tree level can now also be obtained from different types of ground scanning and digital photography (*e.g.* West *et al.*, 2012; Patterson *et al.*, 2011; Buhyoff *et al.*, 1984), as well as a variety of satellite- and aeroplane-supported methods (*e.g.* Ardila *et al.*, 2012; Jutras *et al.*, 2009). Airborne methods have wide application for land use and vegetation inventories at coarser scales (*e.g.*

Jutras *et al.*, 2009; Holopainen *et al.*, 2006; Mausel *et al.*, 1992). However, the different methods all have their limitations regarding the data parameters that can be collected at single tree level and the accuracy of measurements, a fact which needs to be taken into account (*e.g.* Ardila *et al.*, 2012; Abd-Elrahman *et al.*, 2010). Keller & Konijnendijk (2012) therefore argue that more research is needed on the status of urban tree inventories and the accuracy and validity of data that can be obtained from different types of inventories.

The research questions were addressed through a literature review conducted in Web of Science and Scopus. Aiming for high sensitivity, as recommended by Pullin & Stewart (2006), the search was restricted to a single search string, namely: *tree* invent* urban*.* The search terms were considered among the categories 'Title, abstract, keywords' (Scopus) and 'Topic' (Web of Science). After the initial search, articles were included or excluded based on their title and abstract. The remaining papers were reviewed and evaluated for their relevance. A total of 57 studies met the inclusion criteria, which were:

- Using urban tree inventories as the main data source.
- Specifying the inventory method and technical aids applied and the type of parameters collected from each tree.
- Published before 31 December 2012.
- Published in English.

The method used is easy to understand and to replicate, but also carries a risk of overlooking a number of studies in which urban tree inventory methods are described and/or used as data sources. However, despite this risk, we believe that the scientific literature included provides a reliable profile of the research field.

In total, 14 research specific focuses, or research objectives, were found in the studies. Moreover, 153 tree inventory parameters were identified and divided into 15 parameter groups and four types of tree inventory methods.

The most important results of Paper I are presented in Tables 3 and 4. The links between the specific focus, tree inventory parameters and methods in articles are presented in Table 3 and the measurement accuracy obtained from the different tree inventory parameters in Table 4. Field surveys were used as data sources by all 14 types of study focuses, and as method for collection of all 15 tree parameter groups (Table 3). In comparison, data collection at single tree level by use of satellite-supported methods was restricted to the parameter groups 'location', 'coordinates' and 'appearance'. This type of data collection was limited to studies focusing on testing this specific method. Aeroplane-supported methods were restricted to tests of aerial photos as an aid to tree species identification and estimation of urban tree canopy cover. Ground scanning and digital photography had been tested as a method to collect a wider range of tree parameters, and also applied to collect data on crown size/density, diameter at breast height (DBH), and other size parameters in studies focusing on CO_2 storage and/or digitalisation of tree shapes.

Table 3. Type of tree inventory method used for each of the objectives and number of studies using the methods for each of the objectives. Type of tree inventory method: **A**. Satellites, **B**. Aerial photos, **C**. Ground scanning/photos **D**. Field survey (windshield method not included). The numbers of studies using the methods for each of the tree inventory parameter groups are listed as subscripts.

		Tree inventory parameters																
Subject specific focus	**Number of publications that have this objective/purpose**	Age or year of planting	Coordinates	Crown size, density	Damage, insects and pests	DBH (Diameter at Breast Height	Hazard	Infrastructure or buildings close to the tree, damage to these	Location	Maintenance need and history	Management information	Planting/growing site	Size (except crown and DBH)	Species	Tree appearance and use	Vitality	**Total**	**Amount of parameter-groups**
Test of tree inventory methods	13	D_3	A_1	C_3D_5	C_1D_2	C_2D_7		C_1D_1	$A_1C_1D_2$	D_1	D_2		C_2D_5	B_1D_5	$A_1C_1D_2$	C_1D_4	**$A_3B_1C_{12}$ D_{39}**	13
Species distribution and diversity	7		D_1	D_1		D_5			D_1				D_2	D_6	D_1	D_3	**D_{12}**	7
Arboricultural management	5			D_1	D_1	D_4	D_1	D_2	D_4	D_1	D_1	D_2	D_2	D_4		D_3	**D_{26}**	12
Tree vitality	5			D_2	D_3	D_4	D_1	D_2	D_3	D_2	D_1	D_1	D_4	D_4	D_1	D_5	**D_{33}**	13
Transmission of VOC	5	D_1		D_4									D_4	D_4		D_2	**D_{15}**	5
Cost-benefit analysis of urban trees	4			D_3	D_2	D_4					D_1		D_4	D_4		D_3	**D_{21}**	7
Effect on urban climate, greenhouse gases and C storage	3			C_1D_1	D_1	D_3		D_1					D_2	D_2			**C_1D_{10}**	6
Biodiversity aspects	3					D_1							D_1	D_3			**D_5**	3
Digitalisation of tree shape	3			C_3		C_1							C_2				**C_6**	3
Tree architecture and amenity values	2			D_1	D_1	D_2	D_1	D_1	D_1		D_1	D_1	D_1	D_2	D_1		**D_{13}**	11
Land use and land use change	2			D_1		D_1			D_1				D_1	D_2			**D_6**	5
Comparisons of models	2			D_1									D_1	D_1		D_1	**D_4**	4
Urban tree canopy cover	2			B_1D_1								D_1					**B_1D_2**	2
Comparison of trees in different types of urban green space	1					D_1								D_1		D_1	**D_3**	3
Total	57	**D_4**	**D_1A_1**	**$B_1C_3D_{21}$**	**C_1D_{10}**	**C_3D_{32}**	**D_3**	**C_1D_7**	**$A_1C_1D_{12}$**	**D_4**	**D_6**	**D_5**	**C_4D_{27}**	**B_1D_{38}**	**$A_1C_1D_5$**	**C_1D_{22}**		
Number of objectives		2	2	12	6	11	3	5	6	3	5	4	12	12	4	8		

In the articles reviewed, testing and methodological discussions of accuracy of measurement were restricted to 3-5 parameter groups for each inventory method, with on-ground digital photography methods and satellite-supported Google maps being the exceptions. Regarding these, accuracy of measurement had been tested for 7 and 8 parameter groups, respectively (Table 4).

Studies of the accuracy of measurement generally concentrated on the three size parameter groups 'Crown size/density', 'DBH', and 'Tree size other than crown size and DBH'. When synthesising the findings across the studies, very diverse levels of accuracy in measurements for these parameters were revealed for the different inventory methods. Park *et al.* (2010) found that ground scanning by terrestrial laser provided a high level of accuracy in measurements of crown size/density and other tree size information and moderate accuracy for DBH, while the accuracy of measurements obtained from mobile laser scanning and on-ground digital photography methods was moderate for these three parameters (Rutzinger *et al.*, 2011). In comparison, the different satellite- and aeroplane-supported methods generally showed very low levels of accuracy of measurement for tree size parameters, aeroplane-supported laser scanning being the exception (Jutras *et al.*, 2009). Notably, only satellite-supported images and aerial photos had been tested as an alternative to field inventory for species identification, with low and moderate levels of accuracy, respectively (Table 4).

Table 4. Rating of the accuracy of measurements at single tree level obtained from different inventory methods. The rating is based on synthesis of results from studies focusing on method into four levels of precision: 0 = not possible to measure or very low precision, 1 = low precision, 2 = moderate precision, 3 = high precision. Field surveys were used as a reference for high precision.

	Tree inventory parameters															
	Age or year of planting	Coordinates	Crown size, density	Damage, insects and pests	DBH (Diameter at Breast Height)	Hazard	infrastructure or buildings close to the tree, damage to these	Location	Maintenance need and history	Management information	Planting/growing site	Size (except crown and DBH)	Species	Tree appearance and use	Vitality	References
Satellites - QuickBird, Panchromatic and multispectral images, VHR Satellites		2	2					3					0			Arroyo *et al.*, 2010 ⋆; Ardila *et al.*, 2012, Thaiutsa *et al.*, 2008; Cavayas, 2012
Satellites– Google maps		2	0	0	0		3	3				0		2		Ningal *et al.*, 2010; Abd-Elrahman *et al.*, 2010;⋆ Thornhill *et al.*, 2009⋆
Aeroplane-supported LIDAR and Terrestrial Laser Scanning, Optech Laser Terrain Mapping 2050			2		2							1				Jutrasa *et al.*, 2009
Airplane supported methods - Aerial photos			2	3				2					2		2	Miller & Winer, 1984; Goldberg, 1981⋆; Hathout & Simpson, 1986; Mausel *et al.*, 1992; Holopainen *et al.*, 2006⋆
On ground scanning/photos (Terrestrial Laser Scanning)			3		2							3				Park *et al.*, 2010
On ground scanning/photos (Mobile Laser Scanning)			2		2							2				Rutzinger *et al.*, 2011
Ground scanning/photos - Customer grade cameras, digital photos, augmented reality		3	2	2	1		3					2		3		Abd-Elrahman *et al.*, 2010⋆; Tait *et al.*, 2009⋆; Patterson *et al.*, 2011; West, 2012; Thornhill *et al.*, 2009⋆
Field survey – Windshield survey				2		2								2		Rooney *et al.*, 2005⋆
Field survey – *e.g.* supported by GPS receiver or handheld computers	3		3	3	3	3	3	3	3	3	3	3	3	3	3	

⋆= Article not included in the first selection process.

According to Smiley & Baker (2009), the 'why' must be clearly defined before the choice of specific data collected at single tree level can be identified. The main contribution of Paper I is that it went beyond the 'why' question, and established a typology of 'how' urban inventories are conducted (at least those applied as main data sources in published research) and 'how' the different contemporary inventory methods and technical aids affect the type of data parameters that can be collected at single tree level and the accuracy of their measurement. It also identified four main types of urban tree inventory methods: 1) Satellite- and 2) aeroplane-supported methods, which can also provide 'easy access' to tree information on private land and many recent publications use or test such methods (*e.g.* Ardila *et al.*, 2012; Arroyo *et al.*, 2010; Jutras *et al.*, 2009). 3) Ground scanning (*e.g.* Rutzinger *et al.*, 2011; Park *et al.*, 2010) and digital photography methods (*e.g.* West *et al.*, 2012; Patterson *et al.*, 2011), for data collection at single tree level. 4) 'Classical' field surveys' where ground staff conduct direct measurements and visual inspections (most common, 46 articles). A relevant concern regarding field surveys is that they are labour-intensive and generally limited to public trees, simply because of the difficulties of obtaining accessibility to trees on private land (Nowak, 2008).

From the compilation of urban tree research applying data at single tree level in Paper I, it is clear that current technologies and data processing methods limit the reliability of data obtained from satellite- and aeroplane-supported inventory methods and from on-ground scanning or digital photography. Paper I therefore recommends further technological development and scientific testing before these methods can replace field surveys in urban tree inventory programmes.

Paper I also showed the importance of selecting the correct tree inventory method depending on the accuracy needed for the specific tree inventory parameter and research objective. Some parameters *e.g.* crown coverage, can be measured by a large variety of methods with reasonable accuracy, while others, *e.g.* hazard rating, still need to be measured in field surveys. The results from Paper I can be used by researchers and practitioners to choose the best tree inventory method for the specific aims and parameters of a particular tree inventory, while also showing a lack of information regarding the precision of some methods. The information obtained is already being used as part of a project with the Swedish Department of Traffic to better monitor trees standing in rights of way.

5.2 Urban tree inventory parameters (Paper II)

Paper II deals with the problem of which parameters to include in an urban tree inventory, depending on user group. The study was guided by the following two research questions: 1) Which parameters do experts rate as being the most relevant to include in urban tree inventories? and 2) does the rating of parameters deviate between different user groups, *i.e.* city officials, arborists and academics?

Tree inventories are becoming more common, but are conducted in different ways (Lombardi & Morais, 2003; Mausel *et al.*, 1992), and with different parameters. The Delphi method, an established qualitative research technique that seeks to provide a reliable group opinion through the use of expert judgment (Landeta, 2006), was used to draw up a priority list of tree inventory parameters. The steps in the Delphi process were adapted from Okoli & Pawlowski (2004), who describe the methodology for identification and categorisation of experts, and from Graham *et al.* (2003), who describe the method for rating of parameters. Within the study, participants anonymously rated the importance of the different parameters on a scale of 1 (least important) to 10 (most important). The scorings of the individual panellists were then shared within the group, together with the group mean, and the panellists could change their rating according to the other panellists' ratings. The process was repeated until the group had reached consensus.

The survey was conducted in parallel in three separate panels representing different responsibilities for, and interest in, tree inventories: a) employees at city administrations procuring and managing urban tree care and urban tree inventories (termed 'city officials'); b) employees at arboricultural companies and consultants (termed 'arborists'); and c) researchers and teachers at universities and other educational and research institutions (termed 'academics').

The Delphi method was followed rigorously in choosing experts for the Delphi panels and for the whole rating process, but some things could have been more effective. For example, if a smaller number of Delphi items had been used, larger numbers of panellists might have stayed throughout the study. However, the large number of parameters was also important so that no significant parameters were overlooked and so that the panellists could suggest their own parameters. Furthermore, the time from identification of the experts until the study began could have been shorter, which would have reduced the number of panellists excluded from the study or moved to another panel.

Paper II resulted in a list of 148 tree inventory parameters that were rated by the three panels, a mean value for all user groups and separate means for the three user groups. The results revealed large differences between the three groups, with only one parameter (*Scientific name of tree species and genera*) receiving the highest score from all panellists. Paper II also revealed that the arborists and city officials differed most when comparing the groups of parameters used in the study. The top rated parameters after *Scientific name of tree species and genera* were *Vitality*, *Coordinates*, *Hazard class* and *Identification number* (Table 5).

The main outcomes of Paper II were a priority list of tree inventory parameters and the finding that the selection of tree inventory parameters needs to involve more than one group of users to enhance the usability of the inventory. Only involving one of the groups would have led to omission of certain types of parameters of great interest to other groups, or the management of the whole tree population. For example, if only arborists chose parameters, the database issues would have been missed, and if only researchers were asked to choose the amount of free text parameters might have been overwhelming. Communication between the user groups involved is hence crucial for successful use of tree inventories (Schipperijn *et al.*, 2005), as otherwise there is a high risk of important parameters being missed and of tree inventories lacking important information, to the detriment of otherwise successful decision-making. By involving the stakeholders in the process, the outcome can serve a wider variety of purposes. The results from Paper II also indicate that there are possibilities to get agreement on how to choose parameters for a tree inventory in Sweden and that many of these parameters are compatible with international standards, thus enabling international comparisons and research.

Table 5. Tree inventory parameters, their mean rating and (in brackets) their parameter group (**A** - Descriptive inventory parameters, **B** - Vitality and safety, **C** - Tree values, **D** - Measures and maintenance, **E** – Database metadata, **F** - Documentation of management). After the mean rating, rating in the three panels (**CA** =City officials, **AC**= Academics, **AR**= Arborists) is specified in brackets. All parameters are set in order of prioritisation for the three panels.

Parameter placement for the panels	Parameter according to mean value	Mean rating and placements in the individual panels	City officials	Mean	Academics	Mean	Arborists	Mean
1	Scientific name of tree species and genera (A)	10.0 (CA:1 AC:1 AR:1)	Scientific name of tree species and genera (A)	10.0	Scientific name of tree species and genera (A)	10.0	Scientific name of tree species and genera (A)	10.0
2	Vitality (B)	9.8 (CA:3 AC:5 AR:2)	Coordinates (A)	10.0	Identification number (E)	10.0	Vitality (B)	9.8
3	Coordinates (A)	9.6 (CA:2 AC:9 AR:11)	Vitality (B)	9.8	Date of latest inventory (E)	10.0	Identification number (E)	9.8
4	Hazard class (B)	9.4 (CA:4 AC:19 AR:6)	Hazard class (B)	9.5	Date of first inventory (E)	10.0	Name of disease or pest (B)	9.7
5	Identification number (E)	9.2 (CA:26 AC:2 AR:3)	Year of planting (A)	9.4	Vitality (A)	9.9	Free text concerning the time factor for the maintenance and operations (D)	9.7
6	Presence of fungal bodies (B)	9.0 (CA:17 AC:11 AR:7)	Date of latest inventory (E)	9.0	Free text on hazard and damage (B)	9.9	Hazard class (B)	9.6
7	Date of latest inventory (E)	9.0(CA:6 AC:3 AR:50)	Street or park trees (A)	9.0	Date of registration in the database (E)	9.9	Presence of fungal bodies (B)	9.6
8	Category of care (D)	9.0(CA:11 AC:12 AR:23)	Stem circumference at 1 m height at planting (A)	8.9	Free text on diseases and pests (B)	9.9	Free text on new planting of trees (F)	9.4
9	Conservation value (C)	9.0(CA:12 AC:20 AR:13)	Type of planting pit (A)	8.9	Coordinates (A)	9.7	Free text on the cultural value of the tree (C)	9.3
10	Street or park trees (A)	8.8(CA:7 AC:29 AR:40)	Protection value (C)	8.8	Damage class (B)	9.7	Proposed measures (D)	9.2
11	Age class (A)	8.7(CA:21 AC:21 AR:14)	Category of care (D)	8.6	Presence of fungal bodies (B)	9.6	Coordinates (A)	9.1
12	Stem circumference at 1 m height at planting (A)	8.7(CA:8 AC:51 AR:24)	Conservation value (C)	8.6	Category of care (D)	9.6	Establishment pruning (F)	9.1
13	Date of planting (F)	8.6(CA:16 AC:22 AR:30)	Type of constructed planting site (F)	8.4	Free text on tree damage (B)	9.6	Conservation value (C)	9.0

Table 5. Continues

14	Name of disease or pest (B)	8.5(CA:33 AC:52 AR:4)	Proposed measures (D)	8.3	Free text on tree conservation value (C)	9.4	Age class (A)	9.0
15	Reason for felling (E)	8.5(CA:18 AC:30 AR:36)	Date of registration in the database (E)	8.3	Free text concerning the time factor for the maintenance and operations (D)	9.4	Ground coverage under the tree crown (A)	9.0
16	Type of constructed planting site (F)	8.4(CA:13 AC:48 AR:43)	Date of planting (F)	8.1	Free text on inventory information (A)	9.4	Name of fungi (B)	9.0
17	Proposed measures (D)	8.3(CA:14 AC:72 AR:10)	Presence of fungal bodies (B)	8.0	Free text on the management of the tree (D)	9.4	Protected by law (C)	9.0
18	Street address (A)	8.3(CA:29 AC:45 AR:33)	Reason for felling (E)	8.0	Free text concerning identification and location (A)	9.4	Damage class. detailed (B)	9.0
19	Year of planting (A)	8.2(CA:5 AC:37 AR:99)	Date of update in the database (E)	8.0	Hazard class (B)	9.3	Free text on hazard and damage (B)	8.8
20	Date of update in the database (E)	8.2(CA:19 AC:23 AR:69)	Proposals for action time (D)	8.0	Conservation value (C)	9.3	Proposals for action time (D)	8.8
21	Presence of stem protection (A)	8.2(CA:22 AC:31 AR:61)	Age class (A)	7.9	Age class (A)	9.3	Free text on tree vitality (A)	8.8
22	Soil protection around the tree (A)	8.1(CA:32 AC:38 AR:44)	Presence of stem protection (A)	7.9	Date of planting (F)	9.3	Free text on diseases and pests (B)	8.8
23	Free text on hazard and damage (B)	8.1(CA:54 AC:6 AR:19)	Irrigation program for tree (F)	7.9	Date of update in the database (E)	9.3	Category of care (D)	8.7
24	Owner (E)	8.1(CA:28 AC:58 AR:29)	Contractor for planting (F)	7.8	Free text on the cultural value of the tree (C)	9.3	Stem circumference at 1 m height at planting (A)	8.7
25	Date of registration in the database (E)	8.1(CA:15 AC:7 AR:105)	Identification number (E)	7.8	Free text on tree aesthetic (C)	9.3	Pruning (D)	8.7
	Mean	**8.7**	**Mean**	**8.4**	**Mean**	**9.2**	**Mean**	**8.6**

Within the work on Paper II, a national tree inventory standard was developed as a concrete response to the overall goal of the thesis, namely to support the development of a common framework for urban tree inventories that can facilitate synergy between cities, researchers and other actors, irrespective of the focus of the individual inventory.

The standard is freely available to download via www.inventering.nu, the only limitation being that a survey consisting of six type questions has to be completed first. A total of 659 downloads was recorded during the first nine months (standard released 25 March 2012) from nine types of organisations (Table 6). Of these, 459 downloads were by individual organisations. Three organisations (cemetery managers, consultants, and municipal/city authorities) accounted for 57% of all downloads.

Table 6. Number of downloads of the tree inventory standard produced within the work on Paper II, per type of organisation

Type of organisation	Number of organisations	Percentage of downloads
Arborist company	74	11%
Cemetery	126	19%
Consultancy	99	15%
Housing company	39	6%
Municipality/city	150	23%
National Heritage Board	2	0%
Not linked to a particular organisation	34	5%
Swedish Transport Administration	2	0%
University	46	7%
Other	87	13%
Total	**659**	**100%**

The *type of area* to be inventoried is one of the questions in the survey. The standard was created to be used primarily in urban areas, but rural areas were also listed as interesting for the users, with 8% downloads for specifically rural areas and 52% for mixed inventories of both rural and urban areas. However, urban areas clearly dominated, with 33% of the total downloads and 85% when the mixed inventories were also included.

In order to give a more accurate description of the type of area that was to be inventoried, the survey included a question on *type of land*. This question had the possibility for several marks, so in Table 7 the percentiles are given as a percentage of the total number of downloads (659). The type of land was quite evenly distributed between the seven most popular land types, ranging from 32 to 53% of the total amount of downloads (Table 7).

Table 7. Number of downloads in the tree inventory standard produced within the work on Paper II, divided by type of land to be inventoried

Land type to be inventoried	Number of inventories	Percentage of downloads
Cemetery	306	46%
Culture/historically valuable environment	274	42%
Nature area	215	33%
Park	348	53%
Residential	243	37%
Streets	212	32%
Streets and squares	296	45%
Other	109	17%
Do not know	80	12%

Much work was put into finding parameters to include in the Delphi study and the participants also had the chance to recommend their own parameters, but there were still some parameters missing, *e.g.* size of crown in the fully grown tree. Future work in the project will include launching an updated version with some clarifications, more illustrations and also some parameters that the users wanted to see included.

The results in Paper II have not been questioned by any of the users, which would probably have been the case if a round table discussion had been used. The Delphi study is rather easy to understand and it gives the individual experts the same possibility to affect the final outcome, whereas with a round table discussion, some experts may have a greater say than others. The results from Paper II have been communicated to practitioners *via* a report (Östberg *et al.*, 2012b) and a popular science articles in Sweden and Denmark (Östberg & Nielsen, 2012; Östberg *et al.,* 2012), together with a lecture tour of Sweden.

5.3 Comparing existing tree inventories from Nordic cities (Paper III)

In Paper III, the tree species distribution in 10 different Nordic cities was compared using existing urban tree inventories. The study also examined how practitioners could use this information to get a better distribution of their urban tree population. The objectives of Paper III were: 1) To obtain basic information on the diversity and distribution of genera and species of urban trees in the Nordic region, 2) to examine the diversity at different sites within cities, distinguishing between street and park environments, and 3) to analyse the presence of native versus non-native tree species in urban environments of the Nordic region. The work was thus well within the applied research field, with a clear link to the management of urban trees by dealing with problems facing urban tree managers.

Urban tree inventories can be used in order to analyse the susceptibility of the tree population to outbreaks of pests and diseases and its tolerance to more stressful climates. The composition of the urban tree stock has therefore been studied in many cities (Stewart *et al.*, 2009; Raupp *et al.*, 2006; Stewart *et al.*, 2004; Pauleit *et al.*, 2002; Jim & Liu, 2001). A recent issue in planning for greater diversity of tree species and genera is whether non-native species should be used in urban plantations. There have been extensive discussions about the risk of non-native species spreading from the urban environment to natural environments, thereby risking extinction of native species (*e.g.* Alien plant group, 2012; Hitchmough, 2011; Parker *et al.*, 1999). Chytrý *et al.* (2008) and Pysek *et al.* (2009) concluded that for a species to successfully escape from cultivation into natural environments and there develop into a potential invasive species, the propagule pressure (the number of individuals of a species existing in a region) and residence time (how long a species has been cultivated in a region) are essential factors. Therefore it is essential to know the number of non-native species present in an area in order to identify eventual invasion threats at an early stage, *e.g.* by having a tree inventory. With accurate urban tree inventories the urban tree population can be analysed, potential risks concerning the species distribution can be found and the scale of the problem can be demonstrated to *e.g.* politicians and residents.

The option chosen in Paper III of comparing existing tree inventory databases from 10 Nordic cities was effective in terms of time, but reduced the analysis to only a comparison of tree species and their presence in street or park environments, as no other parameter was present in all 10 databases.

For example, vitality was present in only six databases. However, the restricted amount of comparable parameters confirmed the importance of Paper II, where the overall goal was to make tree inventories more comparable.

Although it was only possible to compare two parameters, *tree species* and *street/park* tree, for all cities, Paper III made several analyses of species distribution and the occurrence of native and non-native species. It also compared street and park trees for some cities (5/10) (Table 8). This is in line with Keller & Konijnendijk (2012), who found that only one of the six Nordic and North American cities they studied had inventoried their park trees. The data in Paper III were collected using field surveys, which is the most widely used method in tree inventories (Paper I).

If other parameters had been included the analysis would of course have widened. However, tree species is itself a very important parameter, as evidenced by the large amount of information that can be obtained from this single parameter (Paper III). The importance of the parameters *tree species* and *street/park* was also shown by Paper II, where they were amongst the top 10 parameters.

It would have been very interesting to compare tree vitality and thereby monitor changes in the vitality of different tree species. Some research have for instance revealed changes in growth depending on CO_2 levels (Mortensen & Sæbø, 1996; Sæbø & Mortensen, 1995) and ozone (Faggi & Ignatieva, 2009), which could have been interesting to compare for urban trees in relation to *e.g.* climate change

Paper III revealed a lack of species diversity in many of the cities included in the study, *e.g. Tilia* was the most dominant genus in Arhus, Copenhagen, Espoo, Gothenburg, Helsinki, Oslo and Stockholm, while *Sorbus* was the most dominant in Malmö and *Betula* in Tampere and Turku. The city with the highest amount of *Tilia* was Helsinki, with 44.7%, which was also the highest dominance of a single genus in all cities studied. In Paper III this information is related to recommendations on genus and species distribution, which range from keeping the maximum share of any species to less than 10% of the population (Miller & Miller, 1991) to more specific recommendations that no species should represent more than 10%, no genus more than 20% and no family more than 30% of the population (Santamour, 1990). The only city in which no species exceeded 10% of the total tree population was Malmö, which complied with this recommendation in terms of entire tree population, irrespective of site situation.

The compilation of tree species and genus was also assessed in the context of street and park trees, and *via* a classification into exotic/native species. This grouping allowed a more qualitative discussion on the rather large differences in distribution that exist as regards street and park environments and also exotic and native species. An especially interesting finding was the large number of species with a frequency of less than 2% found in parks in Aarhus, where they made up 68.7% of the total number of park trees (Table 8). This was due to the inventory including the botanical garden and some cemeteries in the city, but no ordinary parks. The data might seem misleading for this reason, but also show how many species can be grown in a small city and thereby provide a huge source of inspiration when selecting species from databases. This is one of the main points raised in Paper III. If cities were to use their own data, and also to share data with other cities, they would be able to identify a large number of species that could be used instead of the already over-used species.

As stated above, the Swedish city of Malmö had the overall best species distribution, probably as a result of how it handled the devastating effects of Dutch elm disease (*Ophiostoma novo-ulmi; O. ulmi*). In total, Malmö currently has around 65 000 street and park trees, but 45 000 elm trees have been cut down since 1984 due to Dutch elm disease. The major over-use of elms in Malmö hence had huge consequences and the species distribution today is a direct effect of the city authority's decision to replant the city with a large diversity of species. One of the solutions to achieving a good species distribution can thus be good crisis management, but it can also be achieved with long-term management goals and better, more strategic planning and establishment. For example, the city of Copenhagen has set up clear regulations and goals for which tree species to plant more frequently, and which species should be used to a lesser extent.

The practical findings from Paper III, in terms of recommendations on how the species distribution can be improved and information on the current species distribution, have led to a number of spin-off effects. The results have been used in a popular science publication written in Swedish, which has been distributed throughout the sector (Sjöman *et al.*, 2012b). Moreover, presentations have been made at several conferences on how a dependence on a limited amount of species can be managed and the results have been used in education to show the problems of having a limited tree stock. The study has also inspired further research, *e.g.* in Denmark, where the urban tree population in several cities and the reasons for urban tree inventories have been analysed (Thomsen, 2012), and in a project analysing why *Tilia* is so dominant in the Nordic countries (Johansson, 2011).

Table 8. Distribution of street trees and park trees in five Nordic cities in terms of the most common species.

	Aarhus		Gothenburg		Malmö		Oslo		Turku	
Species	Street	Park*	Street	Park	Street	Park	Street	Park	Street	Park
Acer campestre					2.5%					
Acer platanoides	10.3%	2.1%			2.6%	3.6%	11.6%	21.2%	9.1%	10.7%
Acer pseudoplatanus	2.5%					3.3%		5.1%		
Acer rubrum				3.1%						
Aesculus hippocastanum	4.0%			3.5%	5.4%	3.4%	10.2%	3.3%		
Alnus glutinosa									2.5%	4.2%
Betula pendula	4.1%	7.0%				4.0%	5.5%	3.1%	12.9%	12.5%
Betula pubescens								3.3%		2.4%
Betula spp.				2.6%			4.7%	5.9%		
Betula utilis		2.0%								
Carpinus betulus		4.9%			2.8%					
Chamaecyparis lawsoniana		3.6%								
Crataegus monogyna						2.3%				
Fagus sylvatica		6.1%		3.2%		7.2%				
Fraxinus angustifolia			3.9%							
Fraxinus excelsior	3.6%			3.6%		4.4%	2.8%	2.3%	3.3%	2.2%
Malus hybr.	2.0%									
Picea abies										2.6%
Picea omorika									2.7%	2.9%
Picea pungens										2.0%
Pinus sylvestris									4.9%	10.3%
Platanus x hispanica	4.2%				5.0%					
Populus canescens				3.6%		3.2%				

Table 8. Continues

Populus nigra										
Populus simonii						3.0%				
Populus tremula									2.9%	
Prunus avium					5.3%	4.2%				
Prunus spp.							3.0%	3.5%		
Prunus padus				2.3%						
Quercus robur	7.9%	2.5%		15.2%	4.0%	3.0%			2.6%	3.6%
Robinia pseudoacacia										
Salix alba	2.3%					3.4%				
Sorbus aria					2.7%					
Sorbus aucuparia	3.7%								9.3%	3.8%
Sorbus x intermedia	5.7%		7.7%	5.3%	11.1%	7.6%			2.9%	
Sorbus latifolia	5.0%									
Sorbus mougeotii	11.3%									
Sorbus spp.			3.7%							
Taxus baccata		3.1%								
Tilia cordata	8.0%		7.0%		3.3%			2.6%		
Tilia plathyphylla										
Tilia spp.			13.9%	19.4%	2.9%		45.3%	17.1%		
Tilia x europaea	7.3%		35.5%	10.0%	16.5%	2.3%			16.7%	10.8%
Ulmus glabra		3.1%	5.8%				4.6%	9.3%	5.9%	5.0%
Ulmus minor			2.8%							
Species with a frequency of less than 2%	18.1%	68.7%	19.7%	29.1%	35.9%	45.1%	21.8%	23.3%	13.1%	42.8%

*The park trees only consisted of the botanical garden and a cemetery.

5.4 Tree inventories and technical infrastructure databases (Paper IV)

Paper IV deals with the problem of root intrusion into underground pipes. It problematises previous accepted 'truths' about this problem, *e.g.* that it is primarily the genera *Salix* and *Populus* that cause root intrusions and that shrubs seldom cause root intrusions. The main aims of Paper IV were 1) to compile a list of woody plant species and cultivars found around root-intruded pipes in Swedish urban areas and to estimate the probability of root intrusion by these species and cultivars, 2) to estimate and compare the ability of specific species and cultivars to cause root intrusion, and 3) to examine differences in the occurrence of root intrusion depending on pipe construction material.

The study was not intended to discredit urban vegetation, but instead to contribute to a more nuanced picture of the ecosystem services and disservices it provides. Bentsen *et al.* (2010, p. 273) write that the "*common understanding of ´green´ as something inherently ´good´ needs to be addressed more critically*" and Kitchen (2012, p. 13) that "*Trees' environmental good depends on context*". It is essential to the study of root intrusion to confirm that trees are good in urban contexts, but also to highlight the problems that can occur when trees are planted too close to urban infrastructure. The conflict between tree roots and technical infrastructure has been examined in several studies (Grabosky & Gucunski, 2011; Grabosky *et al.*, 2011). Conflicts between tree roots and underground pipes are frequent in the urban environment, with up to 50% of all blockages in sewer pipes caused by roots (Randrup *et al.*, 2001b). In fact, in a survey in Denmark, 97% of towns and cities reported that their pipes had problems with root intrusions (Randrup, 2000). In Sweden, the corresponding number was 99% (Stål, 1998). Such problems in Sweden are estimated to have cost SEK 55 million (EUR 5.6 million) in 2003 (Orvesten *et al.*, 2003). In Germany, an estimated EUR 28.4 million per year are spent on root removal and pipe replacement or renovations associated with root intrusion (Bennerscheidt *et al.*, 2009).

Inventories are essential in supplying quantitative data on the numbers of root intrusions, but also on which tree species are growing close to the pipes. This can help identify tree species with a higher probability of causing root intrusions. Recent publications concerning the problem of root intrusion recommend cooperation between city planners and civil engineers to devise a management regime that reduces the damage caused by trees, as concluded previously in Sweden (Östberg *et al.*, 2010a; Östberg, 2008; Orvesten *et al.*, 2003). Previous research also highlights the importance of having an up-to-date tree inventory in order to enable good communication between the stakeholders (Östberg, 2008).

The work reported in Paper IV was not conducted in laboratory experiments or field trials, which are commonly used in previous studies (Ridgers *et al.*, 2006; Pohls *et al.*, 2002; Groninger *et al.*, 1997; Leonard *et al.*, 1974). Instead, existing tree inventory databases were used, together with urban infrastructure databases. The results were hence largely based on existing information that needed to be set into a new context. As in Paper III, the data used in Paper IV were largely acquired from the participating cities and their parks and sewage and water departments. These collected data were complemented with a limited number of additional tree inventories covering 4 107 trees, giving a total of 14 552 trees in the overall analysis.

Paper IV resulted in a list of tree and shrub species with a high probability of having caused root intrusion and indicated that a very large number of species have the potential to cause root intrusion. One example was the high amount of pipe joint intrusions with the roots of *Malus floribunda* Van Houtte, despite the genus *Malus* being considered to cause a low amount of root intrusions (Ridgers *et al.*, 2006; Mattheck & Bethge, 2000). However, Paper IV showed a low risk of intrusion for *M. domestica* (0.189 root intrusions per available joint compared with the mean of 0.216). Thus the number of root intrusions can differ greatly between species of the same genus (Table 9).

Table 9. Mean number of root intrusions per available joint for woody plant species or cultivars regarded to have caused root intrusions, i.e. individuals within a 10 m radius from the root intrusion point and with no other individuals within 20 m from that point. (see Paper IV for full methodological description).

Species	n, trees within 20 m from pipe	Mean number of root intrusions per available joint	Std. dev.	n, possible joints	n, root intrusions	p, Chi-Square Goodness of fit
Acer campestre	37	0.214	0.153	1 285	191	0.000
Acer platanoides	120	0.247	0.257	3 984	705	0.000
Acer pseudoplatanus	37	0.379	0.389	831	176	0.002
Aesculus hippocastanum	55	0.192	0.149	2 085	293	0.000
Betula pendula	115	0.169	0.134	5 055	776	0.000
Betula pendula 'Tristis'	7	0.199	0.111	637	96	0.000
Betula pubescens	62	0.130	0.068	2 446	314	0.000
Carpinus betulus	91	0.190	0.190	5 133	701	0.000
Crataegus laevigata	8	0.115	0.057	415	52	0.000
Crataegus punctata	5	0.091	0.013	233	20	0.000
Fagus sylvatica	17	0.380	0.451	648	108	0.000
Fraxinus americana 'Autumn Purple'	5	0.151	0.059	93	14	0.032
Fraxinus excelsior	61	0.189	0.198	1 907	252	0.000
Juniperus spp.	8	0.124	0.037	230	30	0.000
Kolkwitzia amabilis	10	0.178	0.202	348	42	0.000
Ligustrum vulgare	28	0.172	0.070	1 370	220	0.000
Malus domestica	55	0.189	0.265	1 966	240	0.000
Malus floribunda	11	0.694	0.569	234	99	0.000
Malus sargentii	5	0.195	0.993	88	14	0.055
Malus spp.	27	0.192	0.085	948	171	0.000
Platanus acerifolia	42	0.413	0.297	1 116	319	0.565
Populus canadensis 'Robusta'	107	0.456	0.482	3 398	1 183	0.000
Populus simonii	85	0.156	0.130	3 097	400	0.000
Populus tremula	37	0.123	0.056	1 114	120	0.000
Populus tremula 'Erecta'	12	0.208	0.135	382	50	0.000

Table 9. Continues

Prunus avium	54	0.209	0.186	1 925	282	0.000
Prunus spp.	48	0.177	0.144	1 823	268	0.000
Pyrus communis	13	0.160	0.158	514	59	0.000
Quercus robur	37	0.197	0.220	1 234	158	0.000
Salix alba	379	0.237	0.235	13 006	2 570	0.000
Salix alba var. *vitellina*	3	0.265	0.012	182	49	0.876
Salix caprea	54	0.194	0.130	1 911	337	0.000
Salix spp.	76	0.202	0.133	3 638	666	0.000
Salix x *pendulina 'Elegantissima'*	16	0.164	0.171	431	47	0.000
Sambucus nigra	14	0.146	0.102	487	58	0.000
Sorbus aria	37	0.148	0.152	1 634	197	0.000
Sorbus 'Astrid'	7	0.120	0.038	356	40	0.000
Sorbus aucuparia	52	0.116	0.113	2 221	210	0.000
Sorbus intermedia	47	0.164	0.100	1 812	233	0.000
Spiraea spp.	52	0.220	0.197	2 734	435	0.000
Syringa vulgaris	60	0.148	0.133	2 320	295	0.000
Thuja occidentalis	32	0.142	0.068	1 105	142	0.000
Thuja plicata	4	0.065	0.026	137	8	0.000
Tilia cordata	26	0.365	0.357	943	174	0.000
Tilia spp.	45	0.179	0.135	1 444	206	0.000
Tilia x europaea	52	0.266	0.385	1 972	294	0.000
Ulmus glabra	106	0.226	0.234	3 474	524	0.000
Ulmus glabra 'Horizontalis'	19	0.446	0.317	720	205	0.676
Ulmus minor	5	0.162	0.085	144	24	0.022
Ulmus minor 'Hoersholmiensis'	76	0.402	0.365	1 746	533	0.038
Ulmus minor subsp. *Sarniensis*	42	0.164	0.105	1 389	184	0.000
Ulmus spp.	18	0.190	0.176	383	53	0.000
Total/mean	2 421	0.216	0.247	88 727	14 837	

Many questions on the underlying causes and progression of root intrusion into sewer pipes remain to be answered. Paper IV is the first example of large-scale data collection being used to provide statistical evidence of differences between woody species in their ability to cause root intrusion. However, more research is needed to confirm these results and to analyse other factors that influence the amount of root intrusions, *e.g.* soil properties, distance between trees and pipes, pipe material, *etc.* (Bosseler *et al.*, 2008).

Overall, discussions on root intrusions tend to come down to whether or not to plant trees and shrubs in the vicinity of pipes. Such discussions are very counterproductive and risk jeopardising relations between urban departments (sewage and water, and parks). The discussion should focus more on giving the two types of infrastructure, 'green' and 'blue', the right amount of space and avoiding unnecessary conflicts that often arise when the relevant departments do not communicate or get involved in the planning process too late.

In most cases, the parks department and the sewage and water department want to have a green city with a functioning sewage and water system. However, to reduce the amount of root intrusion problems while retaining trees and shrubs in our cities, there is an urgent need for more communication, mutual respect and recognition between these two departments.

One could argue that findings about root intrusions into underground pipes provide a reason for urban trees to be cut down. However, the problems must be weighed against the benefits of urban trees. It is important that work such as this is conducted by researchers within the green field, because they can show the positive effects of trees in the urban environment.

As with Papers II and III, a popular science version of Paper IV, written in Swedish, has been distributed throughout the sector (Östberg *et al.*, 2010b). The results have been presented at several conferences, *e.g.* the annual conference of the International Society of Arboriculture (ISA) in Sydney, and as part of a national conference tour where representatives from both the blue and green departments were represented and talked about possible cooperation. The findings have also been presented to municipal sewage and water departments in a Swedish report distributed in their language, through their channels, to further increase awareness about the issue (Östberg *et al.*, 2010a).

6 Discussion

Urban forestry is a young science and practice in a phase of rapid development, which will most likely continue within both science and practice, and regarding both specific and general uses. Future developments may include *e.g.* further improvements to data collection methods for urban tree inventories and use of more tree inventory parameters. The work described in this thesis is intended to help in this process, so that the area of urban forestry and urban tree inventories becomes more comparable, with standardised methods for data collection.

6.1 Tree inventory methods and parameters used when conducting urban tree inventories

As described in Papers I and II, there are a large number of parameters and methods that can be used when conducting tree inventories, but the most important point in designing a tree inventory is knowing the ´why´ (Smiley & Baker, 1988). With the large amount of tree inventory parameters and data collection methods available, the questions of 'why' and 'how' can be almost impossible to grasp for *e.g.* researchers, municipal employees, cemetery managers and consultants.

Most tree inventory parameters can be determined with a high accuracy by the use of field surveys (Paper I). However, without knowing how cities use their inventories, it is difficult to know whether this is always the best choice of method. Unfortunately, many of the parameters included in inventories are not needed to meet the objective (Thomsen, 2012). For example, in a past development project I measured 15 tree parameters, but only one, *Conservation class*, was ultimately used in planning and construction work. The prioritisation of tree inventory parameters presented in Paper II will hopefully help users choose tree inventory parameters and will reduce the risk of important parameters are missed and inventories lacking comparability due to the use of different parameters. In the practical report based on Paper II, the top ranked parameters are recommended as standard tree inventory parameters to be used in all inventories, thereby making these comparable between research projects, cities, cemeteries and other users (Östberg *et al.*, 2012b; Östberg & Nielsen, 2012). As a complement to that report, a list has been drawn up of the parameters that should be collected for each specific purpose (Östberg *et al.*, 2012a). It is also important to balance the need for information, both at the time of collection and in the future, against the cost of collecting the data.

The parameters inventoried for a specific purpose can be used for other purposes by setting them in a different context. Furthermore, an inventory that has been conducted for a specific purpose by practitioners can also be used in general research. In all cases it can be of major benefit for both researchers and practitioners to use the same basic parameters. An example of this is hazard tree inventories, where several parameters are used to give a good picture of the hazards a tree can pose to both people and property. In these inventories some kind of size parameter is often included (Lonsdale, 1999), and if this size parameter is of a standard form the inventory can be utilised for a multitude of purposes outside the hazard tree management programme. Papers III and IV are almost entirely based on parameters acquired from the practitioners' own data collections*, i.e.* data collected in the local context, often for specific purposes, but the number of parameters needed was rather low, two per paper (*Tree species* in both articles, *Street or park tree* in Paper III and *Coordinates* in Paper IV). This shows how comparability of only a few parameters can have large positive effects.

The following five tree parameters should be regarded as the most important in any inventory (Paper II): *Scientific name of tree species and genera*, *Vitality*, *Coordinates*, *Hazard class*, *Identification number.* In addition, DBH should probably be included, as it is a commonly used parameter for the description of tree size and in scientific studies (Paper I) *e.g.* as a growth indicator (Grabosky & Gilman, 2004), in climate management (Ningal *et al.*, 2010) and in economic benefit calculations (i-Tree, 2012b), indicating its relevance for city officials and academics.

There was rather high consensus on the top 10 parameters, which all had a total mean score of more than 8.8 out of 10 (Paper II). All the parameters used in Papers III and IV were among these top 10. If other parameters had been comparable, *e.g.* vitality (rated second most important in Paper II), Papers III and IV would have gained an interesting edge. For instance, it would have been possible to see whether exotic species have a higher vitality than native species in street environments (Paper III), and whether tree species that cause root intrusion have higher vitality (Paper IV). However, such comparisons were not possible due to the lack of information on vitality, or of comparable definitions of this parameter in all databases.

In the Nordic countries there does not seem to be any discussion about alternative tree inventory methods other than the classic field surveys, whereas in the United States inventories seem to be conducted with a wider variety of methods and also more plot surveys (Woodall *et al.*, 2010; Cumming *et al.*, 2001; Diem & Comrie, 2000). This could be due to the use of i-Tree and other programmes for assisting US cities in planning and executing their inventories, but it could also be that sampling is quicker and thereby used by researchers with only a single research question to answer. A third, and highly possible, explanation is differences in city size, as many US cities are considerably larger than their Nordic counterparts. The use of field surveys in the Nordic countries can also be due to the previous lack of clear recommendations on other inventory methods available, a shortcoming rectified in Paper I. There can hence simply be a lack of understanding of the other available methods. It is probably not possible to standardise tree inventory methods, but Paper I can help researchers and practitioners choose methods suitable for collecting the tree inventory parameters needed for a specific objective.

6.2 Cooperation between stakeholders

The subject of this thesis, as indicated by the title, was tree inventories in the urban environment, but in Papers II-IV another topic arose. This concerned the importance of cooperation between the various stakeholders, organisations or cities involved, in Paper II between the stakeholders in planning urban tree inventories, in Paper III between cities, and in Paper IV between the parks department and the sewage and water department.

An important aspect of the thesis is that the data used in Papers III and IV were collected from practitioners. The use of these data in research revealed possible areas of cooperation between researchers and practitioners as regards sharing data for various purposes. In Papers III and IV the data were utilised for several purposes, irrespective of the initial purpose for which they were collected. One of the strengths of this thesis is hence that it not only focuses on tree inventories, but uses them in a practical way. The practical implications have already been communicated to the industry, *via e.g.* information newsletters (Sjöman *et al.*, 2012b; Östberg *et al.*, 2010b).

A city's green space department or section can of course work by itself, without entering into dialogue with other stakeholders. However, this is probably not only short-sighted but also counter-productive, because it will almost certainly lead to the isolation of urban forest management. In the long run, this can have the effect of undervaluing the importance of the urban forest and hence losing funding and protection. With good cooperation between stakeholders, the urban forest is less likely to become a series of isolated islands within the city, but instead an integral part of the urban environment and an essential part of a functioning city. By cooperating, the importance of trees will surely be recognised, and the development of new solutions will most certainly appear, such as the open stormwater management solution mentioned earlier (Stahre, 2008; Stahre, 2006). However, in order to achieve this communication the stakeholders involved need to know what they are managing, which for the parks department means having a tree inventory (Gerhold & Frank, 2002).

The importance of the parks department having an updated tree inventory in order to conduct a dialogue with the sewage and water department is clear in Paper IV. Without this basic information, it is difficult to have a systematic discussion on possible concerted efforts between the parks department and pipe managers to reduce the number of root intrusions. It is also of great importance in allowing other collaborations between the departments, *e.g.* on open stormwater management (Stahre, 2008; Stahre, 2006). If there is to be a more long-term solution to the problem of root intrusion, there is a need for cooperation of the type found in Malmö, where the sewage and water department and the parks department have a functioning relationship (Stahre, 2008; Orvesten *et al.*, 2003). One of the many examples in the city is Vanåsgatan, where the water and sewage department paid for the street and green areas to be rebuilt to better handle stormwater and thereby stopped basement flooding. This also gave the residents a popular new green area (Stahre, 2008). This might seem simple, but in some cities it is considered very unorthodox and sometimes even illegal, and the relevant department instead only demands that trees responsible for root intrusion be cut down. The cooperation in Malmö has led to a good solution for open stormwater management and also guidelines for solving root intrusions in other areas of that city (Östberg, 2008).

All places with a tree planting pit and underground pipes in close proximity should be regarded as a conflict zone where cooperation is needed between the relevant managers, a prerequisite for which is mutual respect.

Having shared information about trees and discussions is also important in the cooperation between cities (Paper III) and between other stakeholders (Paper II). It is therefore important to have common meeting places and forums where information can be shared (Sjöman & Nielsen, 2010).

In Paper III the stakeholders were presumably only the 10 cities involved, but several other parties were involved in the selection of urban tree species. There have been extensive discussions about the use of non-native species in rural and urban environments (Alien plant group, 2012; Hitchmough, 2011; Stewart *et al.*, 2009; Stewart *et al.*, 2004; Parker *et al.*, 1999). Such discussions on how best to manage urban trees and on the use of exotic/native should be regarded as normal and could be mutually beneficial, but in some countries have led to an infected debate. It is reassuring to see that the Swedish authorities (City Gardeners, Environmental Protection Agency, National Heritage Board, Provincial government (Länssyrelsen), Transport Department, Swedish Church's National Organizations and Swedish University of Agriculture) have started cooperation over departmental borders to answer this and other questions concerning trees in the urban environment. Without these kinds of cooperation, there is a risk of organisations opposing each other and thereby damaging the whole sector working with urban trees. The fusing of urban tree databases in Paper III creates the overview needed to base these important discussions on facts, rather than estimations.

6.3 Conducting, implementing and using urban tree inventories

A single inventory cannot possibly cover all possible purposes organisations might have for the data, as this would make the number of parameters untenable (Paper II). Organisations must therefore define the purpose for which the inventory is being conducted, and choose parameters for this purpose. There are unfortunately frequent examples of large-scale inventories in which many of the parameters have not served a purpose and the work has hence not been cost-effective. By selecting tree inventory parameters carefully, the practitioner or researcher can also evaluate which tree inventory method is suitable for collecting information on the parameters (Paper I). It is possible to determine most inventory parameters with field surveys, but this is an expensive method because of the time it takes to manually inspect the trees (Paper I).

When tree inventory information is collected, it needs to be accessible and integrated into city management and also shared with other cities, so that it can be utilised internal and external by researchers and practitioners.

With this integration it is possible to foresee future conflicts and also to avoid *e.g.* damage by trees to underground pipes and excavations to deal with root intrusions (Paper IV) (Östberg *et al.*, 2010a). With the help of an urban tree inventory, cities will also have good knowledge of the potential risks with the urban tree population, *e.g.* low amount of species (Paper III), and will have hard data that can be used to gain an understanding from politicians, *e.g.* i-Tree in NY (Peper *et al.*, 2007). In the city of Copenhagen, the tree inventory has led to a management programme to increase species diversity and monitor tree diseases that could affect the urban tree population (Lars Christensen, pers. comm. 2012), which is in line with the recommendation in Paper III.

Without a urban tree inventory, it is almost impossible to have long-term management plans regarding *e.g.* planning new plantation of trees (Escobedo & Andreu, 2008), changing the species distribution (Paper III), selecting tree species for a changing climate (Ignatieva *et al.*, 2011) or governing the urban tree population in a sustainable way (Escobedo & Andreu, 2008).

6.4 Future of urban tree inventories

The overall aim of supporting the development of a common framework that can facilitate synergy between municipal tree managers, researchers and other actors was fulfilled through the work reported in Papers I-IV. Paper I linked objectives, choice of tree inventory parameters to collect and inventory methods, thereby giving a basic framework for urban inventories by showing the methods with the highest accuracy and the advantages and disadvantages of each method. Paper II provided a standard list of tree inventory parameters to include in all inventories and created a link between the common framework and the different actors (city officials, arborists, and academics). Paper III and IV identified possible synergy effects between city officials, arborists, and academics and set them into a new context, irrespective of the initial focus of individual inventories. Paper III showed that an important step in creating synergy effects between cities is to make the data obtained in inventories comparable and to share these between cities. Paper IV identified the synergy effects that can be achieved when tree inventories are combined with an infrastructure database, in that case between different municipal user groups, between the cities involved and between academic researchers.

It is exciting to see the large increase in recent publications dealing with the topic of tree inventories, as shown in Paper I. It is also interesting to see how technological developments are reflected in these publications, from basic databases and heavy equipment inventories to today's processing of databases and development of functions where ordinary digital camera images are used to calculate tree crown volume and size. This may give an indication of the future for the research presented in this thesis; hopefully the information demanded will become more or less routine.

The remaining question is what will be tomorrow's cutting-edge research? More inventory parameters and methods for collecting data are being developed and it would be surprising if this development does not continue. However, my wish for the future is not for more parameters and methods to be made available, but instead for existing parameters to be used more effectively and for any inventories conducted to be better planned so that the right parameters and methods are used.

Much data about tree species used in cities around the world already exists, but is located in city databases and not shared between cities or with researchers. This will hopefully change in the future, so that trees are selected from the combined experience of different cities and researchers. A start to this work can be seen in the Swedish Tree Portal (Trädportalen, 2012) where information on trees can be accessed by anyone. Swedish cities will hopefully soon be able to upload their complete databases onto this website thanks to the work done on standardising tree inventory parameters in Paper II. This Tree Portal will hopefully be an important research instrument, but also a meeting point for cities wanting to know which tree species can grow in different environments and climate zones.

When working with urban forests, we need not only to know what we are governing, but also what other parts of the urban infrastructure are affected, or affect us (Paper IV). By knowing this, we can take appropriate actions to coexist in the best way possible and find solutions that can be of benefit for all areas involved. This is of course difficult, and may require those involved to take a step back and look at the problem from the point of view of the other parties. It is clear that partnerships will be a necessity in managing future urban forest because of the high demands, *e.g.* arising from climate change, and the dwindling resource base, *e.g.* arising from the economic climate.

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The papers

Due to copyright reasons, the original article cannot be published in this online version of the thesis. Paper II, III and IV are although accessible via the following web addresses:

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Urban tree inventories are being employed to an increasing extent by a diverse group of users for a wide range of applications. This has resulted in large numbers of different parameters being recorded and a variety of methods being used by researchers and practitioners. This thesis therefore sought to support the development of a common framework that can facilitate synergies between different groups that use and/or collect data on individual urban trees.

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