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Kan återinventering av urbana träd informera framtida trädval i staden?
- Brösthöjdsdiameter som indikator för utvecklingen av Malmös träd

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Can urban tree re-inventories inform future species selection?

Diameter at breast height as an indicator for tree performance in Malmö municipality's re-inventory database

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Abstract

Using the inventory database of trees for Malmö municipality, Sweden, this study explored the potential of using the diameter at breast height (DBH) measurement in re-inventories, as a decision-making tool for species selection and management in urban forests. With the escalating pressures of urbanization and unpredictable climate change effects, there is an urgent need for urban forest managers to possess reliable tools that can facilitate the selection of resilient tree species capable of thriving in diverse and changing urban contexts. A series of discussion graphs were used in this study's analysis to effectively illustrate the relationship between DBH, growth rates, and the provision of ecosystem services. DBH, acknowledged as a significant inventory parameter, was found to be an effective proxy for crown diameter, which serves as a vital indicator of the extent of ecosystem services provided by urban forests. The study found species-dependent differences in relative performance, as indicated by growth rate, across various planting environments and groundcover types. One method of categorizing trees into age groups was explored to assess any age-dependent performance differences. However, the analysis revealed little variation within species between the selected age groups. Future research could adopt more sophisticated analyses, focusing specifically on species-specific growth curves and performance in younger trees. This study demonstrates that DBH measurements are a valuable tool for guiding species selection. Continued study of this data can help urban tree managers make informed decisions about species likely to perform well in the future. Specifically, understanding species performance in more restrictive environments, such as hardscapes or street environments, can provide predictive insights into species' resilience in increasingly challenging conditions induced by climate change. It is strongly recommended that future re-inventory efforts continue to prioritize the inclusion of DBH measurements in re-inventories to increase the available data for analysis. The continuous incorporation of this parameter will yield a more comprehensive understanding of tree populations, ultimately enabling informed decision-making and facilitating the formulation of effective management strategies for urban forests in the future.

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Abbreviations

DBH	Diameter at breast height
EN	English
SV	Swedish
FGK	Fastighets- och gatukontoret (EN: The property and street office)
GIS	Geographic information system
USDA	United States Department of Agriculture
SLU	Swedish University of Agricultural Sciences (SV: Sveriges lantbruksuniversitet)

1. Introduction

1.1 Background

The challenges posed by climate change and increased urbanization have underscored the necessity for effective and efficient planning and management of the urban forest (i.e. all trees within the urban context). These challenges have driven the need to foster sustainable and resilient urban environments, alongside more cost-effective strategies for urban forest management (Ordóñez and Duinker, 2013; van den Bosch and Ode Sang, 2017).

Urban forestry is an evolving field, but its purview increasingly encompasses all trees in the urban context. This includes groupings of trees and individual specimens in and around urban areas, with a predominant focus of the field centered on delivering ecological, cultural, and economic benefits for urban populations (Konijnendijk *et al.*, 2006; Miller, 2015). Urban forests are recognized for providing essential regulating services, such as mitigating the urban heat island effect, reducing stormwater runoff, enhancing air quality, and supporting biodiversity (McPherson *et al.*, 2005; Tyrväinen *et al.*, 2005; Lerman *et al.*, 2014).

Yet, within the urban environment, trees rarely achieve optimal growth conditions (Ingemansson, 2013). Suboptimally performing trees are less effective in delivering ecosystem services, their reduced vitality and longevity necessitate frequent replacements. This underperformance carries economic repercussions, as the need for alternative sources of regulating services, such as stormwater management, arises. Thus, the selection of suitable tree species, resilient in varied urban settings and capable of delivering crucial ecosystem services, emerges as a cost-effective strategy in urban forest management (Sjöman and Nielsen, 2010). This is especially important in the context of climate change, and in order to avoid these losses, urban forest managers must plan the increase of tree canopy cover in a way that is mindful of the future climatic conditions (Esperon-Rodriguez *et al.*, 2022).

Recently, research has concentrated on examining the ecosystem services offered by urban trees (Nielsen *et al.*, 2014). However, despite the significant role of long-term monitoring of tree inventory data in identifying underperforming species and informing future species selection (Sjöman and Nielsen, 2010; Roman and Scatena, 2011), studies addressing this area are surprisingly scant (Esperon-Rodriguez *et al.*, 2022). Analyzing urban forest re-inventories for parameters that may indicate how best to increase ecosystem services provided by trees and inform future funding allocation to certain species has not been widely studied. It is critical to understand the dynamics and growth patterns of urban tree populations over a period of time in order to effectively manage these resources and inform the development of future, climate-proof, and less vulnerable urban forests.

1.2 Research aim and questions

This study addresses the possibility of using urban tree re-inventories to inform future species selection in urban forests. By focusing on the easily obtainable and standardized trunk diameter at breast height (DBH) measurement data, the primary purpose of this study is to evaluate tree growth and performance across various urban environments, thus contributing to the development of cost-effective and sustainable urban forest management strategies. The study aims to assess the feasibility of utilizing DBH re-inventories as a decision-making tool for species selection and management in urban forests, as well as to compare the growth of different tree species over time in street and park environments. To achieve this, the research questions posed are: *Can DBH re-inventories inform urban tree managers in future species selection decisions?* and *What are the relative growth rates of different tree species in street environments as compared to park environments?*

2. Central principles and metrics

2.1 Urban planting environments

Trees within the urban forest must contend with a complex array of environmental factors that significantly influence their establishment, growth, and overall vitality (Sæbø *et al.*, 2005; Esperon-Rodriguez *et al.*, 2022). The spectrum of urban planting environments could be represented as a gradient, extending from more natural settings like parks and urban woodlands, to more artificial scenarios such as streets and other hardened areas. Trees in park and urban woodlands are subjected to moderate environmental stressors, whereas trees in a street environment may be subject to more challenging factors affecting their survival and vitality, such as the urban heat island effect, soil compaction and limited soil volume, limited soil nutrients, pollution and road salt exposure, and limited water availability, as well as stresses from animals and humans (Sæbø *et al.*, 2005; Sieghardt *et al.*, 2005; Gill, 2006; Bühler *et al.*, 2007; Sjöman and Lagerström, 2007; Parlow, 2011; Sjöman *et al.*, 2012; Esperon-Rodriguez *et al.*, 2022). Management and establishment practices are also variable depending on the planting environment of an urban tree. Trees which are planted near buildings, sidewalks, roads, or cycle paths often require pruning which, when carried out too enthusiastically, can damage the tree or lead to vulnerability to pests, diseases, and storm damage (Steed and Fischer, 2007; Roman *et al.*, 2013). The effects of these stressors are all exacerbated by the ramifications of climate change (McPherson *et al.*, 2018; Esperon-Rodriguez *et al.*, 2022).

'Park trees' and 'street trees' are terms frequently employed in urban forestry and urban tree management to serve as reference points on this urban planting environment gradient. Each term represents a degree of exposure to urban stressors and, consequently, distinct survival and growth prerequisites. Notably, while these terms are common, few definitions of 'park trees' and 'street trees' appear within the existing literature. Where they do exist, they are vague and often open to interpretation. Steed and Fischer (2007), writing about this lack of a clear definition, say that street trees can be "[l]oosely defined as trees lining municipal streets" or defined as "trees that are in close proximity to streets". Sjöman and Östberg (2019) write that street trees "are defined as trees placed in or close to streets or roads and needing special management in order to meet the demands of the street environment". Bolund and Hunhammar (1999) define street trees as "stand alone trees, often surrounded by pavement". Although no definitions of 'park trees' were found during the review of the literature, Bolund and Hunhammar (1999) do define "lawns/parks" as "managed green areas with a mixture of grass, larger trees, and other plants".

The environment within which a tree is to be planted is of paramount importance when selecting a tree species. To select a tree which is not tolerant to the environment in which it is planted increases the cost of future maintenance, decreases the ecosystem services it provides, and can ultimately lead to costs related to removal and replacement of the tree (Pauleit, 2003; Sæbø *et al.*, 2005; McPherson *et al.*, 2018).

2.2 Urban tree inventories

Urban tree inventories entail a systematic collection of vital data including tree species, location, size, and health, among other parameters. These inventories serve as cornerstones in urban forest management, functioning not only as detailed records of the managed resources but also as critical sources of insights into species composition, age distribution, and overall tree health (Bassett, 1978; Miller, 2015; Morgenroth *et al.*, 2016). Beyond providing a comprehensive overview of the resources, inventories streamline strategizing, coordination, and oversight of maintenance efforts, assisting in the formulation of management decisions, especially in the realm of budget planning. They also mark the commencement of long-term assessment and monitoring of an urban tree population, thereby playing an indispensable role in urban forest stewardship (Bassett, 1978; Baker, 1993; McPherson, 1993; Cumming *et al.*, 2008; Nowak *et al.*, 2008).

In the realm of urban forestry, a diversity of tree inventory methodologies are employed. Complete inventories, for instance, offer a meticulous, tree-by-tree appraisal of the urban forest, capturing comprehensive data on each specimen. While this approach provides unparalleled precision, it is often practicable only for smaller tree populations due to the prohibitive costs associated with larger surveys. Partial inventories emerge as an economical alternative for the evaluation of extensive tree populations (Baker, 1993). This approach, however, may result in increased variance, implying potential uncertainty concerning the representation of the wider tree population (Nowak *et al.*, 2008). These inventories might encompass a contiguous area, be characterized by trees sharing a common parameter, such as species, or be constructed based on a random sampling technique (Nowak *et al.*, 2008). Moreover, some inventories are specifically tailored to identify and record issues within a tree community, including the incidence of diseases or potential threats to people and property. Cover type surveys, traditionally employed to characterize commercial forest lands, have recently been adapted to urban contexts for quantifying canopy cover and tracking changes in urban vegetation. They offer a holistic examination of the entire tree population, including privately owned trees. As these surveys do not collect individual tree data, they are primarily suited for long-term land use planning rather than detailed work planning or contract preparation. Moreover, they can be cost-efficient if existing aerial photographs are utilized (Smiley and Baker, 1988). Notably, tree inventories may be classified according to their temporal characteristics: static or continuous. Static inventories remain unchanged post initial data collection, while continuous inventories undergo regular updates, thereby offering a dynamic and evolving dataset (Bassett, 1978; Smiley and Baker, 1988; Baker, 1993; Nowak *et al.*, 2008).

Urban tree inventories can be conducted using different methods, which can generally be categorized into two main approaches: top-down aerially based approaches and bottom-up ground-based approaches (Nowak, 2018). Top-down approaches encompass various techniques such as ground surveys, remote sensing, airborne (ALS), terrestrial (TLS), satellite imaging, aerial photography, mobile laser scanning (MLS), and drone technology (Randrup *et al.*, 2020). These methods involve capturing data from above, providing a comprehensive view of the urban tree canopy (Nowak, 2018). On the other hand, bottom-up approaches primarily rely on fieldwork conducted by professionals or through citizen science initiatives. In bottom-up approaches, volunteers may receive instructions on how to carry out the inventory, contributing to data collection efforts (Randrup *et al.*, 2020). This approach allows for a more hands-on and participatory approach to inventorying urban trees. In practice, an urban tree inventory can utilize a single approach or a combination of these methods, depending on the specific goals and resources available. The choice of approach depends on factors such as the scale of the inventory, the desired level of detail, and the available technology and expertise. By considering and selecting appropriate methods, researchers and practitioners can gather comprehensive and reliable data on urban trees, supporting informed decision-making and effective urban forest management.

According to a landmark paper on urban forest monitoring by F.A. Baker (1993), the quality control of data plays a pivotal role in inventorying a tree population, as it ensures the accuracy and reliability of the collected information. It's essential to incorporate this facet into the inventory process. Despite their infrequent use, quality control procedures have the potential to significantly enhance the precision of the data gathered. The efficacy of this data relies heavily on the quality of the collected information. To achieve this, the individuals conducting the inventory should be adequately trained. Proper training mitigates the chances of inaccuracies arising from species misidentification or errors in data recording. Nevertheless, despite comprehensive training, errors can still emerge at various stages, including during data entry for further analysis. Technological advancements provide an effective solution to these challenges. Handheld tablet computers, for instance, can be used for field data recording. This not only streamlines the process but also reduces costs associated with the inventory. With instant data storage and processing capabilities, this digital method eliminates the need for paper-based notes and subsequent manual data entry. The adoption of a digital approach also enhances accuracy by reducing the chances of transcription errors, ultimately improving the overall integrity of the inventory process (Baker, 1993).

There has been an increased interest in tree inventories in recent decades due to factors such as pest and disease challenges and the recognition of ecosystem services provided by urban trees (Raupp *et al.*, 2006; Roy *et al.*, 2012; Hubacek and Kronenberg, 2013). Municipalities in North America and Europe have increasingly conducted tree inventories, albeit with differing focuses at times (Keller and Konijnendijk, 2012; Sjöman *et al.*, 2012).

North American inventories have largely employed i-Tree (i-Tree, 2023) to perform economic valuations of urban trees, while Northern European inventories have centered more on ecological and management issues, such as tree health, monitoring the dynamics of urban tree stands, and biological values (Kielbaso, 2008; Sörensson, 2008; Morgenroth and Östberg, 2017).

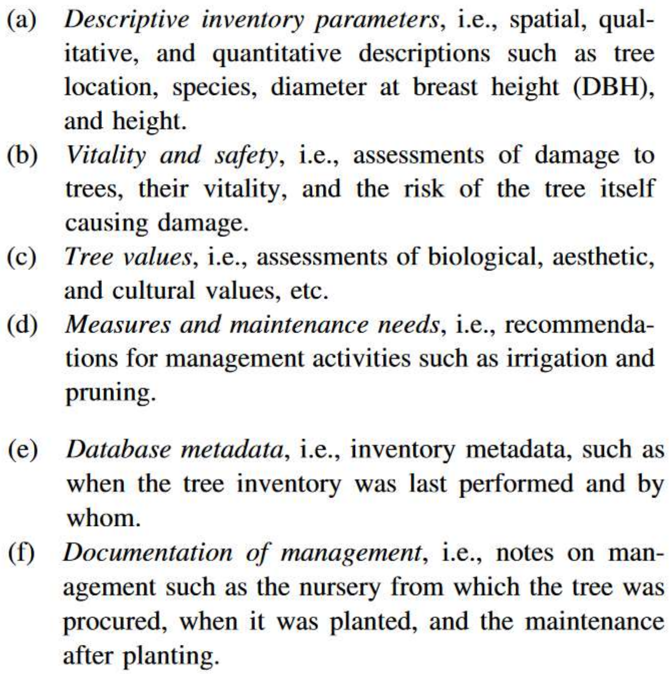
In 2019 a survey was conducted to assess the state of urban tree inventories in Australian cities. 66% of the 116 local government areas surveyed reported having a tree inventory. The most common attributes collected in these inventories were species' scientific name, location, and planting date. The presence of an inventory and the area it covered were positively associated with human population density. However, the research shows that there has not been a significant advance in the adoption and use of urban forest inventories over the past three decades (Esperon-Rodriguez *et al.*, 2022).

2.3 Key inventory parameters

Urban tree inventory and management involve multiple academic disciplines and professions, which may result in varying perceptions and valuations of different parameters. For instance, urban forestry professionals, including arborists and urban foresters, may prioritize provisional and cultural ecosystem services, whereas ecologists and biologists may exhibit a stronger interest in supporting services such as biodiversity, although biodiversity has lately become increasingly important to urban forestry professionals (Östberg, 2013). However, increasing the quantity of parameters in a given inventory may escalate the expense related to executing and updating the inventory, which underscores the importance of judicious selection of parameters (Östberg *et al.*, 2013b). As R.W. Miller (2015) put it, "A… tree inventory need not be complex or expansive in the attributes that are measured, but should at least provide some minimal lever of information that will allow the manager to make intelligent management decisions".

In a 2013 study (Roman *et al.*, 2013) in which 32 participating urban forestry organizations in the United States were surveyed about their urban tree-monitoring programs, it was found that the most commonly recorded parameters were species (96%), condition rating (89%), mortality status (76%), DBH (71%), and specific health problems (67%).

A 2013 study in Sweden by Östberg and co-authors used the Delphi method to gain feedback from panels of different backgrounds such as city officials, arborists, and academics, on the usefulness of various parameters. They rated 148 parameters, which were compiled using several references such as urban tree inventories in several large Nordic countries, USDA urban forestry standards, and tree risk manuals. They were classified into six thematic groups (Östberg *et al.*, 2013b):



(a) *Descriptive inventory parameters*, i.e., spatial, qualitative, and quantitative descriptions such as tree location, species, diameter at breast height (DBH), and height.
(b) *Vitality and safety*, i.e., assessments of damage to trees, their vitality, and the risk of the tree itself causing damage.
(c) *Tree values*, i.e., assessments of biological, aesthetic, and cultural values, etc.
(d) *Measures and maintenance needs*, i.e., recommendations for management activities such as irrigation and pruning.
(e) *Database metadata*, i.e., inventory metadata, such as when the tree inventory was last performed and by whom.
(f) *Documentation of management*, i.e., notes on management such as the nursery from which the tree was procured, when it was planted, and the maintenance after planting.

Figure 1: The thematic groups into which the 148 parameters in the Delphi study were classified. © Springer Science+Business Media.

The five parameters which were found to be the most useful by the participating panels were: *Scientific name of the tree species and genera, Vitality, Coordinates, Hazard class,* and *Identification number* (Östberg *et al.*, 2013b). In the most recent version of "Standards for Conducting Tree Inventories in Urban Environments" by Östberg and co-authors (2022), these five parameters are identified with slightly different terminology: *Scientific name, Vitality, Coordinates/Location, Risk class,* and *ID number.* They identify these as proposed standard parameters in all tree inventories. To this list, they also include *Trunk diameter at chest height (which is measured at a height of 1.3 meters).* In a previous version of the standards (Östberg *et al.*, 2013a), it is explained that, in the aforementioned Delphi study,

"Of the parameters relating to trunk circumference or trunk diameter …Trunk diameter 1.3 metre height emerged as the parameter that received the highest score (5.7). Since this parameter is very commonly used nationally and internationally, and is also very important in many models, we opted to include it as one of the most important parameters."

As an example of how these parameters may be defined and collected during an inventory, the following is a brief description of each of the six parameters mentioned above, taken from several versions of tree inventory standards developed by Johan Östberg and his fellow authors (Östberg *et al.*, 2013a; Östberg and Rowicki, 2022):

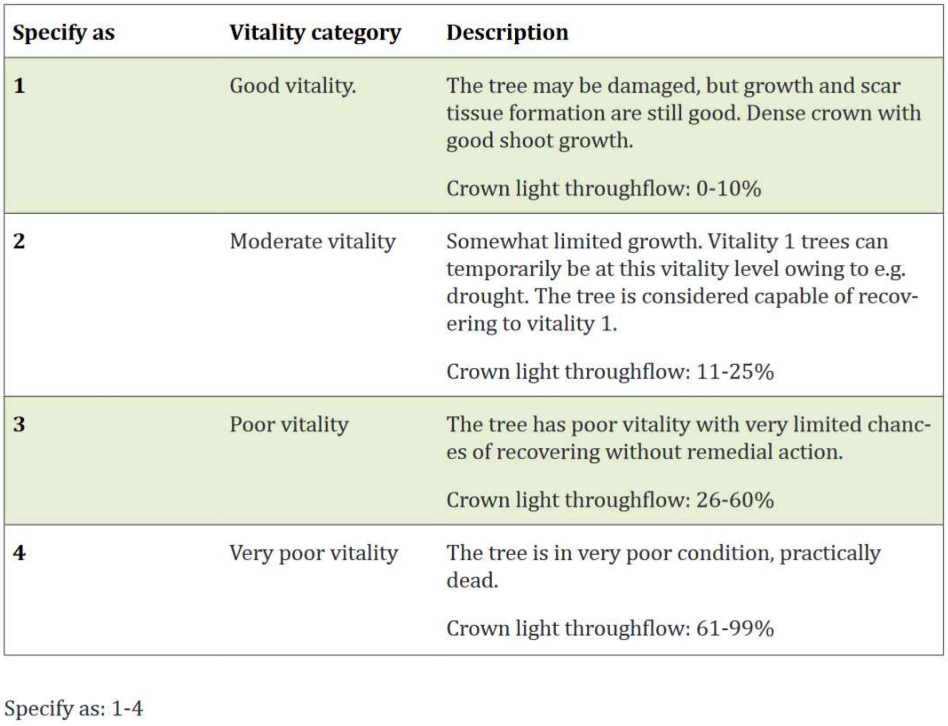
Scientific name:

From version 3.0: “Enter the genus, species and variety and, where applicable, whether the tree is an E-plant. The name should be entered in accordance with the Swedish Cultural Plant Database (SKUD). If there is uncertainty, only those parts of the name of which the enumerator is certain should be entered” (Östberg and Rowicki, 2022).

From version 1.0: “It is recommended that Family, Species, Variety and E-status are recorded as separate parameters (in other words in separate columns) in databases, since this makes it considerably easier to carry out searches in the material. Specify as: *Genus – species* -‘Variety’ – E” (Östberg *et al.*, 2013a).

Vitality:

From version 1.0: “An assessment of vitality class. Vitality assessment based on factors such as a visual evaluation of the tree’s crown structure according to the table and picture examples below. Vitality assessment using light throughflow comes from a German manual (Roloff, 2001). However, it should be pointed out that this method is not suitable for all types of trees, since for example the maidenhair tree, Ginkgo biloba, would never achieve vitality 1. It is also important to note that tree vitality and degree of damage are two different parameters. For example, a willow stool can be vitality 1 despite having a damaged crown and sometimes a hollow trunk.” (Östberg *et al.*, 2013a)

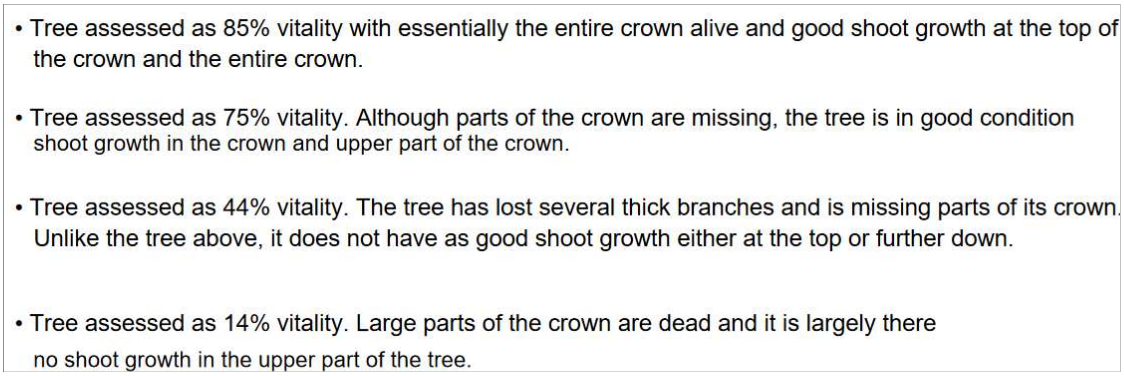


Specify as	Vitality category	Description
1	Good vitality.	The tree may be damaged, but growth and scar tissue formation are still good. Dense crown with good shoot growth. Crown light throughflow: 0-10%
2	Moderate vitality	Somewhat limited growth. Vitality 1 trees can temporarily be at this vitality level owing to e.g. drought. The tree is considered capable of recovering to vitality 1. Crown light throughflow: 11-25%
3	Poor vitality	The tree has poor vitality with very limited chances of recovering without remedial action. Crown light throughflow: 26-60%
4	Very poor vitality	The tree is in very poor condition, practically dead. Crown light throughflow: 61-99%

Specify as: 1-4

Figure 2: Table of vitality class specification descriptions from Östberg, Delshammar and Nielsen, 2013 standards version 1.0. © 2013 Authors and illustrator

In version 3.0 of the standards, the practitioner is called upon to record the vitality as a percentage, as opposed to on a scale from one to four. From version 3.0: “Vitality is a measure of the tree's vitality. Vitality is indicated as a visual assessment of the tree's crown structure according to the image example below, and is made with regard to the species being assessed. This parameter is synchronized with the Swedish Environmental Protection Agency's publication Inventory of trees worthy of protection in the cultural landscape (2020). The vitality is given in % where 1% is basically dead and 100% is fully vital” (Östberg and Rowicki, 2022). In the publication, there are associated illustrations of tree crowns to support the assessment of vitality.



- Tree assessed as 85% vitality with essentially the entire crown alive and good shoot growth at the top of the crown and the entire crown.
- Tree assessed as 75% vitality. Although parts of the crown are missing, the tree is in good condition shoot growth in the crown and upper part of the crown.
- Tree assessed as 44% vitality. The tree has lost several thick branches and is missing parts of its crown. Unlike the tree above, it does not have as good shoot growth either at the top or further down.
- Tree assessed as 14% vitality. Large parts of the crown are dead and it is largely there no shoot growth in the upper part of the tree.

Figure 3: Vitality assessment percentage descriptions from Östberg and Rowicki, 2022 standards version 3.0. © 2013 Authors and illustrator

Coordinates/Location:

From version 1.0 of the standards: “Enter the geographic coordinates of the tree, as well as which coordinate system was use. Enter according to: X and Y coordinates” (Östberg *et al.*, 2013a).

Risk class:

According to version 3.0, “Risk is defined according to Swedish Standard 990000 (2020) as: “The effect of uncertainty on targets”. Risk is specified according to this standard as levels 1-4” (Östberg and Rowicki, 2022). In this ranking system, a risk class 1 tree is defined as a “low-risk tree which shows no signs of risk to people or property for the foreseeable future”. A risk class 4 tree is defined as a tree which “poses a very high risk to property or person”.

ID number:

Considered metadata, the tree ID is a unique number given to each tree (Östberg *et al.*, 2013a).

Trunk diameter at breast height:

Commonly referred to as DBH, this refers to the measurement of a tree trunk's cross-sectional diameter, taken at a right angle to the trunk's axis, at a height of 1.3 meters above the ground, although the height may vary slightly depending upon which standard is followed or in which geographic region the measurement is being taken (West, 2015). The most common standards followed in Swedish municipalities are those created by the SIS, the Swedish Institute for Standards, under Svensk Standard 199000 (SIS, 2014), and those published by Svenska Trädföreningen, which are based largely on those created by SIS (Östberg and Rowicki, 2022). DBH is a widely used and relatively reliable metric for manually measuring trees, as it aims to provide a standardized approach that can be easily applied across different tree species and urban environments (West, 2015).

DBH is most often obtained by manual measurement in a field inventory, using tools such as the Biltmore stick, diameter band (D-tape), measuring tape, or caliper. If none of these tools are appropriate for a particular case, estimation of the DBH may be used (Östberg and Rowicki, 2022).

2.4 The importance of DBH

In forest science, the measurement of a tree's stem diameter or circumference is considered to be of paramount importance. This metric exhibits a strong correlation with various other challenging-to-measure attributes, including the tree's stem wood volume, overall biomass or specific biomass components (e.g., leaves, branches, stem, and roots), as well as its competitive standing within the forest ecosystem (West, 2015). It's crucial to note that a significant portion of the ecological benefits derived from urban trees are intimately linked with the size of their crowns (Coombes *et al.*, 2019). While the leaf area index (LAI) is a more accurate measurement to assess these dimensions, it is often a more expensive and time-consuming metric to assess. Crown diameter or area is also a useful tool to measure ecosystem services provided, but difficult to measure accurately in the field. In Malmö, crown diameter is recorded by estimating meters via steps, while trunk diameter is most often measured with a tape measure (Bellan, 2023a).

As stated previously, in a 2013 study (Roman *et al.*, 2013) 71% of the participating urban forestry organizations in the US identified DBH as being a parameter in their standard tree inventories, coming in as the fourth most-used inventory parameter. In a 2021 study by SLU which surveyed Swedish municipalities on their management of green areas and trees (Wiström and Östberg, 2022), it was reported that 67.9% of the municipalities' tree inventories contained information regarding trunk diameter or trunk circumference. This was an increase from the 58.5% who gave the same answer as reported in 2016.

Future technological advancements may transform how DBH is measured. An example of this is the multisource single-tree inventory (MS-STI), which utilizes an existing tree map created through Terrestrial Laser Scanning (TLS) and a Global Navigation Satellite System (GNSS) in combination with Airborne Laser Scanning (ALS) data. This approach could enhance DBH estimation accuracy. Its potential was demonstrated in a 2014 study of urban trees in Helsinki, showing that DBH could be accurately predicted using metrics derived from

ALS data. This suggests MS-STI may significantly improve urban-forest attribute updating, potentially marking a new era of precision in tree DBH measurements (Saarinen *et al.*, 2014).

2.5 Urban tree re-inventories

The periodic updating and assessing of tree inventories over time can allow urban forest managers to monitor changes in tree populations, assess management practices, and make informed decisions on future planting strategies (Roman *et al.*, 2013). It is essential to recognize that tree inventory is merely the preliminary step, while monitoring encapsulates a more comprehensive approach, usually entailing repeated measurements, or tree re-inventories. Whether the goal is to safeguard tree populations from pests or to craft an urban forestry initiative, monitoring furnishes the necessary information to outline program objectives and assess progress in achieving them. This data is indispensable for ensuring effective urban forest management. It's crucial to consider that urban forest monitoring extends beyond the realm of biology, demonstrating relevance in political and social contexts as well. It can fuel the development of educational programs aimed at equipping the public with the knowledge required to make informed political decisions, a factor that can potentially stimulate program budgets. Furthermore, monitoring serves as an early warning system, enabling the detection of hazardous trees and thereby safeguarding citizens from potential risks (Baker, 1993).

Roman and colleagues (2013) outlined several challenges urban forestry practitioners face in implementing tree-monitoring programs, primarily due to resource constraints, data management issues, and the development of suitable protocols. The advent of laser-scanning technology, however, has revolutionized this field, presenting unprecedented opportunities for efficient and accurate tree mapping and attribute updating. The demand for current tree data in city parks and forests is escalating, and the key concern revolves around maintaining digital databases updated for various applications. Traditional updating methods, such as digital aerial image interpretation or field measurements via tachymeters, have proven either imprecise or cost intensive. Hence, the appeal of remote sensing data which, in many cases, are automatically collected for other urban planning objectives, making them cost-effective for database updating. For instance, in Helsinki, aerial photographs and airborne laser scanning (ALS) data are routinely collected for mapping buildings, roads, and other constructed entities. The evolution of laser-scanning technology has paved the way for newer possibilities in tree mapping and attribute updating, making the monitoring of the urban forestry more efficient and precise (Saarinen *et al.*, 2014).

In the United States, the Forest Inventory and Analysis program, in collaboration with states and cities, is engaged in long-term monitoring of urban forests. This program collects annual data on urban forests to evaluate their structure, benefits, values, and changes over time. Austin, Texas was the first city to complete a baseline assessment, and in 2017, 26 cities were included in the monitoring program. Additional cities are expected to continue joining the monitoring initiative in the coming years (Nowak *et al.*, 2016; Nowak, 2018).

2.6 Tree inventories in Sweden

In the early 2010s several studies pertaining to tree inventories took place in Sweden (Sjöman *et al.*, 2012, 2012; Östberg *et al.*, 2013b; Nielsen *et al.*, 2014).The Environmental Monitoring and Assessment program at the Swedish University of Agricultural Sciences (SLU), also known as FoMA, is connected to both Sweden's national environmental goals and global environmental collaborations. Since 2009, FoMA has facilitated the advancement of urban tree inventory as a specialized area of focus within SLU in a collaboration with Movium Partnerskap and a number of urban tree and green space management organizations (Randrup *et al.*, 2020). Funded, in part, by Malmö municipality, a tree inventory project was developed in 2012 (the Swedish Tree Inventory Standard, STIS), (Östberg *et al.*, 2012). Since then, STIS has become a distinct national standard for cataloging urban trees, which is now widely adopted by Swedish urban tree management organizations (Randrup *et al.*, 2020). In 2015, STIS underwent an update, and a subsequent database called Curio was created in collaboration with the European Space Agency to enable comparisons outside of Sweden (Östberg, 2015).

According to a survey of 161 Swedish municipalities carried out by Östberg *et al.* (2018), 52.8% had a municipal tree inventory. It was also reported that, "Most municipalities reported that they conduct inventories on *street trees* (93%) and *park trees* (79%), but inventories are also conducted on other municipal areas, although to a lesser extent: *Municipal urban woodlands*, i.e. woodlots (26%), *green corridors managed by the municipality*, i.e. greenbelts (20%), *other municipal buildings such as urban real estate/ kindergarten/school/home for the elderly* (15%), and *private trees* (2%)." In this same study, it was found that relatively few of the inventories in Sweden are used for future urban forest planning, such as tree selection. The majority are used for maintenance of existing trees, including tree removal and pruning (Östberg *et al.*, 2018).

3. Malmö, Sweden

3.1 Malmö's urban forest

In the context of urban forestry, the city of Malmö presents a unique case study due to its distinct landscape characteristics. Unlike many other municipalities, Malmö lacks large amounts of forested land within its boundaries and has very limited areas with long tree continuity. The city's land area is divided between compact urban structures, which comprise half of the area, and rural regions characterized by large-scale agriculture. Malmö's countryside is understandably sparse in trees due to this position in the agricultural region of Scania in southern Sweden; however, the city itself, despite its dense construction, features a relatively large number of trees. Consequently, it is crucial to recognize the urban environment as a vital habitat for trees in Malmö. Key locations for trees include city parks, cemeteries, large nature and recreational areas, streets, and private orchards. The city's favorable climate and a history of tree planting have contributed to a diverse range of tree species and habitats.

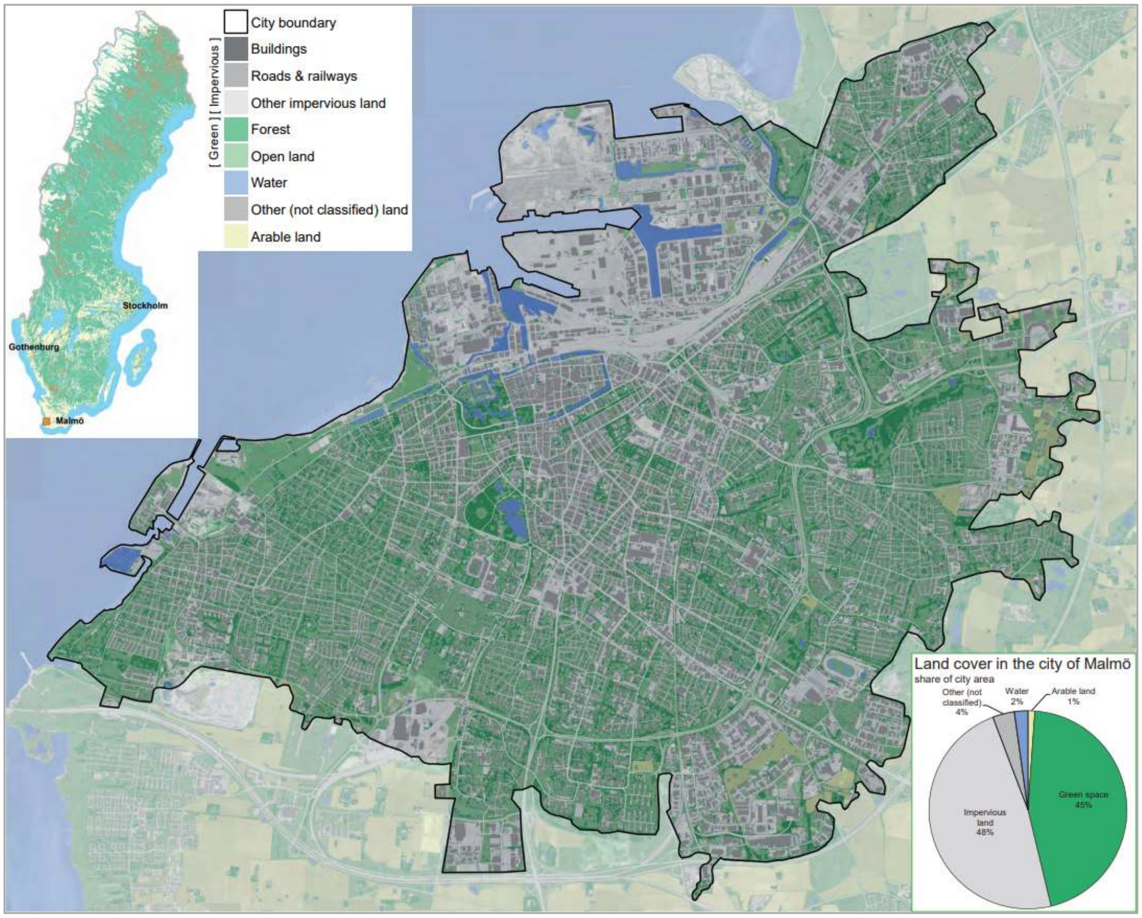


Figure 4: Map of land cover in the city of Malmö, as well as Malmö's position in the southern region of Sweden. Note that Malmö municipality extends beyond these borders. In the city of Malmö, the amount of green space is roughly equivalent to that of impervious land. (Statistics Sweden and Lantmäteriet, 2015)

There is some older vegetation in the city which exists in old orchard farms and near older high-rise buildings in certain parts of the city. However, many older tree habitats have been lost and not replaced due to insufficient resources, lack of interest, or negligence (Malmö stad, Gatukontoret, 2005). Efforts to plant trees within the city began in the second half of the 19th century. Because of close connections with neighboring countries and the rest of Europe, many non-native species were introduced to Malmö when English landscape parks were gaining popularity. This tradition of planting and supporting non-native species remains today in the city and is celebrated as a unique cultural aspect of Malmö's urban forest. The book "Träd i Malmö", released in 2018 as a collaboration between ABF Malmö (Arbetarnas Bildningsförbund), Malmö municipality and Malmö's FGK, and published by Kira förlag, depicts 163 of Malmö's tree species, as well as trees which are especially culturally important, old, or unique (ABF Malmö *et al.*, 2018). Additionally, in 2020, a mobile app was released which offers 12 unique tree walks in Malmö, showcasing 20 trees each, taking users through the city's parks, city center, and various residential areas (Do-Fi, 2020). The app helps users discover various local and non-native tree species found in Malmö. These community engagement efforts not only raise awareness about the importance of urban forests, but also fosters a sense of ownership and stewardship among Malmö residents, which is crucial for the long-term success of the urban forest management program.

During the 1980s and 1990s, Malmö experienced a significant loss of approximately 40,000 elm trees due to the devastating effects of Dutch elm disease. Subsequently, ash, linden, and horse chestnut trees also fell victim to various severe diseases, further impacting the city's tree population (Jensfelt, 2018). Presently, Malmö faces significant challenges in maintaining tree vitality, particularly in areas with poor root environments, and addressing the widespread losses resulting from Dutch elm disease. Thus, the city's urban forest requires proactive management and conservation efforts to ensure the long-term health and growth of its tree population (Malmö stad, Gatukontoret, 2005).

A primary goal expressed by FGK in interviews was to rapidly increase tree size, particularly in situations where canopy cover and ecosystem service-providing attributes are lost due to new development (Bellan, 2023b). Rapid restoration of these services is in the best interest of Malmö municipality and its residents. Various factors drive the need for swift tree growth in urban areas, including the demand for immediate impact when transplanting trees into urban and residential settings. Rapidly growing trees can provide valuable regulating ecosystem services earlier, such as mitigating pollution and reducing the urban heat island effect (Tyrväinen *et al.*, 2005). Quick expansion of canopy coverage is vital for optimizing these services. Malmö stad, for example, has set a goal of achieving a 25% canopy cover in the city, which currently stands at 13% (Malmö stad, 2023a). It's worth noting that older, more mature trees offer increased biodiversity and hydrological benefits compared to younger ones. They also play a crucial role in many other ecosystem processes (Lindenmayer *et al.*, 2012; Lindenmayer and Laurance, 2017). The Swedish government, recognizing the value of these services, has made it mandatory for all municipalities to devise a strategic plan for ecosystem services (Riksdagsförvaltningen, 2013). This legislation highlights the importance of ecosystem services and the need to prioritize the cultivation of fast-growing trees in urban and surrounding areas.

3.2 Malmö's tree inventory and database

In the city of Malmö, a comprehensive tree inventory and database have been developed and maintained by Malmö municipality's Fastighets- och gatukontoret, hereafter FGK, the municipality's administration which owns, develops, and manages the city's land (Malmö stad, 2023b). This inventory and database aim to catalog and monitor the urban forest's health, diversity, and ecological services. The majority of trees in Malmö's streets and parks have been cataloged in the database, with approximately half of them undergoing risk classification and species identification. Notably, all elm trees within the city have been inventoried at least once (Malmö stad, Gatukontoret, 2005). In 2001, a comprehensive inventory of trees was made, including capturing inventory data for around 22,000 trees with trunk diameters of 0.5 meters or more, and just under 400 so-called "giant trees", with trunk diameters of 1 meter or greater (Malmö stad, 2009). After the publication and adoption of Malmö's Tree Plan (Trädplan för Malmö) in 2005, the inventory of trees in the municipality became a regular practice in 2008.

The inventory database aims to encompass all publicly owned trees within the municipality, including those in parks, streets, cemeteries, and other public spaces. As of October of 2022, this database contained inventory information for 80,861 trees, with each having been inventoried at least once. The tree inventory is conducted using a combination of field data collection techniques, with an FGK employee or team of employees gathering information manually and recording the information with the assistance of a handheld tablet.

The database, which is regularly updated by FGK's GIS technicians, contains detailed information from the inventory about each tree, including geographical location, species, age, height, DBH, health condition, and maintenance needs. This information allows Malmö municipality to make informed decisions regarding tree management, such as planting, pruning, and removal, as well as identify areas in need of increased tree canopy coverage. The specific location of each tree in the database is integrated into GIS. Using the information in the tree database, Malmö municipality has also implemented a public-facing web application based on the FGK database, enabling citizens to access an interactive map featuring some of the inventory information, including location, species, and estimated or actual year planted for each tree (see Figure 5) (Malmö stad, 2023c).

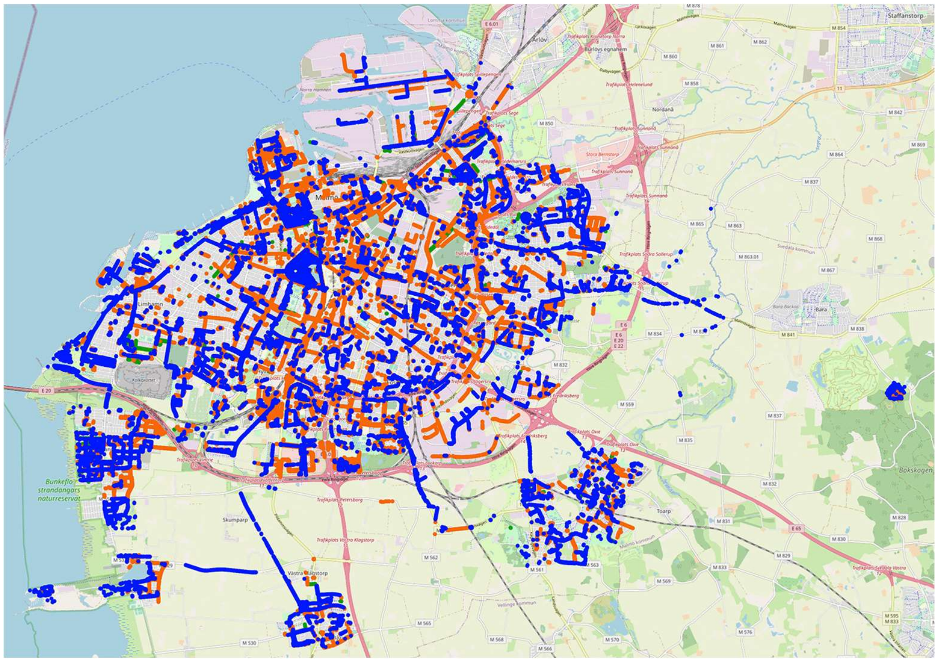


Figure 5: Location of all trees on Malmö's publicly accessible tree map. © Stadsbyggnadskontoret, Malmö stad

3.3 Re-inventory in Malmö

The city of Malmö conducted its first comprehensive tree re-inventory between 2022 and 2023, during which approximately 6,670 trees were assessed. This initiative included the evaluation of trees previously identified as potentially posing a high risk of injury to individuals or property. A significant portion of the re-inventory took place in November and December of 2022, focusing on trees situated along proposed new or future transportation lines outlined in the Metropolitan Package of 2018. These areas have experienced or are slated for development in conjunction with the expansion of the bus and GC road networks (Malmö kommunfullmäktige, 2018).

In the process of selecting trees for the re-inventory, a methodical approach was employed by Malmö municipality, beginning with the central lanes of the targeted roads. A search radius of 50 meters in each direction was established to identify potential trees for assessment. Subsequently, trees that had been recently inventoried, were newly planted with an active warranty treatment, or were situated in expansive parkland were excluded from the selection. This filtering process aimed to maximize the number of trees subject to re-inventory, thus ensuring a comprehensive and efficient evaluation Like FGK's previous inventory efforts, the inventory did not include trees which stand on private land. When recording the re-inventory information, a handheld tablet was used and information from the previous inventory of each tree was available to the person/people carrying out the re-inventory (Bellan, 2023a).

4. Materials and methods

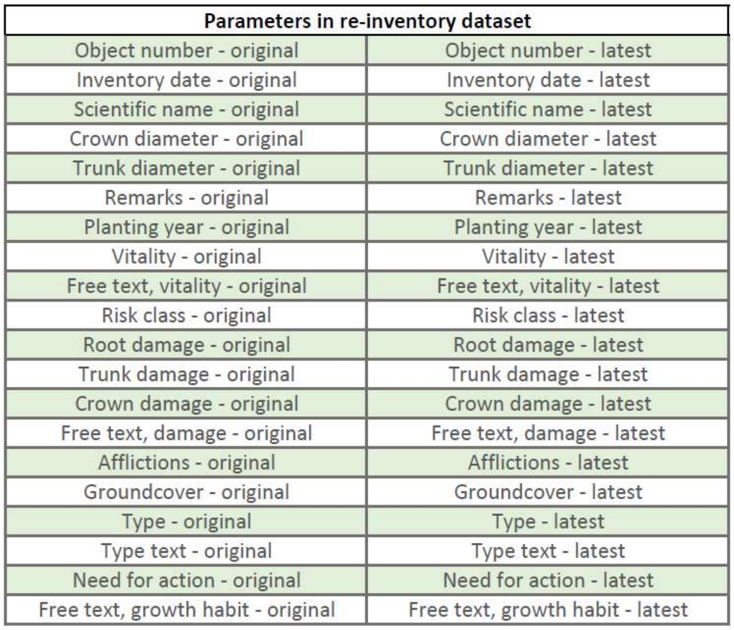
4.1 Methodology overview

The methodology employed in this study involves the analysis of re-inventoried tree data obtained from Malmö municipality's tree database, with a focus on DBH measurements. A dataset consisting of 6,668 trees re-surveyed in 2022 and 2023 was investigated to assess changes in DBH between the initial inventory and the re-inventory for each tree. The data was divided into two primary categories: trees in street environments and trees in park environments. The differences in DBH measurements between the current and previous records were examined to establish the average annual DBH growth and identify any growth trends within or between these categories, as well as among various tree species and cultivars.

4.2 Material

Malmö FGK's tree inventory is stored in an SQL database, which is integrated with a GIS system to provide geolocated data. FGK provided an Excel file (.xlsx) containing the inventory data of 6668 trees, which had been re-inventoried between 29 January 2022 and 7 February 2023, as well as their original inventory data. GIS data for these trees were also provided in the form of shape files (.shp).

The inventory parameters included in the excel database, translated from Swedish to English, were named as follows:



Parameters in re-inventory dataset	
Object number - original	Object number - latest
Inventory date - original	Inventory date - latest
Scientific name - original	Scientific name - latest
Crown diameter - original	Crown diameter - latest
Trunk diameter - original	Trunk diameter - latest
Remarks - original	Remarks - latest
Planting year - original	Planting year - latest
Vitality - original	Vitality - latest
Free text, vitality - original	Free text, vitality - latest
Risk class - original	Risk class - latest
Root damage - original	Root damage - latest
Trunk damage - original	Trunk damage - latest
Crown damage - original	Crown damage - latest
Free text, damage - original	Free text, damage - latest
Afflictions - original	Afflictions - latest
Groundcover - original	Groundcover - latest
Type - original	Type - latest
Type text - original	Type text - latest
Need for action - original	Need for action - latest
Free text, growth habit - original	Free text, growth habit - latest

Figure 6: Parameters existing in the re-inventory database from FKG.

Each inventory parameter was represented in two distinct forms; one with the suffix "- original" and the other with the suffix "- latest" to distinguish between the initial inventory conducted and documented, and the subsequent re-inventory of the same tree. The content of the fields pertaining to each parameter are clarified below:

Object number: A unique, six-digit identification number for each tree.

Inventory date: The date on which the measurements and observations were carried out, including day, month, and year.

Scientific name: The scientific name of each tree, and variety if identifiable. If it is known that the tree is an E-plant, this may also be indicated under this parameter. Some species are identified by genus name only (i.e. “Tilia sp.”).

Crown diameter: Crown diameter recorded in meters.

Trunk diameter: Diameter at breast hight recorded in centimetres.

Remarks: A free text field containing comments such as “fungus on trunk”, “change T-class to T3”, “high stump, about 3 meters”, and other miscellaneous remarks.

Planting year: The year in which the tree is estimated or known to have been planted.

Vitality: An assessment of the tree’s vitality class through visual inspection. The fields contain a number between 1 and 4, with “1” representing vitality class 1 (trees of the highest vitality possible) and “4” representing vitality class 4 (trees of the lowest vitality possible).

Free text, vitality: A free text field containing comments such as “dieback”, “dead”, “dead tree”, “sparse crown”, “stunted growth”, and other miscellaneous remarks.

Risk class: An assessment of the tree’s risk class through visual inspection. The fields contain a number between 1 and 4, with “1” representing risk class 1 (trees which are of little risk to safety or property) and “4” representing risk class 4 (trees which are of high risk to safety or property).

Root damage: An assessment of the tree’s root damage class through visual inspection. The fields contain a number between 1 and 5, with “1” representing root damage class 1 (trees with the lowest amount of root damage possible) and “5” representing root damage class 5 (trees with the highest amount of root damage possible).

Trunk damage: An assessment of the tree’s trunk damage class through visual inspection. The fields contain a number between 1 and 4, with “1” representing trunk damage class 1 (trees with the lowest amount of trunk damage possible) and “4” representing trunk damage class 4 (trees with the highest amount of trunk damage possible).

Crown damage: An assessment of the tree’s crown damage class through visual inspection. The fields contain a number between 1 and 4, with “1” representing crown damage class 1 (trees with the lowest amount of crown damage possible) and “4” representing crown damage class 4 (trees with the highest amount of crown damage possible).

Free text, damage: A free text field containing comments such as “small dead branches”, “digging near trunk”, “major trunk injuries”, “hollow”, “pruning damage”, and other miscellaneous remarks. This field often contains a description of what may have caused the identified damage.

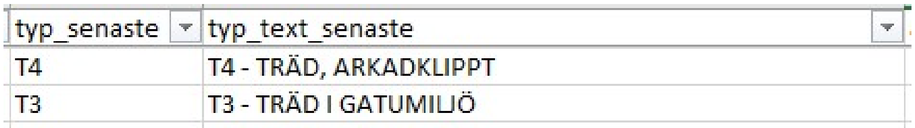
Afflictions: Referring to sicknesses of the tree that may cause damage of a biological, rather than mechanical nature. It is a free text field containing comments such as “Elm disease”, “bleeding canker”, “bacterial flows from the trunk”, “hoof fungus”, “fungus on trunk”, and other miscellaneous remarks. There is no standard way to indicate the severity of the affliction.

Groundcover: A free text field identifying the material surrounding the trunk of each tree. Note that in some cases the groundcover identified is not immediately surrounding the trunk. Rather, it may lie several centimetres away from the trunk (Figure 8).

Type: This field indicates either the type of planting environment in which the tree exists, or physical characteristics of the tree, and is recorded using a code for different types of tree. This identification is used to guide maintenance practices such as pruning (Bellan, 2023c). There are 21 types used in the dataset. These are the codes that exist under the "Type" parameter in the data set, along with how they are defined in the parameter of "Type text":

T0- Tree or bush stand
T1- Shape-pruned tree
T1U- Shape-pruned tree, 5 years or younger
T2- Tree in park environment
T2U- Tree in park environment, 5 years or younger
T2UG- Tree in park environment, 5 years or younger, guaranteed
T3- Tree in street environment
T3U- Tree in street environment, 5 years or younger
T3UG- Tree in street environment, 5 years or younger, guaranteed
T4- Arcade-pruned tree
T5- Pollarded willow
T5U- Pollarded willow, 5 years or younger
T5UG- Pollarded willow, 5 years or younger, guaranteed
T6- Fruit tree
T6U- Fruit tree, 5 years or younger
T6UG- Fruit tree, 5 years or younger, guaranteed
T7- Re-pollarded tree
T7U- Tree in park environment, pollarded linden, young tree
T8- Tree in Pildammsparken, sightline
T9U- Tree in pot, 5 years or younger
T10- Tree particularly worthy of protection

Type text: A text field which repeats the Type code found in the "Type" parameter field and appends the code with the definitions found above.



typ_senaste	typ_text_senaste
T4	T4 - TRÄD, ARKADKLIPPT
T3	T3 - TRÄD I GATUMILJÖ

Figure 7: Example of how fields are filled in under the parameters "Type - latest" and "Type text - latest"

Need for action: A free text field containing comments such as "replace collision protection", "remove groundcloth", "prune eastern part of crown", "supervision and re-inventory in 1 year", "fell tree", and other miscellaneous remarks. This field often contains a description of what future maintenance measures are deemed necessary.

Free text, growth habit: A free text field containing comments such as “bush”, “high stump”, “2 stemmed”, “leaning”, “pillar form”, and other miscellaneous remarks. This field often contains a description of a tree’s physical form.

Figure 8: Tree in a street planting environment. The groundcover for this tree would most likely be identified as "stone pavement".

4.3 Data collection and pre-processing

Microsoft Excel for Microsoft 365 MSO was used to view and assess the Excel file. In order to facilitate the comparison between the initial and subsequent inventory data for each tree, the dataset was restructured such that corresponding parameters were positioned adjacently. For instance, "Inventory date - latest" was situated directly beside "Inventory date - original".

In order to maintain consistent language throughout the analysis, the term “Trunk diameter” was replaced with “DBH” in the parameters of “Trunk diameter – original” and “Trunk diameter – latest”.

In certain instances, the characters within comments were observed to be misrepresented, which could be ascribed to data entry errors or data corruption during file format conversion. For example, the term "Återhamling" was sometimes rendered as "Ã…terhamling"? . To maintain accuracy and consistency in the dataset, identified instances were manually corrected when detected.

4.4 Data filtering

In this study, a multi-stage filtering approach was employed to refine the dataset. Items were sequentially filtered out based on a set of predefined parameters, with each filtering step removing items that met specific criteria. It is important to note that the filtering process was cumulative in nature. Consequently, as items were removed in earlier filtering stages, some items that would have met the criteria for subsequent filters were no longer available for consideration in later stages. This sequential filtering process, therefore, resulted in a progressively reduced dataset, with each step further refining the pool of items under analysis.

The filtering process was initiated by removing 1,550 trees with an unknown original inventory date (recorded as 1901-01-01), as the average change in DBH per year of these trees could not be analyzed without that date.

Following this initial step, trees with an original DBH which had been recorded as “0” were filtered out, as well as a single tree who’s DBH had been recorded as “>20”. These 2061 trees, as well as 19 trees with the latest DBH recorded as “0”, could not be analyzed for a change in DBH.

The dataset contained 268 trees that were identified as multi-stemmed in some form. However, locating and categorizing these trees proved to be challenging due to inconsistencies in the recording of multi-stemmed trees within the inventory. Specifically, these inconsistencies manifested in several ways:

1. Lack of standardization: The dataset exhibited no uniform approach to recording multi-stemmed trees, resulting in the information being scattered across various parameters and locations within the inventory.

2. Terminological variations: Different terms were used to describe multi-stemmed trees, including "two-stemmed," "three-stemmed," "four-stemmed," and so on, which further complicated the identification process.

3. Implicit information: In some cases, the recorder of the inventory did not explicitly mention that a tree was multi-stemmed. Instead, they provided a series of numbers representing the diameter at breast height (DBH) measurements for each stem, necessitating additional interpretation.

4. Measurement uncertainty: The dataset did not provide clear information about the DBH measurement methods used, as general knowledge and standards for recording DBH have evolved over time. Consequently, it is difficult to ascertain whether the measurements were performed consistently across different instances of the inventory.

5. Inconsistent measurement heights: Although some recorders specified the height at which DBH measurements were taken (e.g., "30 cm above ground height"), the lack of uniformity in measuring height and method between the first and second inventories made it challenging to confidently analyze the change in DBH over time.

Given these complexities, analysis of the multi-stemmed trees in the dataset would require careful consideration and interpretation to account for the varying recording practices. In light of this, the decision was made to remove all multi-stemmed trees from the dataset.

14 dead trees were removed from the dataset, as there was often no way to be sure of how long the tree had been dead, and therefore it could not be known when the tree ceased growing.

Trees which were recorded as being high stumps (“högstubbe”) or high-lopped (“högkappat”) were removed from the dataset, as well as those requiring maintenance described as cutting from a high-lopped tree to a high stump ("högkapat till högstubbe"). There were 17 of these trees in total.

Trees infected with horse chestnut bleeding canker (caused by the bacterial pathogen *Pseudomonas syringae pv. aesculi*) or Dutch elm disease (caused by the fungi *Ophiostoma ulmi and Ophiostoma novo-ulmi*, spread by elm bark beetles) were removed from the dataset. Both diseases compromise the tree's vascular system, which is responsible for transporting water and nutrients, leading to stress, reduced growth, and potentially death (Trust, 2019a, 2019b). 29 trees were filtered out during this step.

Upon infection with *Meripilus giganteus*, also known as giant polypore, a tree may exhibit a decline in growth rate as a consequence of wood decay, which can impair the tree's capacity to transport water and essential nutrients. Additionally, the tree may allocate a greater proportion of its resources to defense mechanisms in response to the fungal infection, which can exacerbate the reduction in growth rate (Schwarze *et al.*, 2000). Because a mild infestation of *Meripilus giganteus* does not always have an impact on tree growth, and because no indication of the severity of the infestation was recorded in the inventory, only one tree was removed from the dataset during this step, as it had a recorded vitality of 4, which may have been caused in part by the *Meripilus giganteus* observed.

Figure 9: Fagus sylvatica infested with an infestation of Meripilus giganteus at its base. (Watson Lindsey Arboriculture Ltd., 2020)

114 coppiced or pollarded trees, mostly of the species *Salix*, were removed from the dataset, as coppicing and pollarding disrupts the growth of a tree, keeping it in a smaller form than the tree would otherwise realize (McPherson and Van Doorn, 2016).

Other pruned trees, such as those which had undergone arcade-style or shaped pruning, will also grow at a slower rate than those left unpruned. Even trees which have only been pruned on one side exhibit this tendency, such as the seven *Fagus sylvatica* specimens located around Tallriken in Pildammsparken (Figure 10), which were left in the dataset before this step of filtering and were shown to be in the lower part of the growth spectrum for *F. sylvatica* overall (see Figure 11). In total, 58 trees including the Pildammsparken *F. sylvatica* were filtered out of the dataset because they had been heavily pruned.

A total of 96 trees were recorded as having a decline in DBH when comparing the initial and updated inventories. While tree diameters may temporarily contract during the growing season as a result of water depletion, negative annual growth measurements are typically associated with human error rather than physiological or physical factors (Pastur *et al.*, 2007). Owing to the challenge of determining whether a reduction in trunk diameter is a consequence of water loss or of a human clerical error, the dataset was modified to exclude the 96 trees that displayed a negative overall change in DBH.

4 trees were removed from the dataset because of obvious clerical errors in their recorded DBH measurements. For example, one such tree was reported as gaining 200 centimeters in diameter in 6 years.

Figure 10: Pruned on one or two sides, the beeches in Pildammsparken's Tallriken area and along the park’s sightlines. (User Jorchr on sv.wikipedia, 2005)

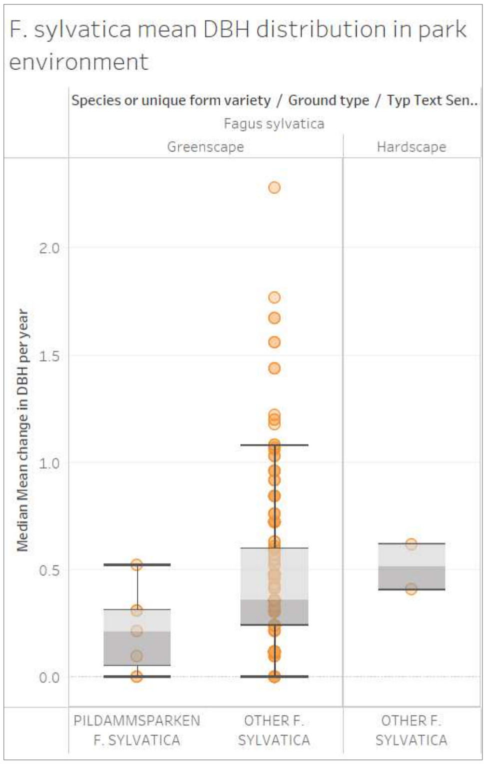


Figure 11: All F. sylvatica found in the filtered re-inventory data which grow in a "greenscape" ground cover type. Comparing the average change in DBH of those specimens found in Pildammsparken and those found elsewhere in Malmö.

The refined dataset, which consolidates 2,427 trees with consistent and relevant information, was derived through the systematic removal of records containing missing or inconsistent data and the retention of only the most pertinent parameters. This process resulted in a 63.6% reduction from the original 6,668 records, facilitating a more focused analysis of tree growth and development patterns in Malmö FGK's inventory and ultimately enabling more accurate conclusions.

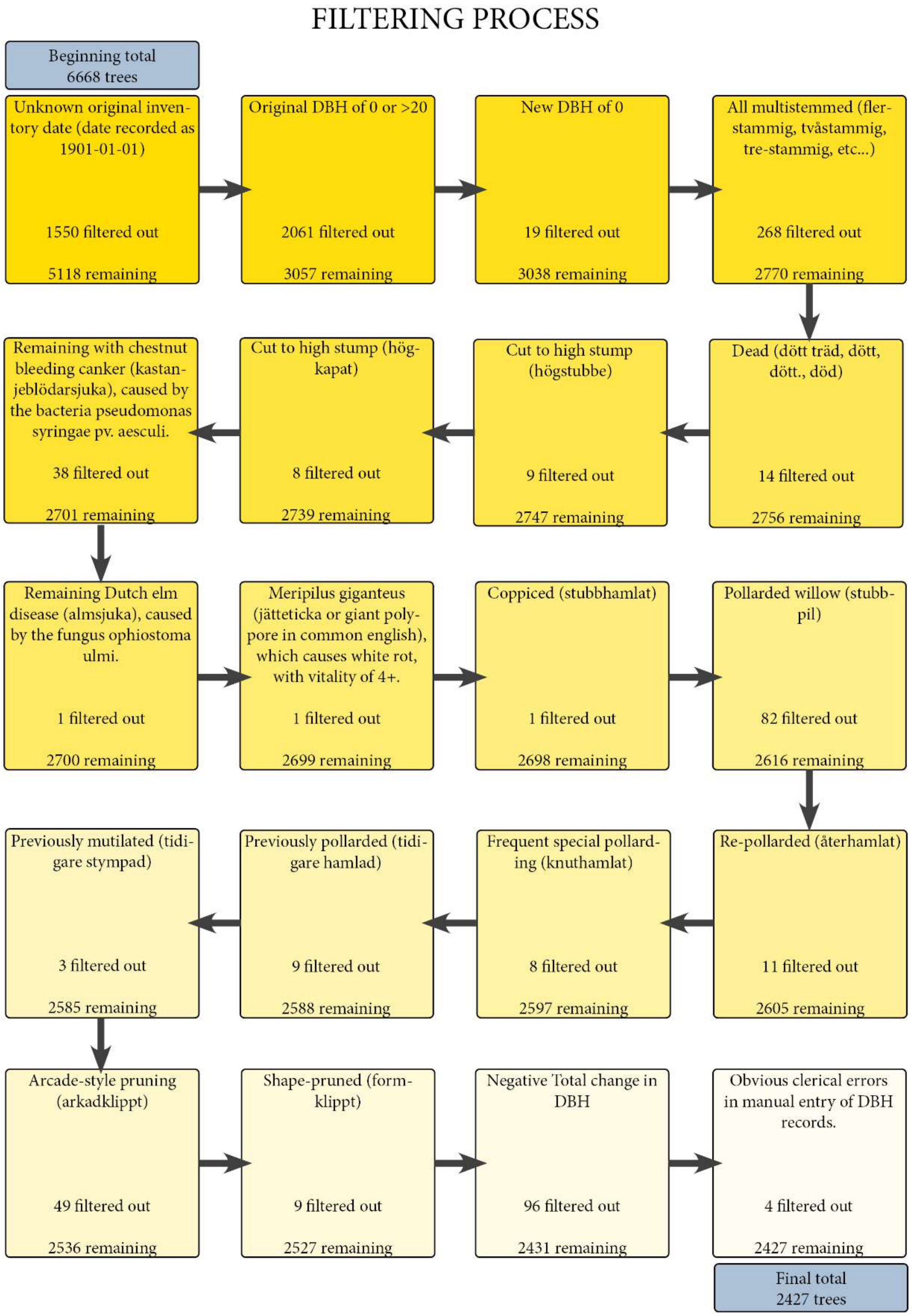


Figure 12: Flowchart of the filtering process including Swedish keywords filtered out (in parentheses), bringing the total count of trees in the dataset from 6,668 to 2,427.

4.5 *Delimitation*

Although the geographic distribution of trees which were re-inventoried in Malmö municipality were primarily along the route of new of future bus lines (Bellan, 2023a) and appeared to primarily be comprised of street trees, they were fairly uniformly distributed across Malmö, with no quadrant of the municipality being completely without representation (Figure 13). Geographically, the data points retained in the dataset after the filtering process appeared to be rather uniformly distributed across the locations of tree points prior to the filtering process (Figure 14).

Figure 13: Extent of 6668 trees (green icons) re-inventoried in Malmö municipality by FGK in 2022-2023. © Lantmäteriet

Figure 14: Extent of 2427 trees (green icons) re-inventoried in Malmö municipality by FGK in 2022-2023 which make up the dataset that was analyzed for this study. © Lantmäteriet

4.6 Analysis methods

DBH ANALYSIS

In the analysis process, various formulas were applied within the Excel spreadsheet to compute and manipulate the dataset. Three ew columns were created, headed as, "Days elapsed", "Total change in DBH", and "Average change in DBH per year". A formula for each item (each tree) was used to fill in the value of each cell under the new columns.

In the "Days elapsed" column, the data from "Inventory date – original" (t_1) was subtracted from "Inventory date – latest" (t_2) for each tree, giving the total number of days which had elapsed between the date of each inventory:

$$Days\ elapsed = t_{2-}\ t_1$$

For the "Total change in DBH", (Δdbh_{total}) the data from the "Tree diameter – original" parameter (dbh_1) was subtracted from that of "Tree diameter – latest" (dbh_2) to get the total change in diameter between the measure taken during the original inventory and the measure taken during the re-inventory of each tree:

$$\Delta dbh_{total} = dbh_{2-} dbh_1$$

To calculate the “Average change in DBH per year” (Δdbh_{annual}), the difference in the two DBH measurements ($dbh_{2-} dbh_1$) was calculated, and then divided by the difference in time between the two measurements ($t_{2-} t_1$):

$$\Delta dbh_{annual} = \frac{(dbh_{2-} dbh_1)}{(t_{2-} t_1)}$$

As shorthand, this average change in DBH per year in the interval between the two inventory dates will sometimes be referred to as “growth rate”.

AGE ANALYSIS

To facilitate the graphing of trees by age, new columns labeled “Age at inventory – original” and “Age at inventory – latest” were added to the dataset.

In the “Age at inventory – original” column, the data from “Inventory date – original” (t_1) was subtracted from “Planting year – latest” (p_2) for each tree using the Excel function “YEAR” to calculate the total number of years which had elapsed between the date of the original inventory and the year in which the tree was planted:

$$Age\ at\ original\ inventory = YEAR(t_1) - YEAR(p_2)$$

In the “Age at inventory – latest” column, the data from “Inventory date – latest” (t_2) was subtracted from “Planting year – latest” (p_2) for each tree using the Excel function “YEAR” to calculate the total number of years which had elapsed between the date of the latest inventory and the year in which the tree was planted:

$$Age\ at\ latest\ inventory = YEAR(t_2) - YEAR(p_2)$$

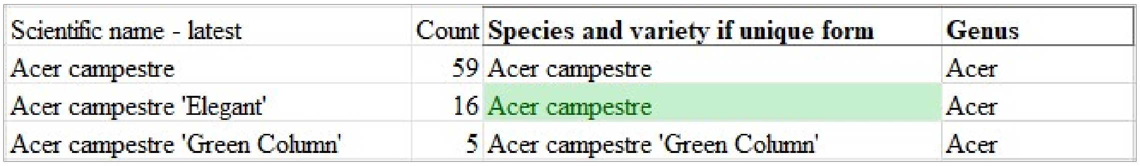
The "Planting year - latest" variable was utilized for both calculations. This approach was chosen to account for the possibility that new information regarding the age of the tree could have surfaced in recent years. Additionally, those conducting the latest inventory would have had access to the original identification, allowing them to assess and verify the accuracy of the initial classification.

SPECIES GROUPINGS

The dataset included various trees that belong to the same species but represent different varieties. Some of these varieties exhibit growth habits that are similar to their non-variant counterparts, while others have dissimilar growth habits. To facilitate a more effective analysis and enable clearer comparisons between species groups, trees with similar growth habits were categorized into larger data pools. This categorization was irrespective of whether they were non-variant specimens or specific varieties within the same species.

For example, the variety *Acer platanoides* 'Cleveland' has a slightly more compact crown than the non-variant *Acer platanoides*. However, their growth habit is not vastly different. In contrast, the variety *Acer platanoides* 'Globosum' is a small ornamental tree that has a low, compact form quite different from the non-variant *Acer platanoides*. As a result, specimens of *Acer platanoides* 'Globosum' remained grouped as "*Acer platanoides* 'Globosum'" under the new column, while 'Cleveland' was grouped as "*Acer Campestre*" with other trees that were recorded simply as "*Acer Campestre*".

All three - 'Cleveland', 'Globosum', and *Acer Campestre* - were categorized as "Acer" under a new column called "Genus". This approach allowed us to make a clearer comparison between the different species groups in the dataset.



Scientific name - latest	Count	**Species and variety if unique form**	**Genus**
Acer campestre	59	Acer campestre	Acer
Acer campestre 'Elegant'	16	Acer campestre	Acer
Acer campestre 'Green Column'	5	Acer campestre 'Green Column'	Acer

Figure 15: New columns "Species and variety if unique form" and "Genus" were created to group similar varieties of the same species together. In this example, the highlighted Acer campestre was a new identifier attached to Acer campestre 'Elegant', allowing it to appear in analysis which includes all Acer campestre.

This approach allowed for a more legible examination of relationships between species groups and the analyzed DBH data, ultimately enhancing the clarity and interpretability of data visualizations. In cases where the scientific names differed between the original and latest inventory, the name recorded during the latest inventory was used. This decision assumed that older trees are easier to identify than younger trees. Additionally, those conducting the latest inventory would have had access to the original identification, allowing them to assess and verify the accuracy of the initial classification. A similar approach was used to group similarly growing E-plants with plants of the same species which did not have the E-plant identifier.

PLANTING ENVIRONMENT TYPES – PARK AND STREET

The column "Type text - latest" was renamed to "Planting environment type" for the purpose of categorizing each tree into one of two categories: "T2 - Tree in park environment" or "T3 - Tree in street environment", as there is no standard way to categorize trees as being exclusively "Park trees" or "Street trees" (Bellan, 2023c). The "Type text - latest" parameter in the dataset was used as a guide to achieve this objective. Assessing all 6,668 original trees to determine whether they fit better into the category of "T2 - Tree in park environment" or "T3 - Tree in street environment" if they were not already recorded as being of those types would have been challenging, given that the "Type text" parameter either the type of planting environment a tree was in or the physical characteristics of the tree.

Below are the six "Types" of trees which remained in the dataset after the filtering process had occurred, as well as the number of trees given each designation:

T0- Tree or bush stand (18)
T2- Tree in park environment (1755)
T3- Tree in street environment (647)
T3U- Tree in street environment, 5 years or younger (1)
T6- Fruit tree (4)
T10- Tree particularly worthy of protection (2)

One specimen of *Tilia platyphyllos* 'Örebro' was recorded as being of type “T3- Tree in street environment” in the original inventory but was recorded as “T3U- Tree in street environment, 5 years or younger” in the latest inventory. After a visual inspection in the field, it was found that this tree was likely planted in 2006, as stated in the original inventory record, not 2018, as stated in the latest inventory. Therefore, its planting year was changed in the database to “2006” and the “Type” was changed to “T3- Tree in street environment” for the latest inventory, as it was previously recorded in the original inventory.

There were 18 trees of the type “T0 – Tree and bush stand”. The locations were found using longitudinal and latitudinal GPS coordinates included in the GIS file, and the trees were visually assessed either in the field or using Google Street View to ascertain whether each belonged in the category of "T2 - Tree in park environment" or "T3 - Tree in street environment". Seven trees were re-categorized as "T3 - Tree in street environment" and 11 were recategorized as "T2 - Tree in park environment".

There were four trees recorded as the type “T6- Fruit tree”. These were recategorized as being in the category "T2 - Tree in park environment" based on visual assessment.

Two trees were recorded as being type “T10- Tree particularly worthy of protection”. One was recategorized as "T2 - Tree in park environment", and one "T3 - Tree in street environment" after visual assessment.

After these changes, the remaining “Type” categories were “T2- Tree in park environment”, hereafter referred to as “Park”, and “T3- Tree in street environment”, hereafter referred to as “Street”. Below are the final counts of each category in the “Planting environment” parameter:

Park: 1771
Street: 656

With these categories of planting environment, understanding, though imperfect, could be gained of the conditions the trees in the dataset had been growing in.

GROUNDCOVER TYPES – GREENSCAPE AND HARDSCAPE

A new column was created and named “Groundcover type”. The purpose of this new parameter was to gain an additional lens through which to view the environments in which the trees are planted. Using the groundcover categories found in the records under “Groundcover - latest”, the following groundcover categories were designated as either “greenscape” or “hardscape” in the newly created “Groundcover type” column:

	New *Groundcover type* designations	
	Greenscape	**Hardscape**
Groundcover - latest categories	Grass	Alphalt
	Natural land/meadow	Gravel
	Open ground	Gravel/fine gravel
	Planting	Stone pavement

Figure 16: Categories from "Groundcover - latest" sorted in to new "Groundcover type" designations.

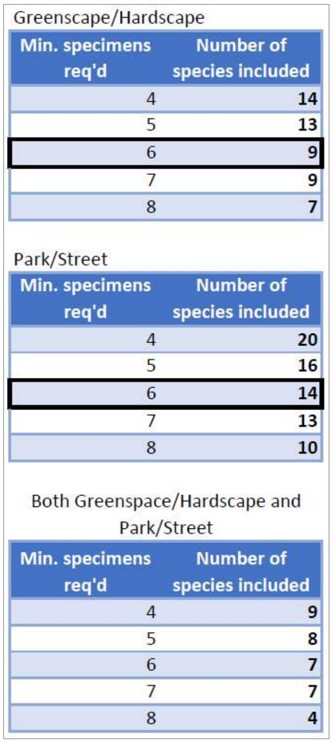
Categories found in “Groundcover – latest” were used because the categories under this parameter had been simplified since the original inventories were carried out. There were six instances of the field under “Groundcover – latest” being left blank. These trees were categorized during this study by visual inspection. Five were found to be in the “Open ground” category and one in the “Grass” category and designated as greenscape in the new “Groundcover type” column.

GRAPHING

To ascertain whether DBH is a reliable measure to use as a proxy for other less cost-effective and less easily measured parameters in Malmö and whether species selection decisions might be made using this information, data from the pre-processed, filtered, and thus-far analyzed data was imported from Excel into Tableau to create discussion graphs.

Some graphs in this study examined subsets of species in order to draw comparisons between environment types. The first set of comparisons in the “Planting environment type”, where trees were classified as belonging to either a “park” or “street” planting environment type. The second was the “Groundcover type”, where trees were classified as having either “greenscape” or “hardscape” groundcover types.

When analyzing differences in tree performance between planting environment types, only species with six or more trees in both the park and street categories were displayed or discussed. Similarly, when comparing performance between groundcover types, only species with at least six or more trees in both greenscape and hardscape categories were shown. The appropriate minimum number of trees per subcategory was determined by evaluating several categories (Figure 17), with the goal of determining a minimum sample size that balanced the number of different species available for comparison in each set against sufficient representation in each subcategory to facilitate meaningful analysis.



Greenscape/Hardscape

Min. specimens req'd	Number of species included
4	14
5	13
6	9
7	9
8	7

Park/Street

Min. specimens req'd	Number of species included
4	20
5	16
6	14
7	13
8	10

Both Greenspace/Hardscape and Park/Street

Min. specimens req'd	Number of species included
4	9
5	8
6	7
7	7
8	4

Figure 17: Several combinations of minimum tree number requirements were analyzed to arrive at a minimum that was meaningful and informative.

Hereafter, the set of species meeting the requirement of having at least six trees in both park and street environments will be referred to as the “planting environment set”, and the group of species meeting the requirement of having at least six trees in both greenscape and hardscape types will be referred to as the “groundcover set”.

DBH at latest inventory is often used in the graphical analysis, as it is a known factor which has been recorded at the latest inventory. In this analysis it was sometimes used as a proxy for the age of the tree. Although a tree’s year of planting is recorded in the inventory, these may be estimates, often based on the DBH measurement. The older the tree, the more likely the recorded planting year is an estimation.

To enable a comparison between different age groups, some graphs in this study classified trees as belonging to either the "Trees younger than 40 years" or "Trees 40 years or older" sets. 40 years was chosen as the age of division because the median age of all trees in the dataset was 37 years (see appendix 1). This approach resulted in an age distribution that fell on either side of the division, minimizing the cases in which trees were underrepresented in each age range.

To investigate the performance of DBH as a proxy for crown diameter in the context of park trees versus street trees, scatter plot graphs were generated, maintaining the same axes as the previous graph but segregating park trees, street trees, greenscape trees, and hardscape trees into separate visuals (Figures 18 - 22). Similar graphs were made to investigate the performance of DBH as a proxy for age for park trees, street trees, greenscape trees, and hardscape trees (Figures 23-26). In these graphs, the p and r^2 values automatically calculated by Tableau were used to describe correlation strength.

A series of graphs showing the average change in DBH per year for different combinations of planting environment types, groundcover types, and age classifications were created. Box and whisker plots were used as an overlay to aid in visualizing the distribution. The boxes show the median and interquartile range (the middle 50% of all data points), with the whiskers extending to 1.5x the interquartile range to show where the outlier boundary lay.

Several graphs were also created showing the average change in DBH per year by vitality class. In one instance, box and whiskers were overlaid to investigate the distribution, and in another, the overall mean growth rate with 95% confidence intervals was calculated for each vitality class.

Four graphs were created plotting the overall median, overall mean, and per-species mean growth rate for each subcategory in the planting environment type set and the groundcover set.

5. Results

5.1 *Comparison of crown diameter and latest DBH*

The analysis of tree crown diameter and DBH at the latest inventory for all trees revealed a strong correlation ($p < 0.0001$, r^2 = 0.737) between these two parameters (Figure 18). The relationship appeared most consistent in smaller (younger) trees, becoming less precise as DBH (and age) increases. This observation was evidenced by the "fan" shape of the data distribution, where data points were densely packed on the left side of the graph, becoming sparser and more dispersed towards the right side.

The analysis of the relationship between crown diameter at latest inventory and DBH at the latest inventory for all species in the planting environment set revealed a stronger correlation for park trees ($p < 0.0001$, r^2 = 0.761) and a comparatively weaker correlation for street trees ($p < 0.0001$, r^2 = 0.645) (Figures 19 & 20). A similar pattern emerged when examining the relationship between DBH and crown diameter for trees in the groundcover set (Figures 21 & 22). The correlation was stronger for greenscape trees ($p < 0.0001$, r^2 = 0.740) and slightly weaker for hardscape trees ($p < 0.0001$, r^2 = 0.688).

5.2 *Comparison of tree age at latest inventory and latest DBH*

The analysis of the relationship between tree age at latest inventory and DBH at the latest inventory for all species in the planting environment set revealed a strong correlation for park trees ($p < 0.0001$, r^2 = 0.719), as well as for street trees ($p < 0.0001$, r^2 = 0.712) (Figures 23 & 24). A similar pattern emerged when examining the relationship between age at latest inventory and DBH at latest inventory for trees in the groundcover set (Figures 25 & 26). The correlation was also strong for greenscape trees ($p < 0.0001$, r^2 = 0.719) and hardscape trees ($p < 0.0001$, r^2 = 0.692).

5.3 *Comparison of average change in DBH per year by species*

The results of comparing average change in DBH per year between park and street trees in the planting environment set showed some variability in relative performance between park and street planting environments between different species (Figure 27). Some species' growth rates were roughly similar between park and street planting environments considering the interquartile range encompassing 50% of data points closest to the median, such as *Acer campestre*, *Carpinus betulus*. *Platanus x hispanica*, *Quercus robur*, and *Sorbus intermedia*. Some species appeared to perform significantly better in park environments compared to street environments, such as *Quercus rubra*, *Tilia cordata*, *Tilia europaea*, whose median growth rate was more than double in park environments, as well as *Prunus* 'Accolade', *Prunus avium* 'Plena', and *Tilia Platyphyllos*, whose median growth rate in street environments was 0.0 cm. There were, however, outliers and counterexamples in the case of some of these species. For example, the majority of *T. platyphylllos* did not grow at all in street environments, but interestingly, the best-performing *T. platyphyllos* was found in a street environment. Similarly, most *T. cordata* did worse in street environments, but the two fastest-growing specimens were in street environments. Some species' median growth was slightly better in street environments, such as *C. betulus*, *P. hispanica*, *Q. robur*, and *S. intermedia*.

Figures 28 and 29 shows the average change in DBH per year in the planting environment set for trees younger than 40 and for trees 40 and older. Most species were represented in both age categories, but many had few to no trees in each planting environment type or age category. Species which appeared in both age groups with sufficient representation in both park and street environments included, *A. platanoides, A. hippocastanum, S. intermedia, and T. europaea.* The relative performance between park and street trees did not change appreciatively between age groups, although the absolute growth rate was clearly higher in younger trees.

The results of comparing average change in DBH per year between greenscape and hardscape trees in the ground type set showed some variability in relative performance between species in the two groundcover types (Figure 30). Some species' growth rates were roughly similar between greenscape and hardscape groundcover types considering the interquartile range encompassing 50% of data points closest to the median, such as *A. campestre* and *Tilia platyphyllos 'Örebro'*. Some species appeared to have performed significantly better in greenscapes compared to hardscapes, such as *A. platanoides*, *Aesculus hippocastanum*, *T. cordata*, *Tilia sp.*, and *T. europaea*, who, with the exception of *A. platanoides*, had a median greenscape growth rate at least double the median hardscape growth rate. *P. hispanica* and *S. intermedia* both appeared to fare better in hardscape than in greenscape groundcover types overall, although in both species, the best-performing samples were in greenscape ground cover types.

When breaking up the groundcover set into trees younger than 40 and trees 40 and older, this age breakdown reduced sample sizes and removed certain trees from consideration altogether, depending on the age distribution of the species (Figures 31 & 32). For example, there were no *T. cordata* 'Örebro' which were older than 40 years of age in the dataset. There were also no *A. campestre, A. platanoides, or S. intermedia* in hardscape over 40 years of age. Given those limitations, while there was little change in relative success when comparing hardscape to greenscape for a given species as compared to when all ages were analyzed together, it does show differences in the absolute DBH change per year, with younger trees growing faster. For example, *A. campestre* younger than 40 years in greenscape had a median change in DBH per year of 0.76, whereas *A. campastre* older than 40 years in a greenscape had a median change in DBH per year of 0.38 cm per year.

5.4 Comparison of average change in DBH per year by vitality class of all trees

In the graph comparing all trees' average change in DBH per year to their vitality class recorded at the latest inventory (Figures 33, 34, & 35), it was found that trees with a higher average change in DBH per year tended to be recorded as being of a lower vitality class; that is, of higher vitality. Of trees with a vitality of 1, the mean average change in DBH per year was 0.719 cm, whereas of trees with a vitality of 4, the mean average change in DBH per year was 0.203.

5.5 Mean average change in DBH per year by planting environment types and ground types by species

When comparing all species in the planting environment set for park trees (Figure 36), *Q. rubra* was shown to have the highest mean average change in DBH per year, at 1.006 cm change per year. The lowest among park trees was *C. betulus*, with 0.406 cm of change in DBH per year. The overall mean average change in DBH per year for all species in the planting environment set for park trees was 0.533 cm, while the overall median was 0.44 cm.

In comparing all species in the planting environment set for street trees (Figure 37), *Q. rubra* again was shown to have the highest mean average change in DBH per year, at 0.688 cm change per year. The species with the lowest mean average change in DBH per year was *P. avium* 'Plena', with 0.075 cm of change in DBH per year. The overall mean average change in DBH per year for all species in the planting environment set for street trees was 0.397 cm, while the overall median was 0.33 cm.

When comparing all species in the groundcover set for greenscape trees (Figure 38), *T. cordata* was shown to have the highest mean average change in DBH per year, at 0.778 cm change per year. The lowest among greenscape trees was *A. hippocastanum*, with 0.408 cm of change in DBH per year. The overall mean average change in DBH per year for all species in the groundcover set for greenscape trees was 0.532 cm, while the overall median was 0.43 cm.

In comparing all species in the groundcover set for hardscape trees (Figure 39), *P. hispanica* was shown to have the highest mean average change in DBH per year, at 0.752 cm of change per year. The species with the lowest mean average change in DBH per year was again *A. hippocastanum*, with 0.156 cm of change in DBH per year. The overall mean average change in DBH per year for all species in the groundcover set for hardscape trees was 0.341 cm, while the overall median was 0.285 cm.

5.6 Proportion of groundcover types in planting environment types

Figure 40 shows that in park planting environment types, 96.10% of trees had a greenscape groundcover type and 3.90% of trees had a hardscape groundcover type. In street planting environment types, 79.42% of trees has a greenscape groundcover type and 20.58% has a hardscape groundcover type.

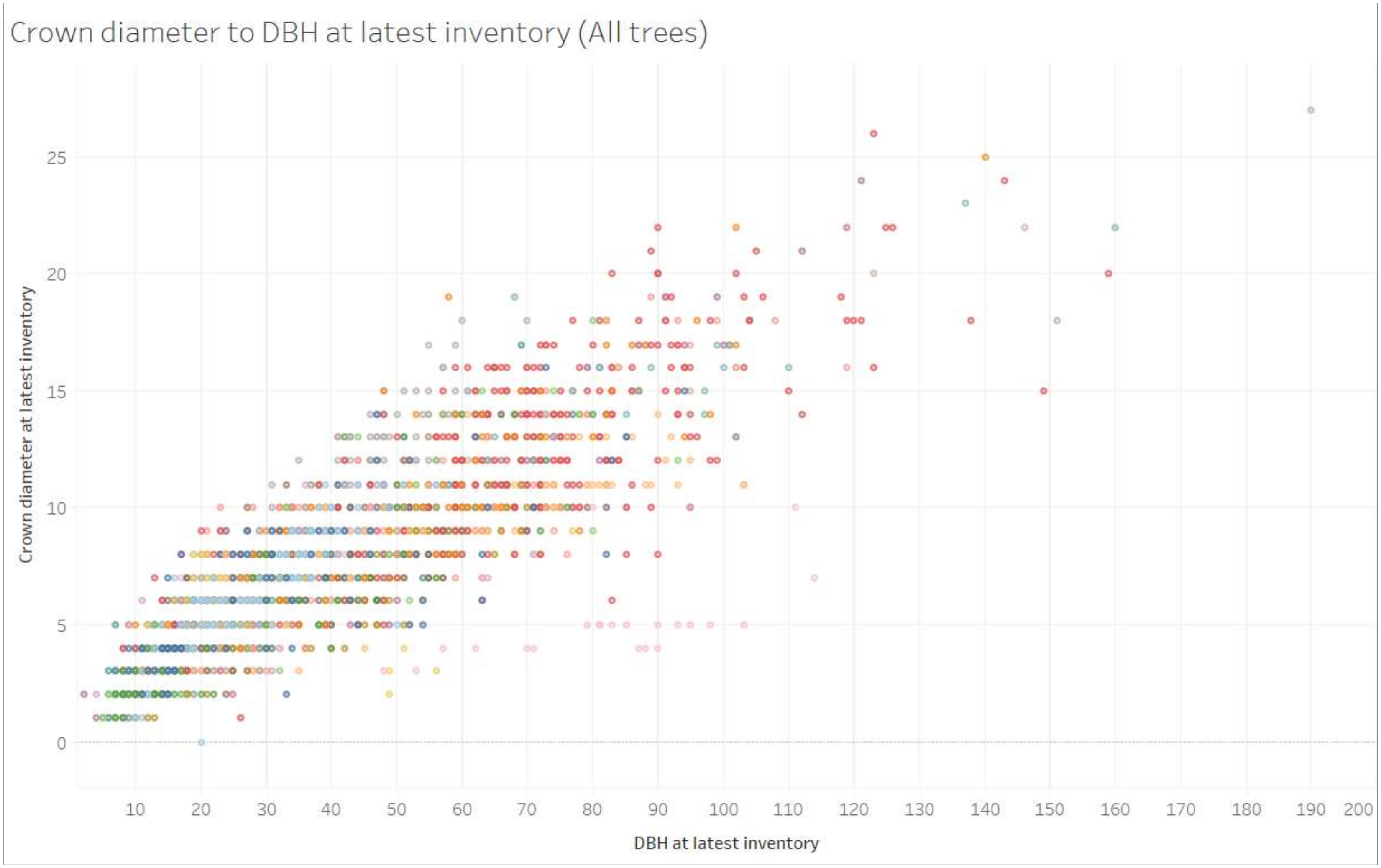


Figure 18: Crown diameter of all trees at latest inventory compared to DBH at latest inventory.

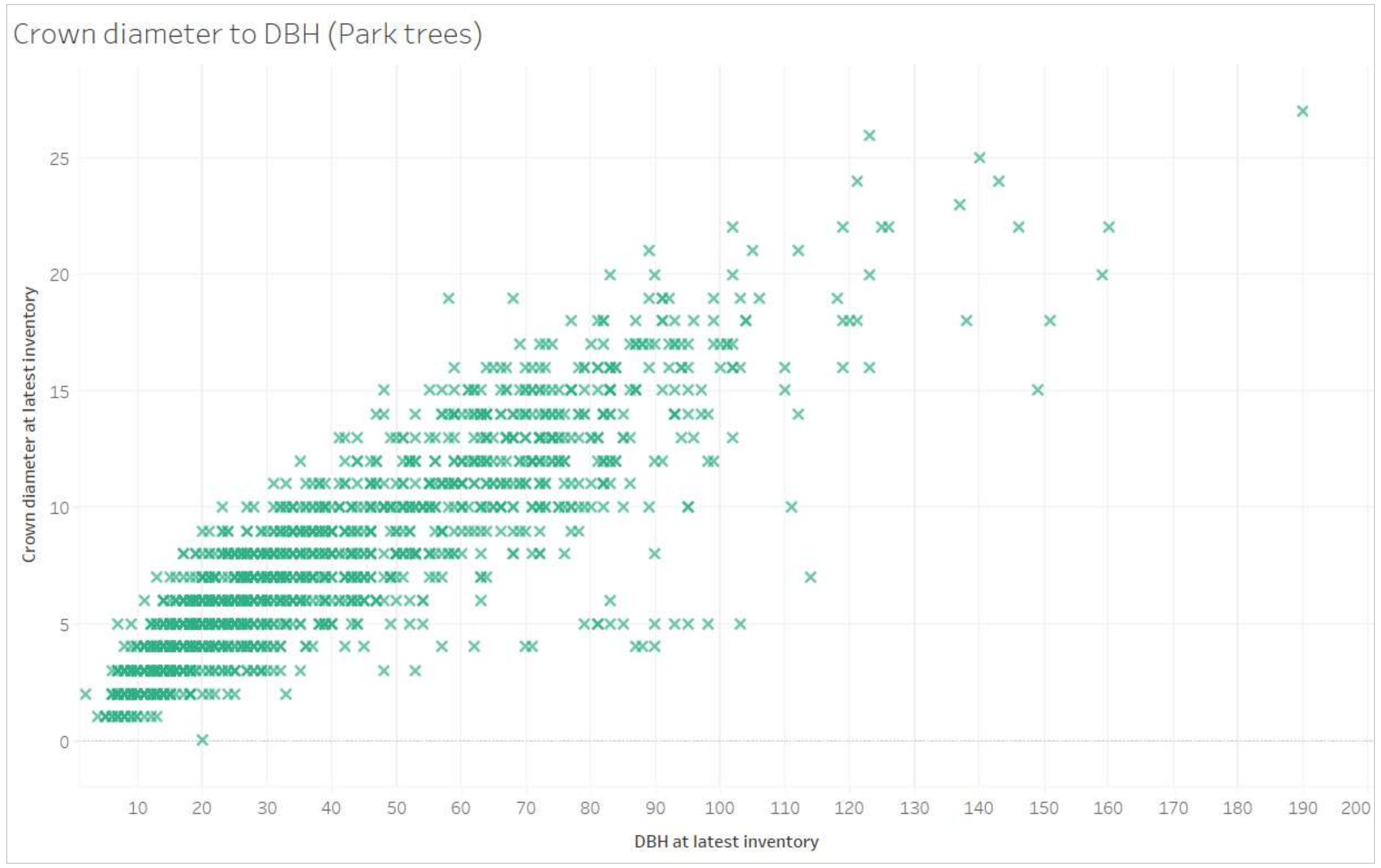


Figure 19: Crown diameter at latest inventory compared to DBH at latest inventory for all trees recorded as being planted in a park environment.

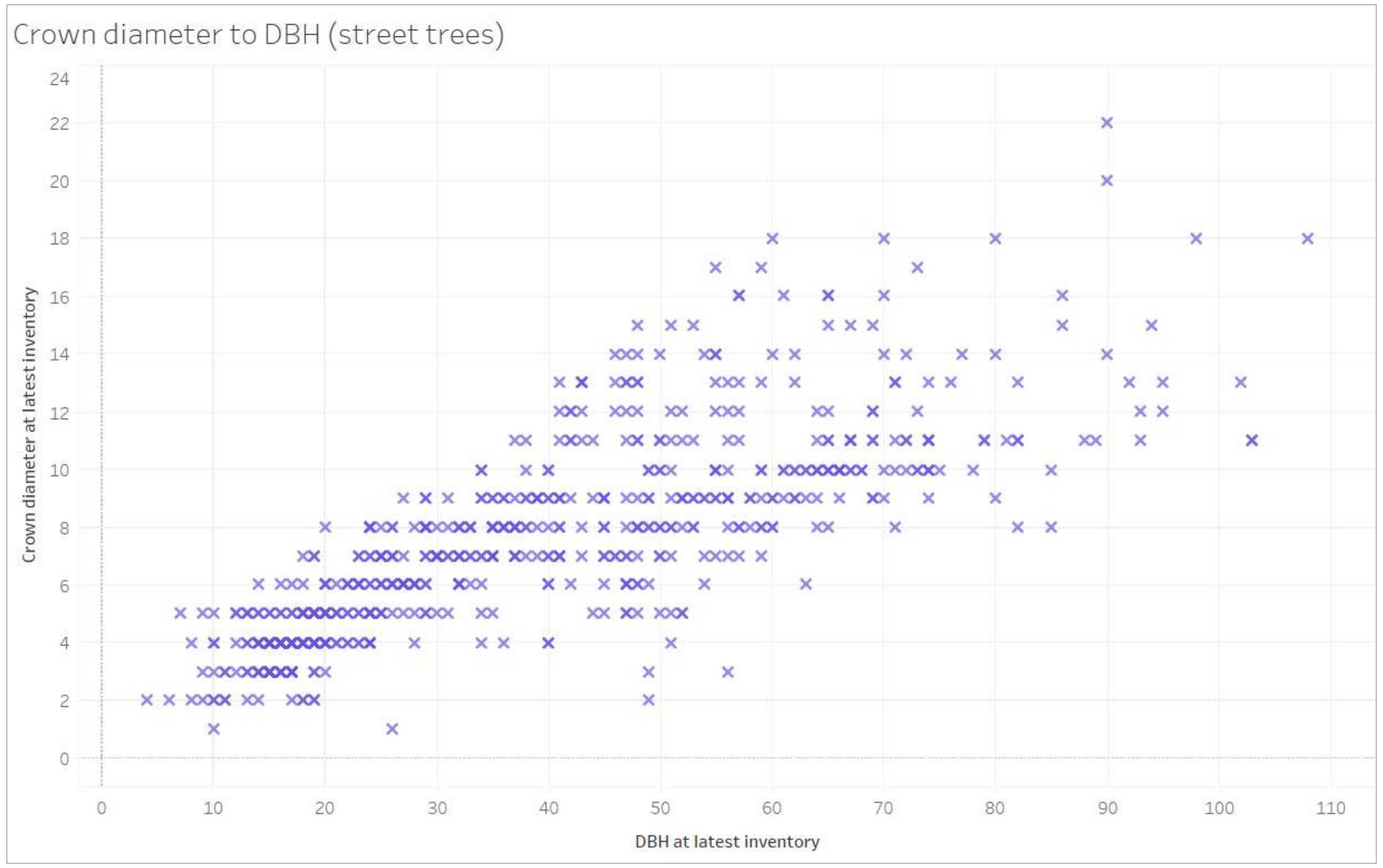


Figure 20: Crown diameter at latest inventory compared to DBH at latest inventory of trees recorded as being in a street environment.

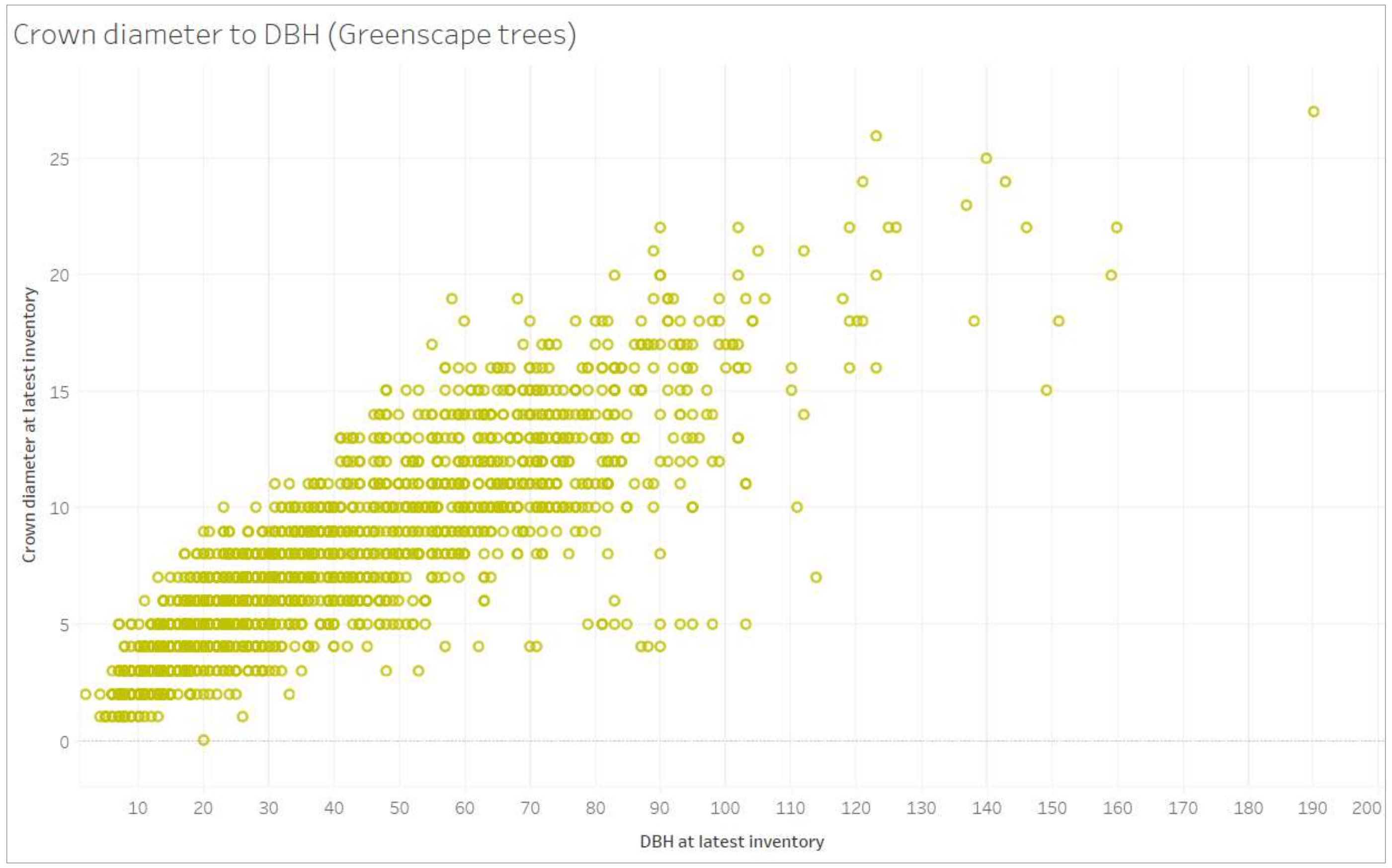


Figure 21: Crown diameter at latest inventory compared to DBH at latest inventory for trees categorized as being planted in a greenscape groundcover type.

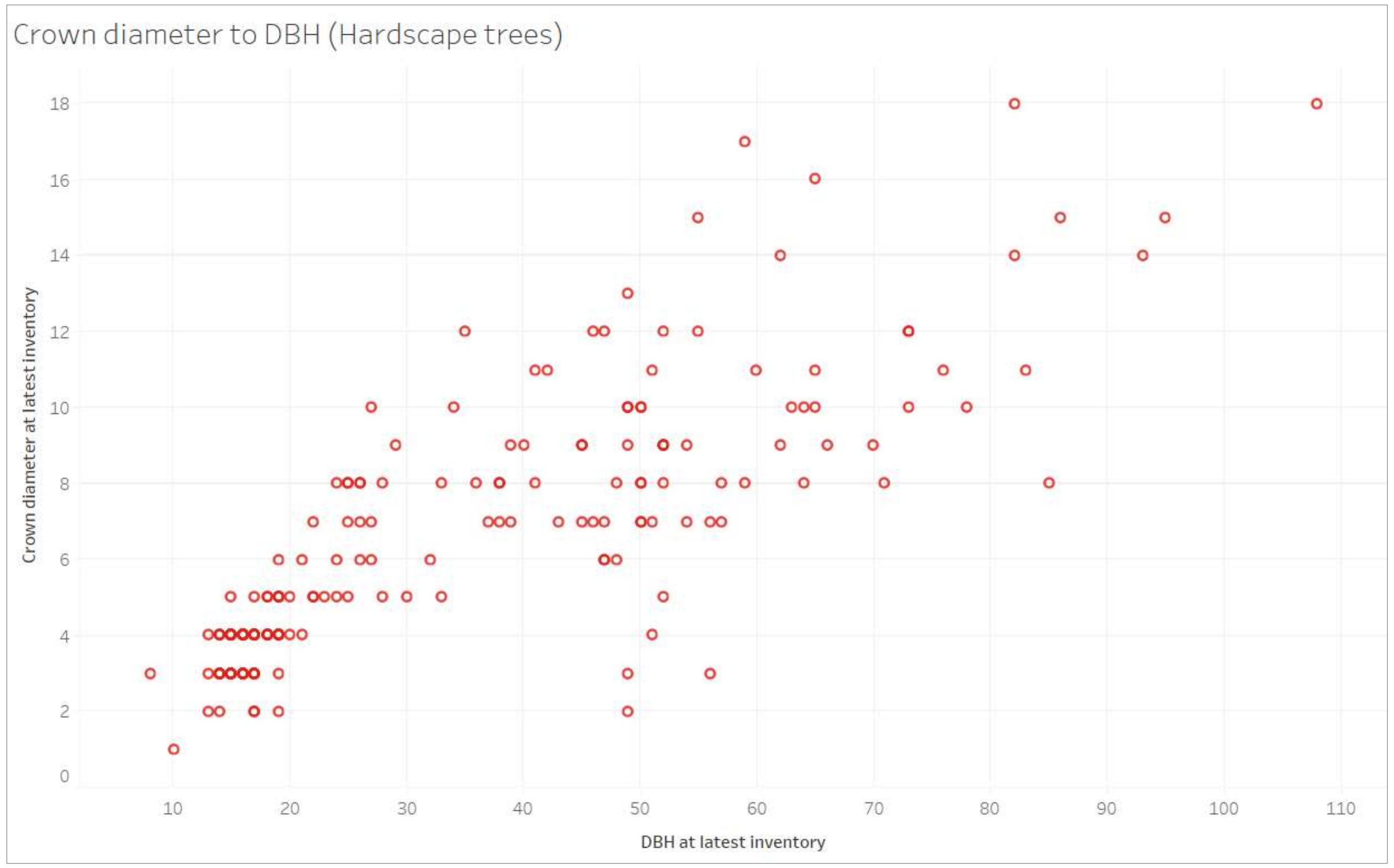


Figure 22: Crown diameter at latest inventory compared to DBH at latest inventory for trees categorized as being planted in a hardscape groundcover type.

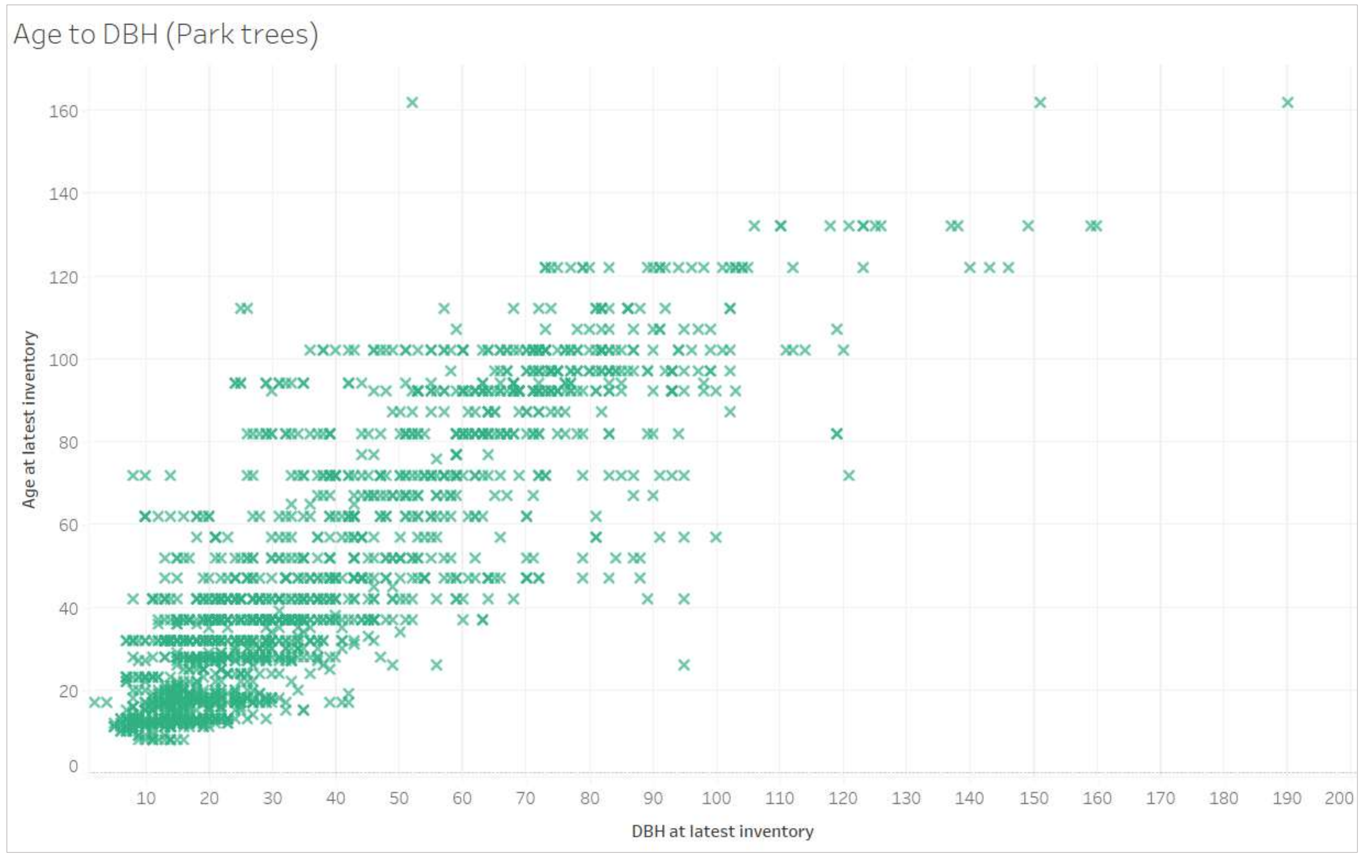


Figure 23: Tree age at latest inventory compared to DBH at latest inventory for all trees recorded as being planted in a park environment.

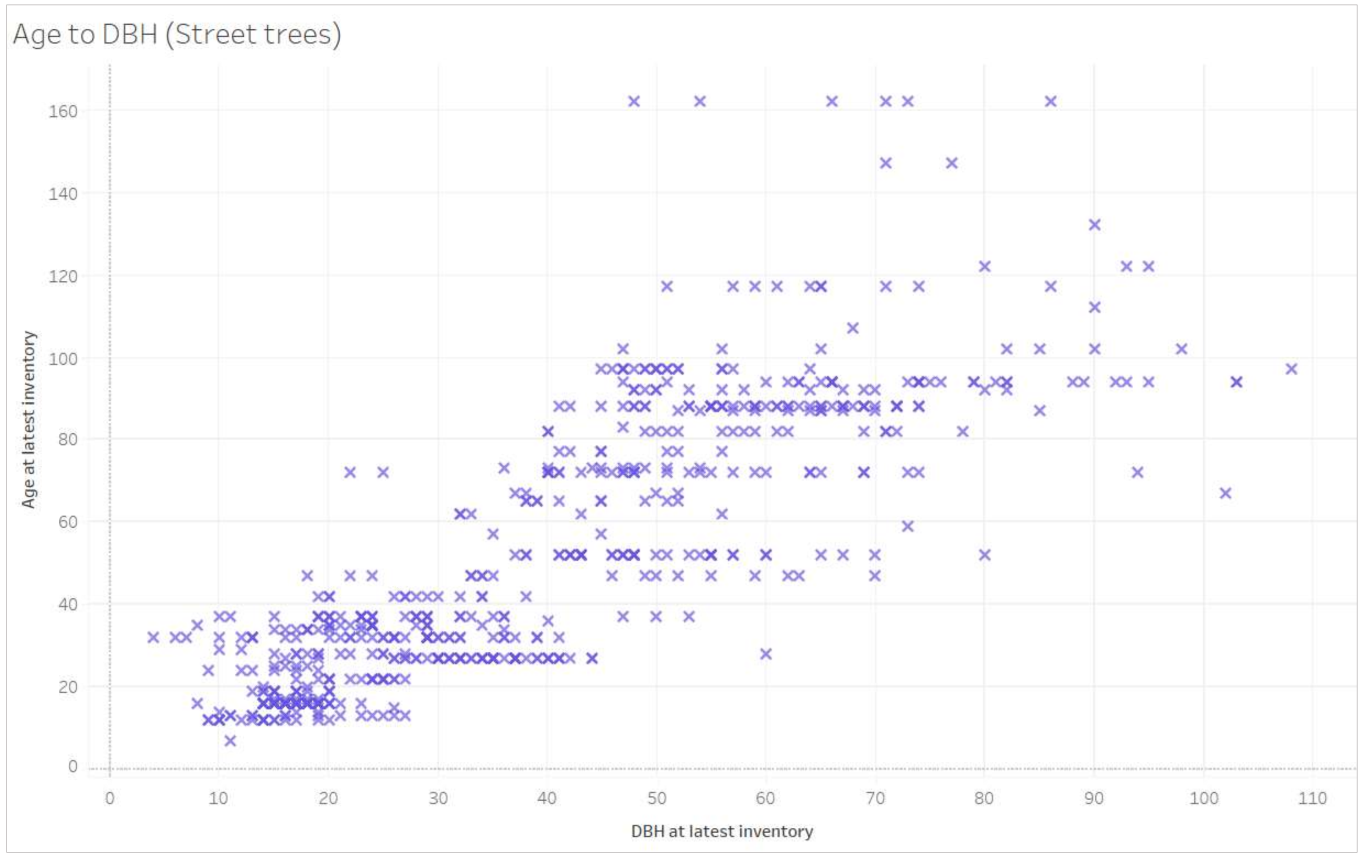


Figure 24: Tree age at latest inventory compared to DBH at latest inventory of trees recorded as being in a street environment.

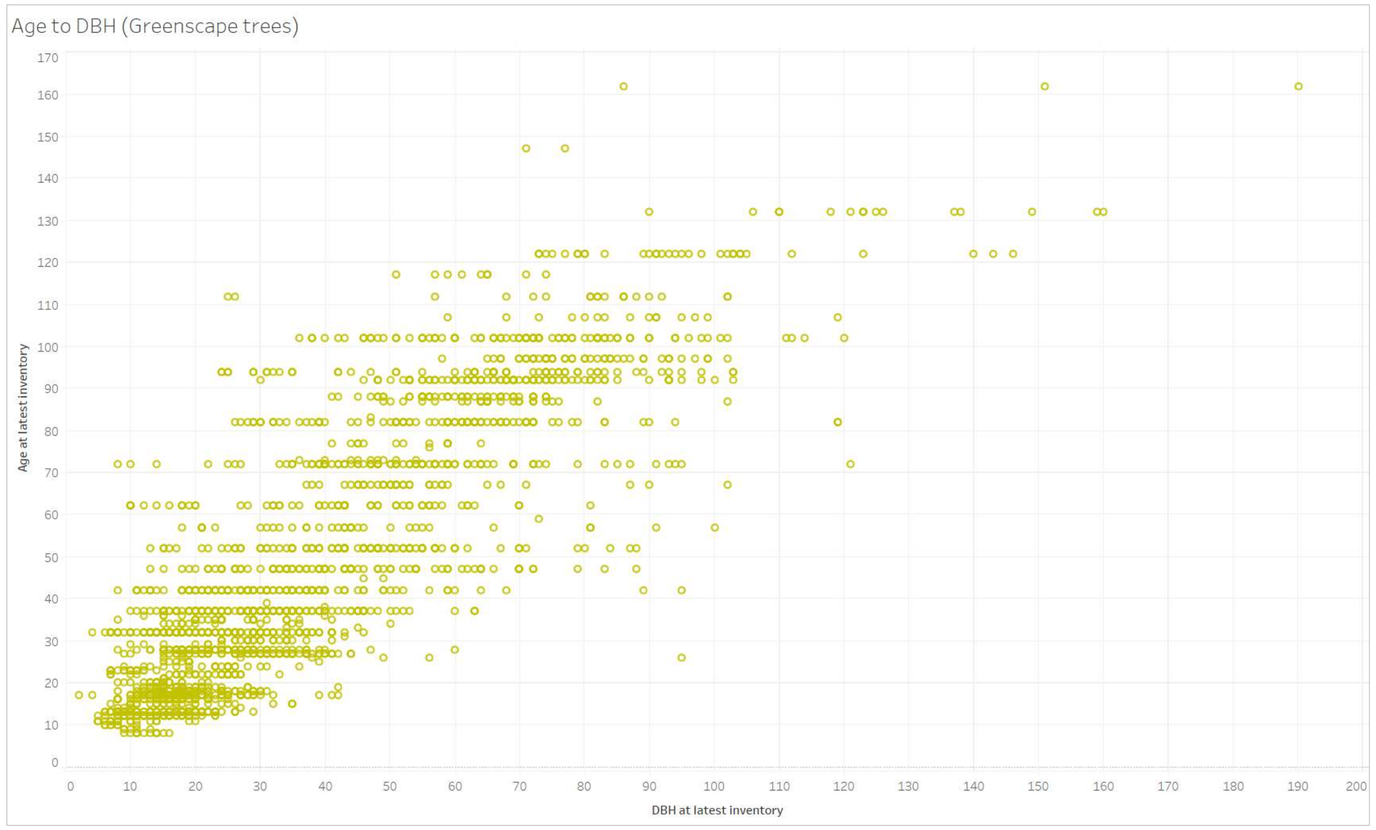


Figure 25: Tree age at latest inventory compared to DBH at latest inventory for trees categorized as being planted in a greenscape groundcover type.

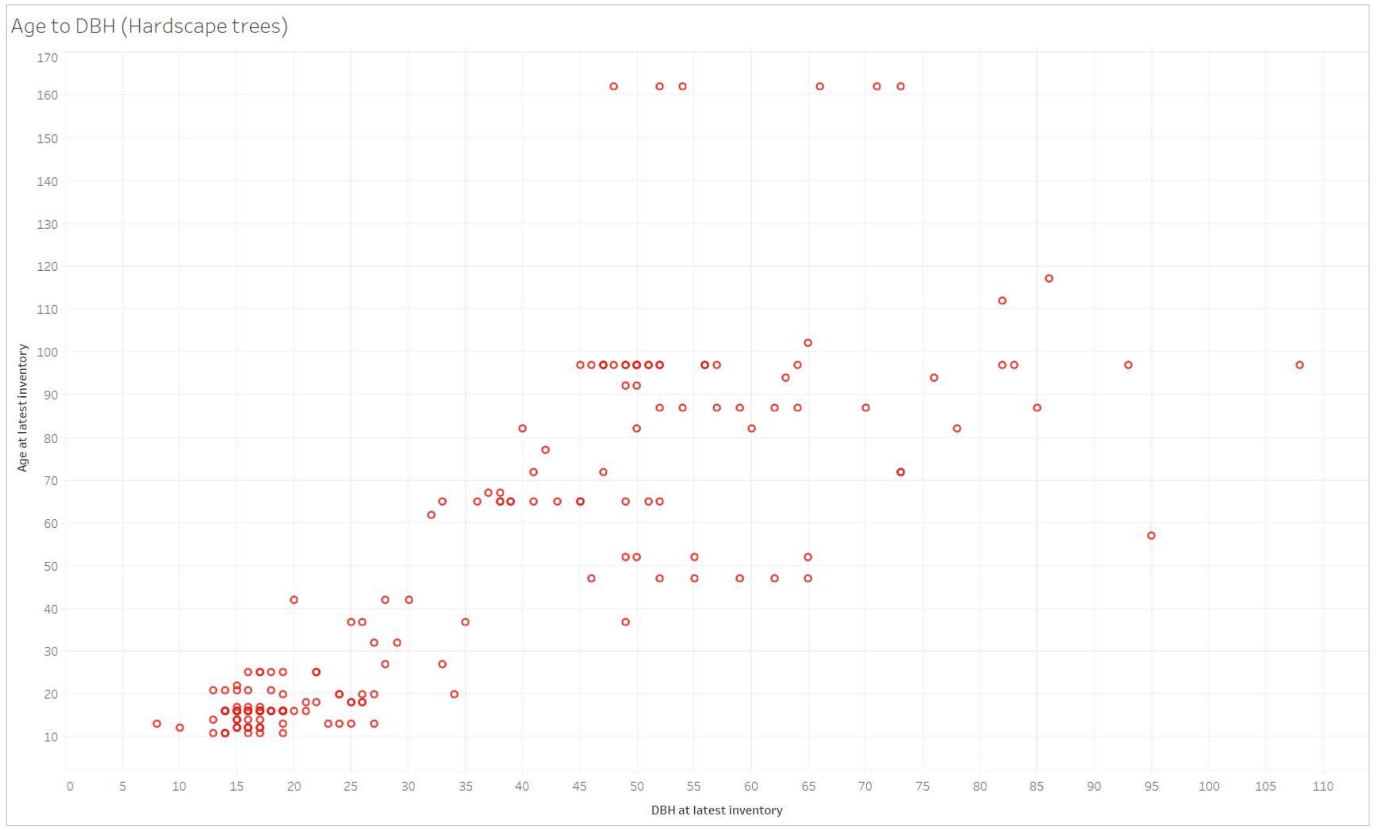


Figure 26: Tree age at latest inventory compared to DBH at latest inventory for trees categorized as being planted in a hardscape groundcover type.

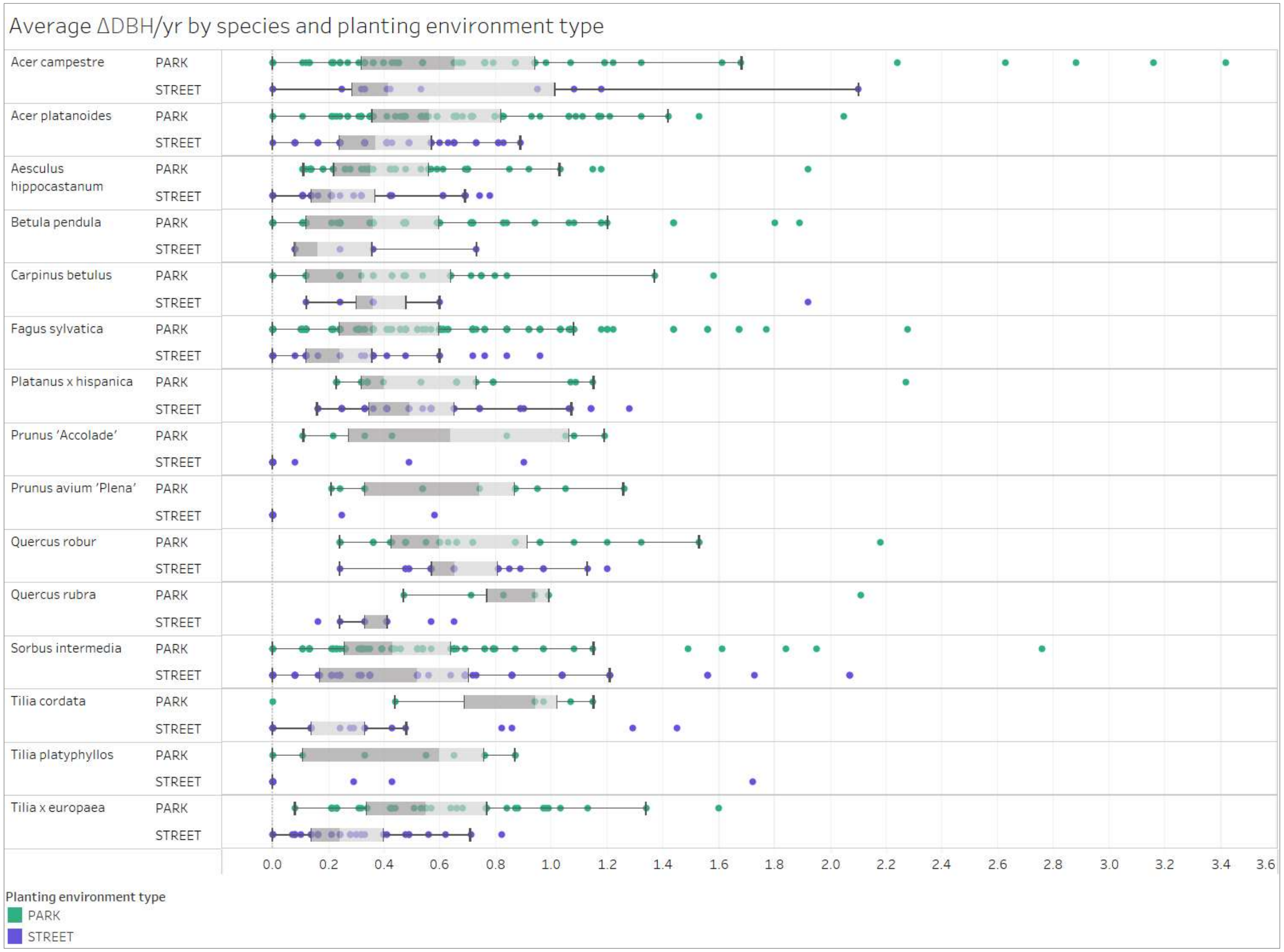


Figure 27: Average change in DBH per year by species, comparing trees recorded as planted in a park environment and in a street environment for each species which has 6 or more trees planted in each category.

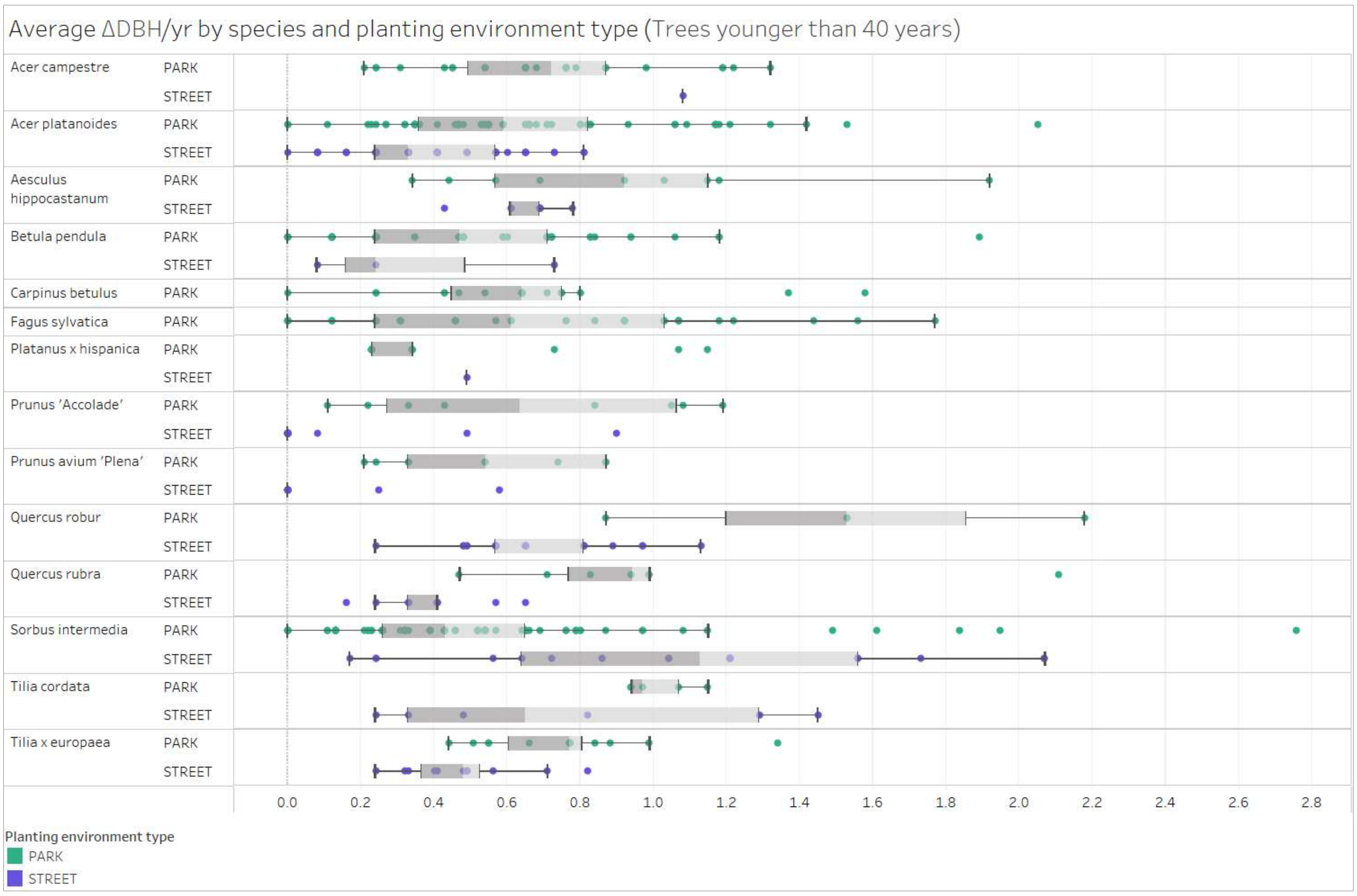


Figure 28: Average change in DBH per year by species, comparing trees recorded as planted in a park environment and in a street environment for each species which has 6 or more trees planted in each category, and which were younger than 40 years old when the latest inventory was taken.

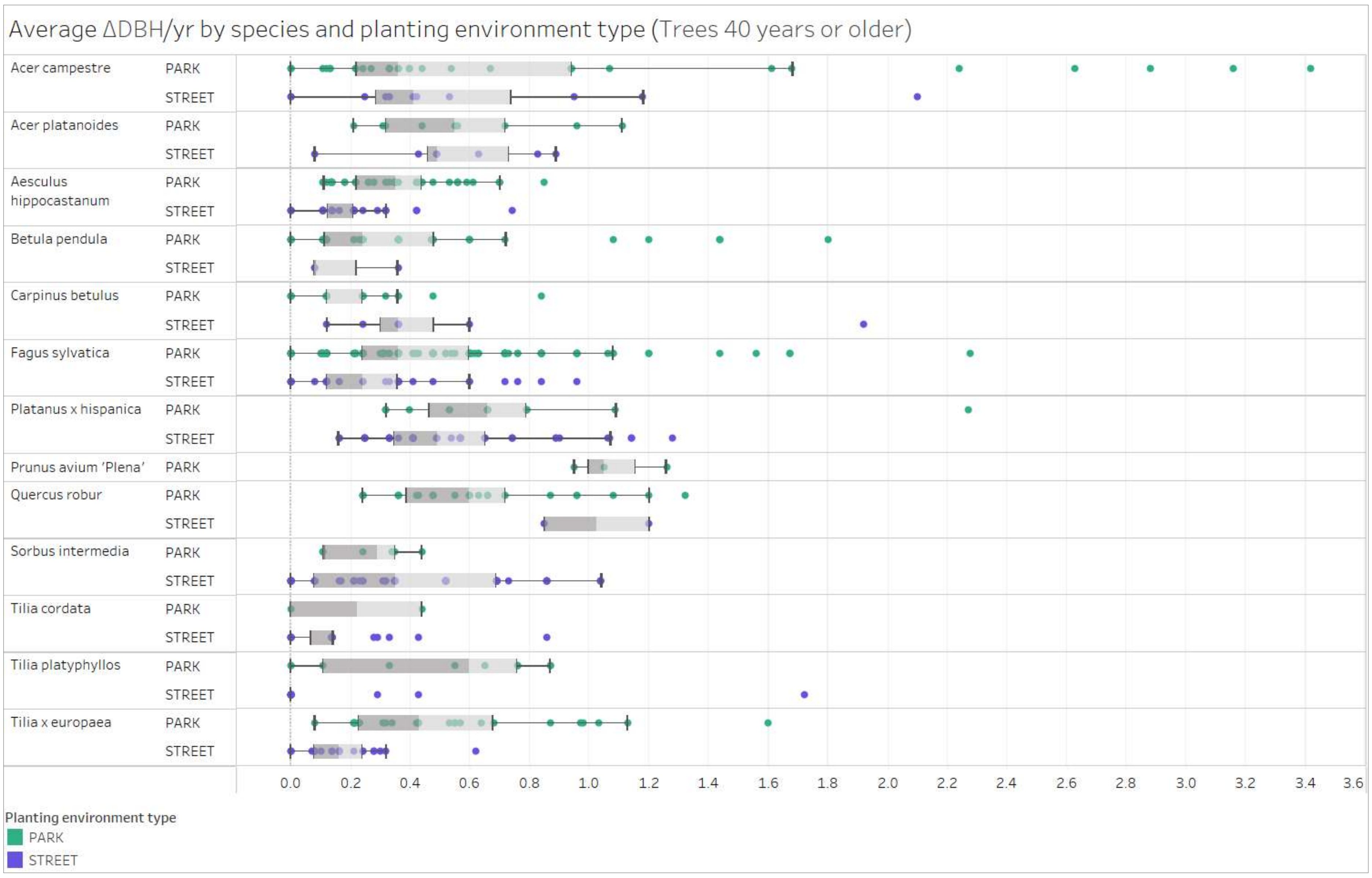


Figure 29: Average change in DBH per year by species, comparing trees recorded as planted in a park environment and in a street environment for each species which has 6 or more trees planted in each category, and which were 40 years or older when the latest inventory was taken.

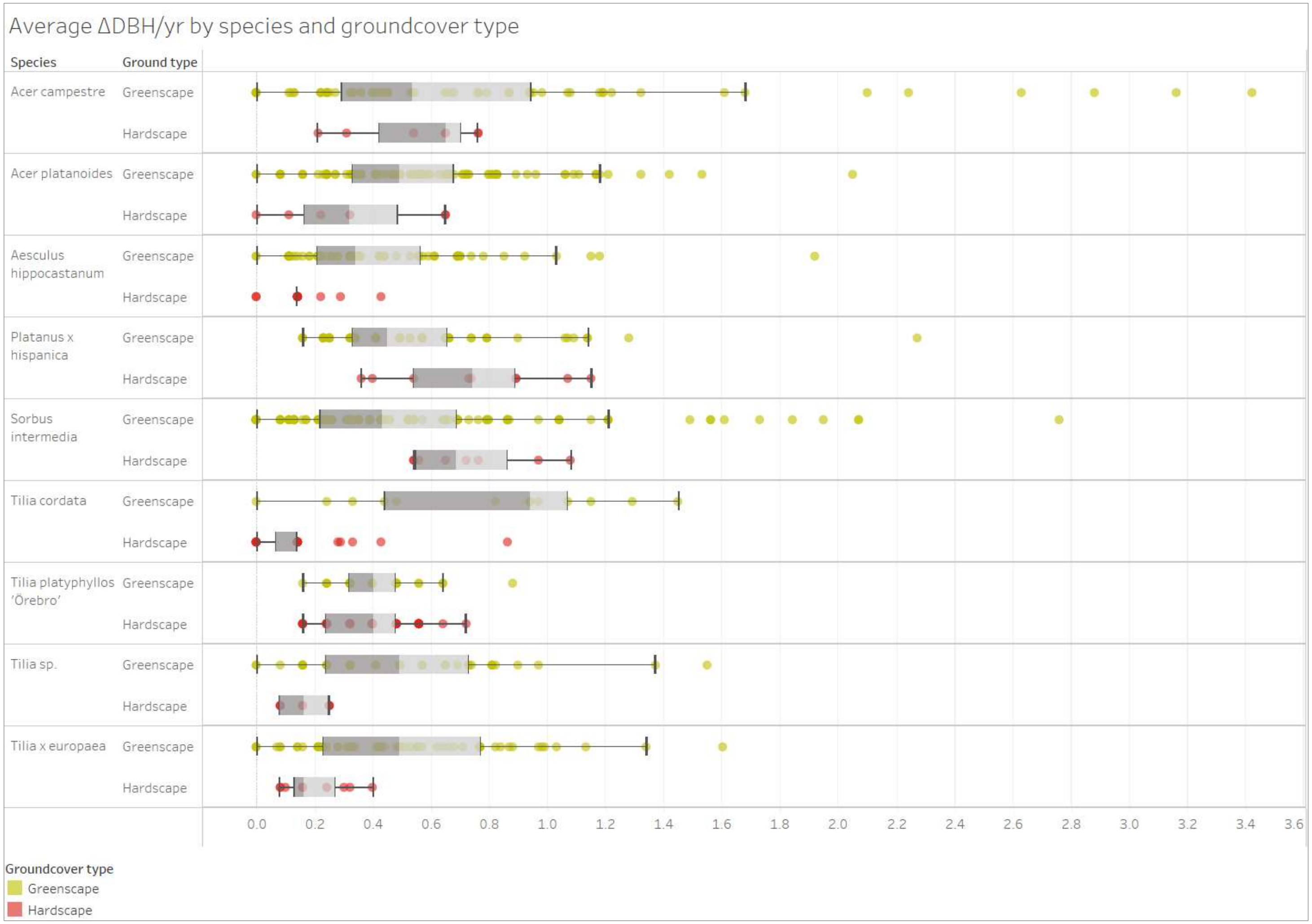


Figure 30: Average change in DBH per year by species, comparing trees categorized as planted in a greenscape groundcover type and in a hardscape groundcover type for each species which has 6 or more trees planted in each category.

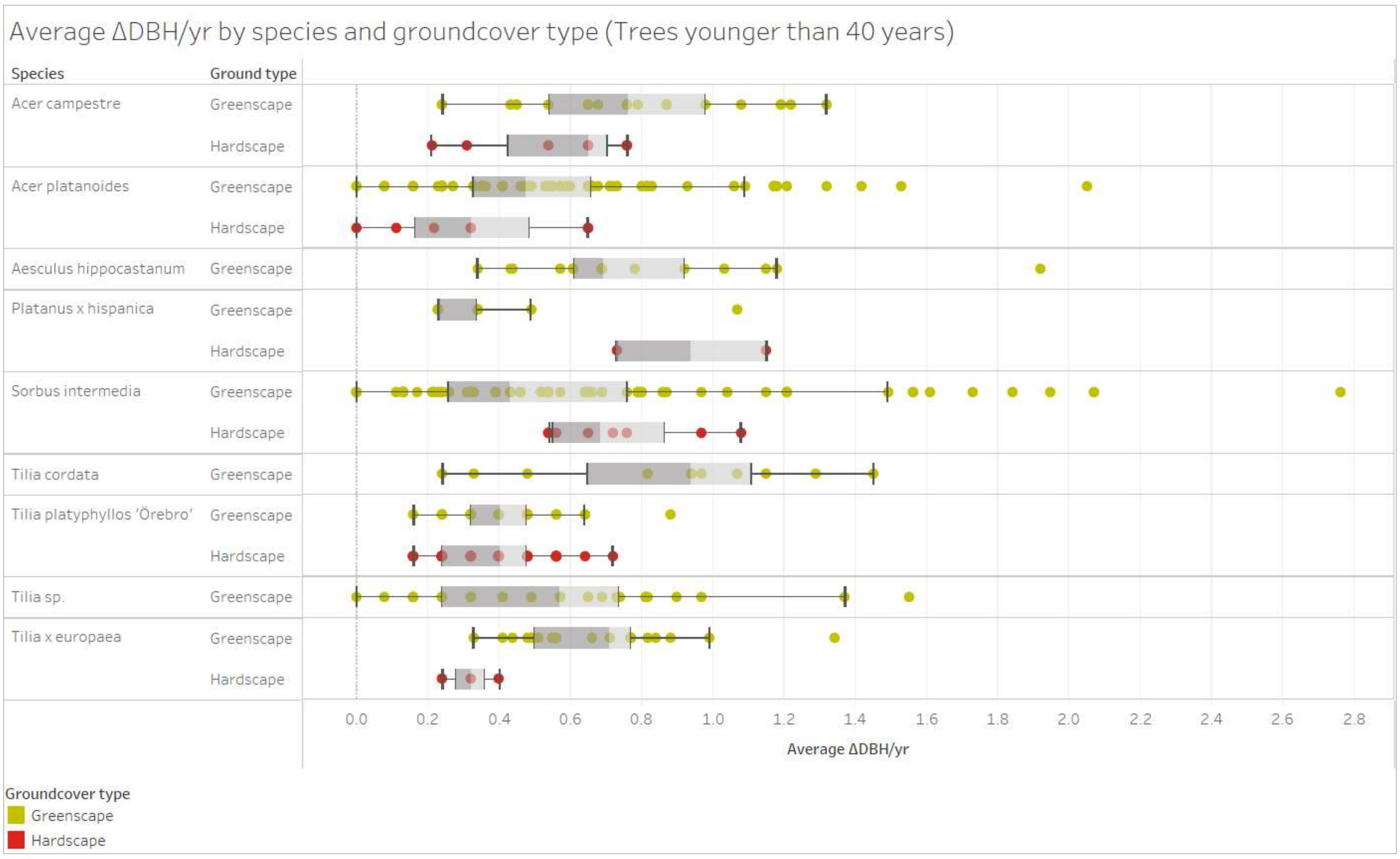


Figure 31: Average change in DBH per year by species, comparing trees recorded as planted in a greenscape groundcover type and in a hardscape groundcover type for each species which has 6 or more trees planted in each category, and which were younger than 40 years old when the latest inventory was taken.

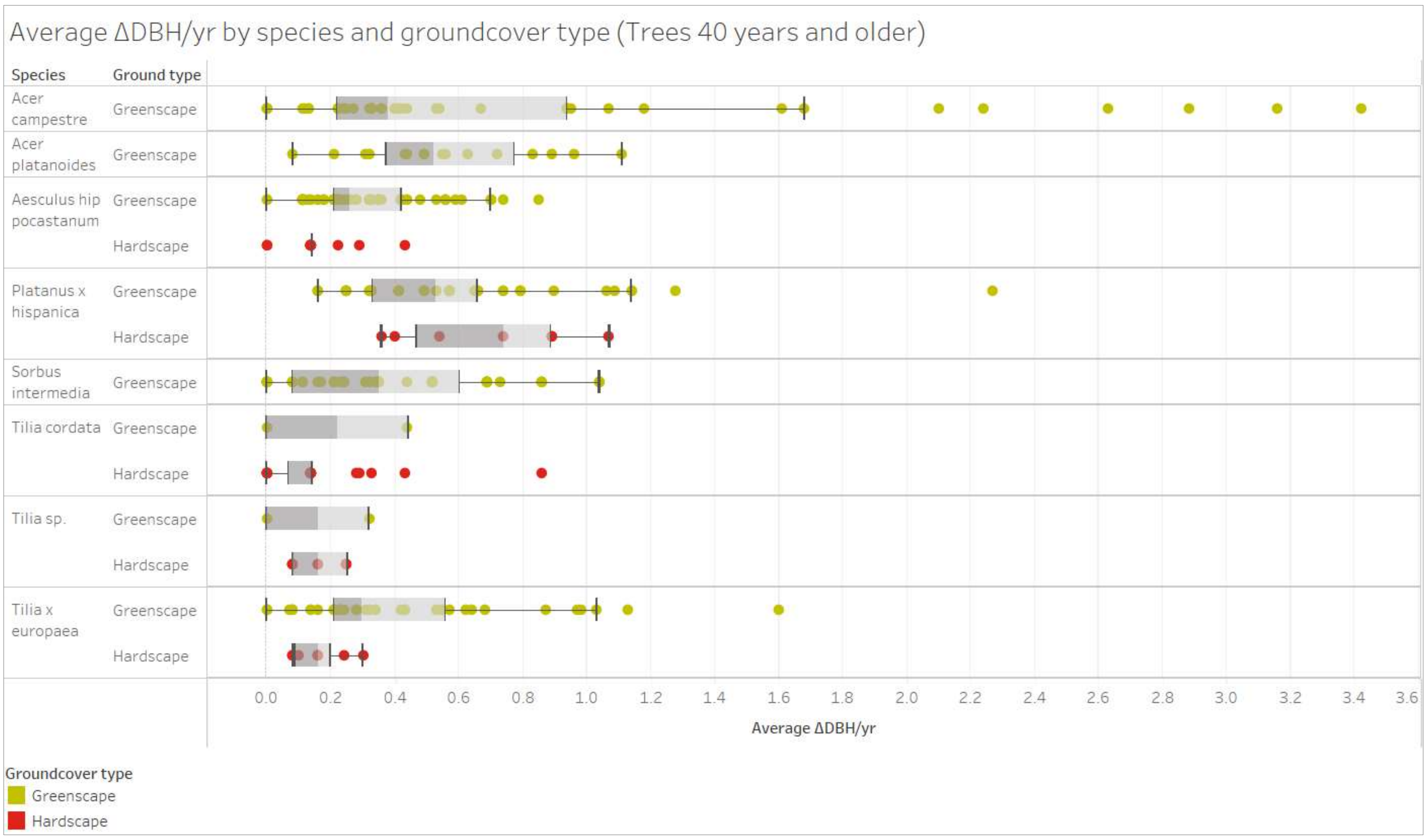


Figure 32: Average change in DBH per year by species, comparing trees recorded as planted in a greenscape groundcover type and in a hardscape groundcover type for each species which has 6 or more trees planted in each category, and which were 40 years or older when the latest inventory was taken.

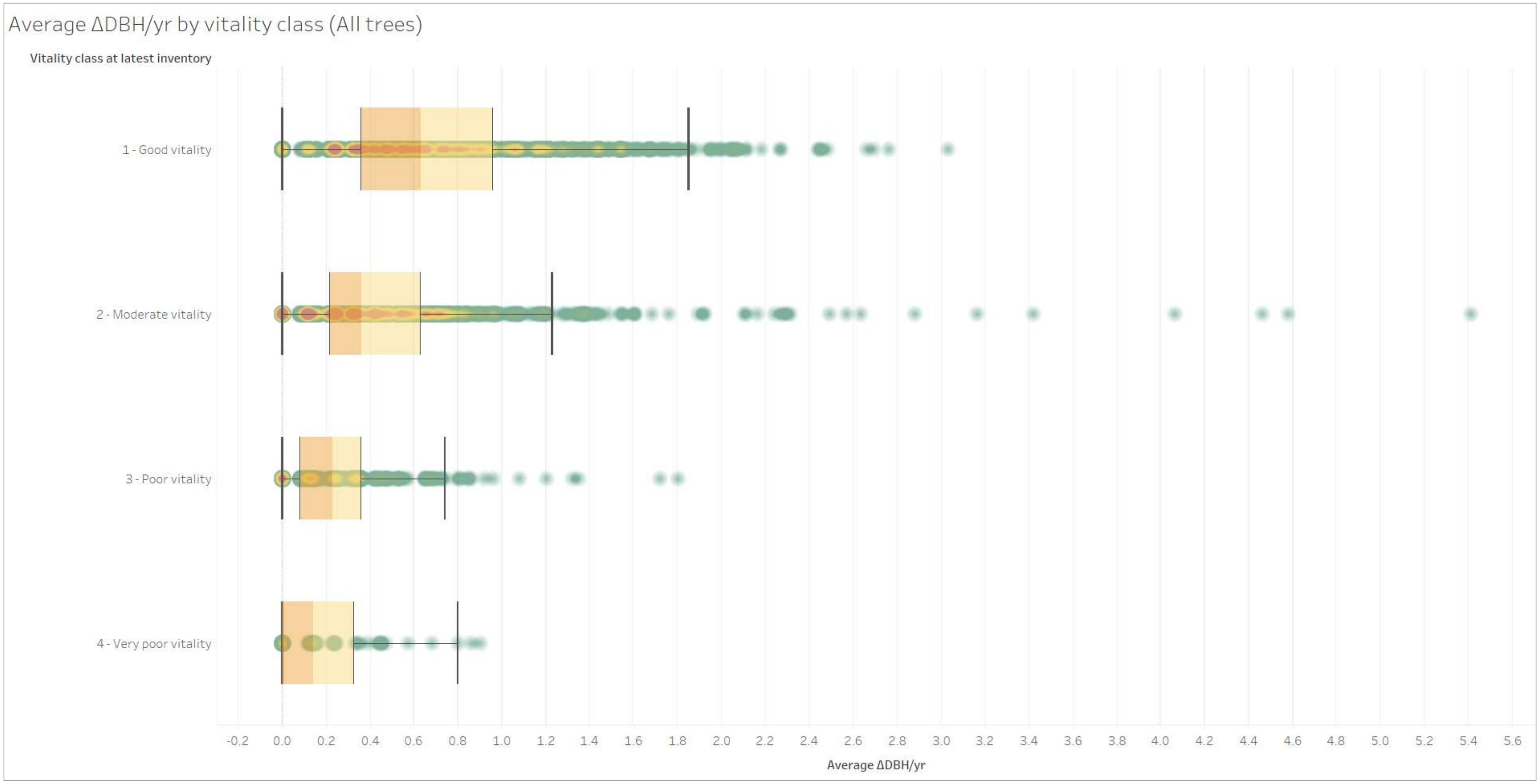


Figure 33: Average change in DBH per year for all trees in each vitality class recorded at the latest inventory.

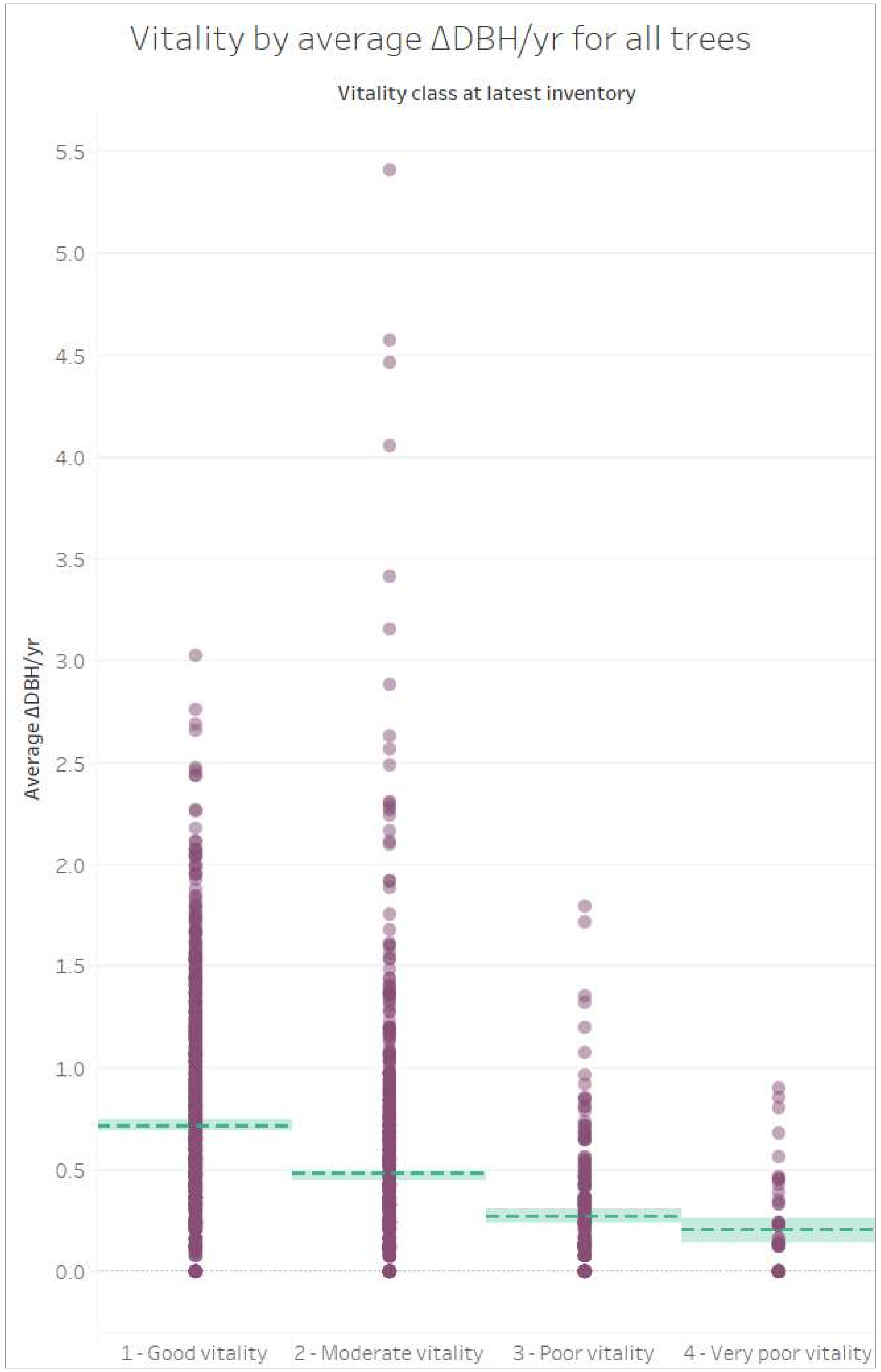


Figure 34: Average change in DBH per year of all trees in each vitality class. 95% confidence intervals are shown in blue.

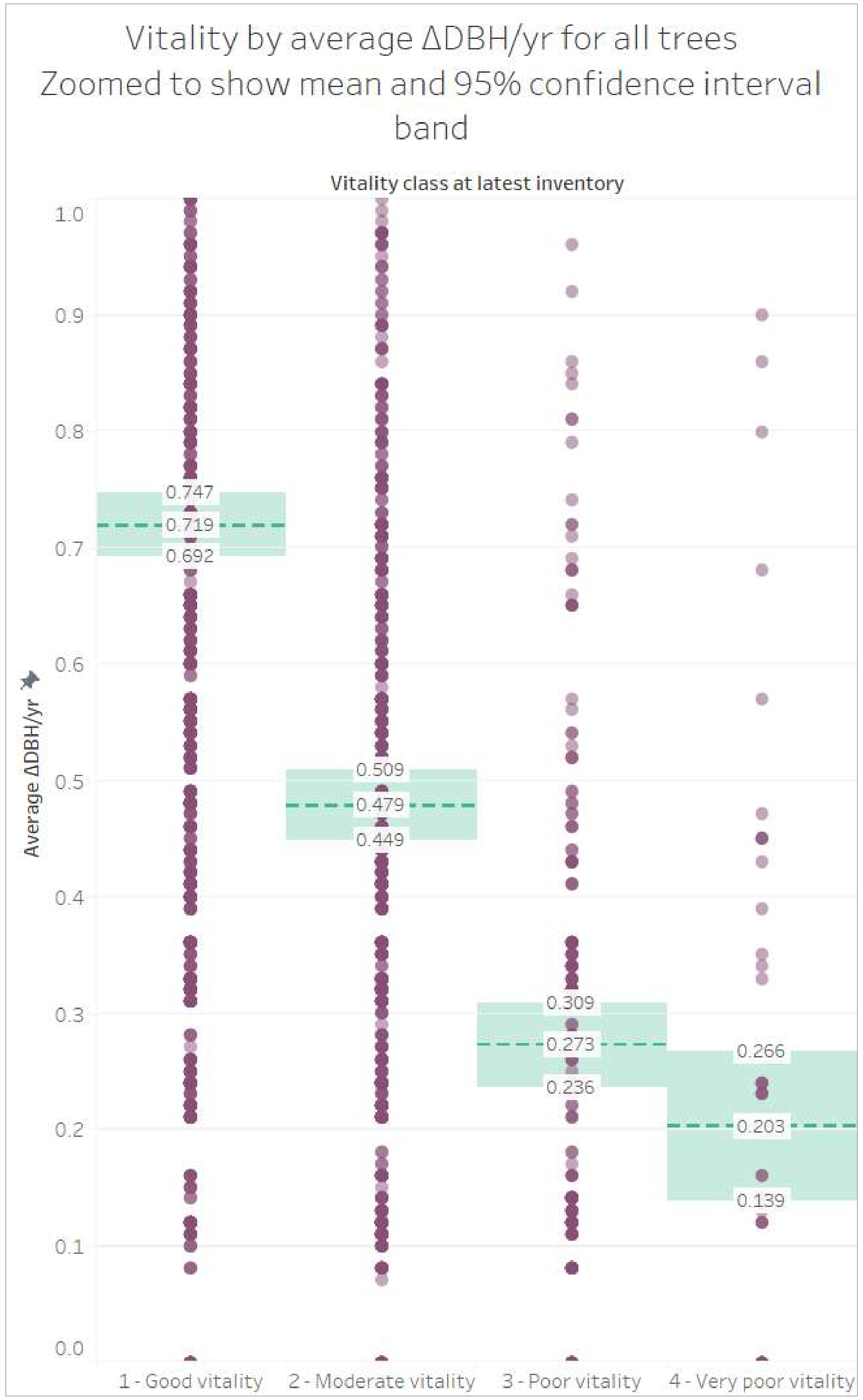


Figure 35: Average change in DBH per year of all trees in each vitality class, with adjusted scale to center the visualization on the means and 95% confidence intervals within each vitality class. 95% confidence intervals are shown in blue, as well as values for the means and tops and bottoms of confidence intervals.

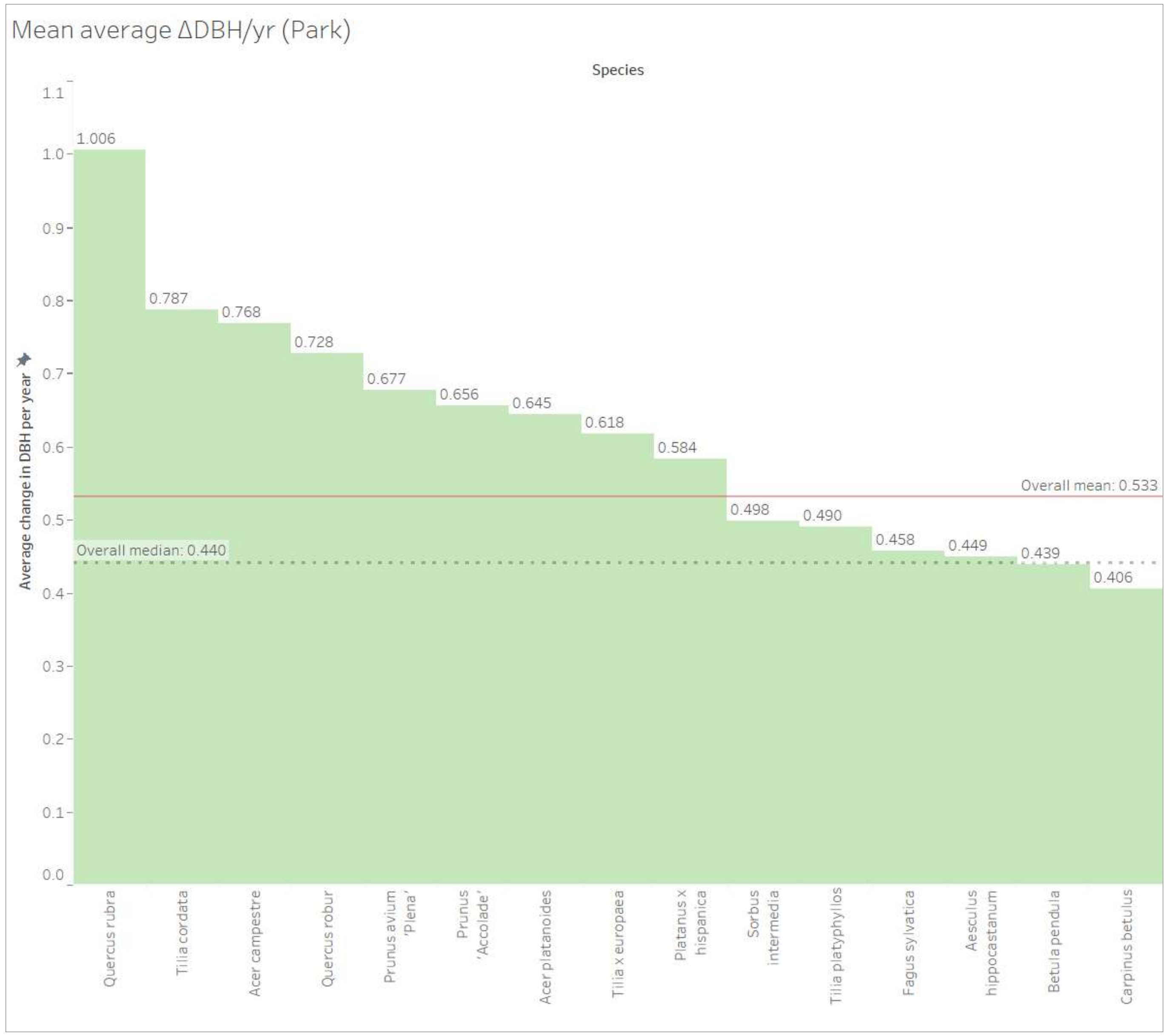


Figure 36: Overall median, overall mean, and per-species mean average change in DBH per year, showing trees recorded as planted in a park environment for each species which has 6 or more trees planted in both park environments and street environments.

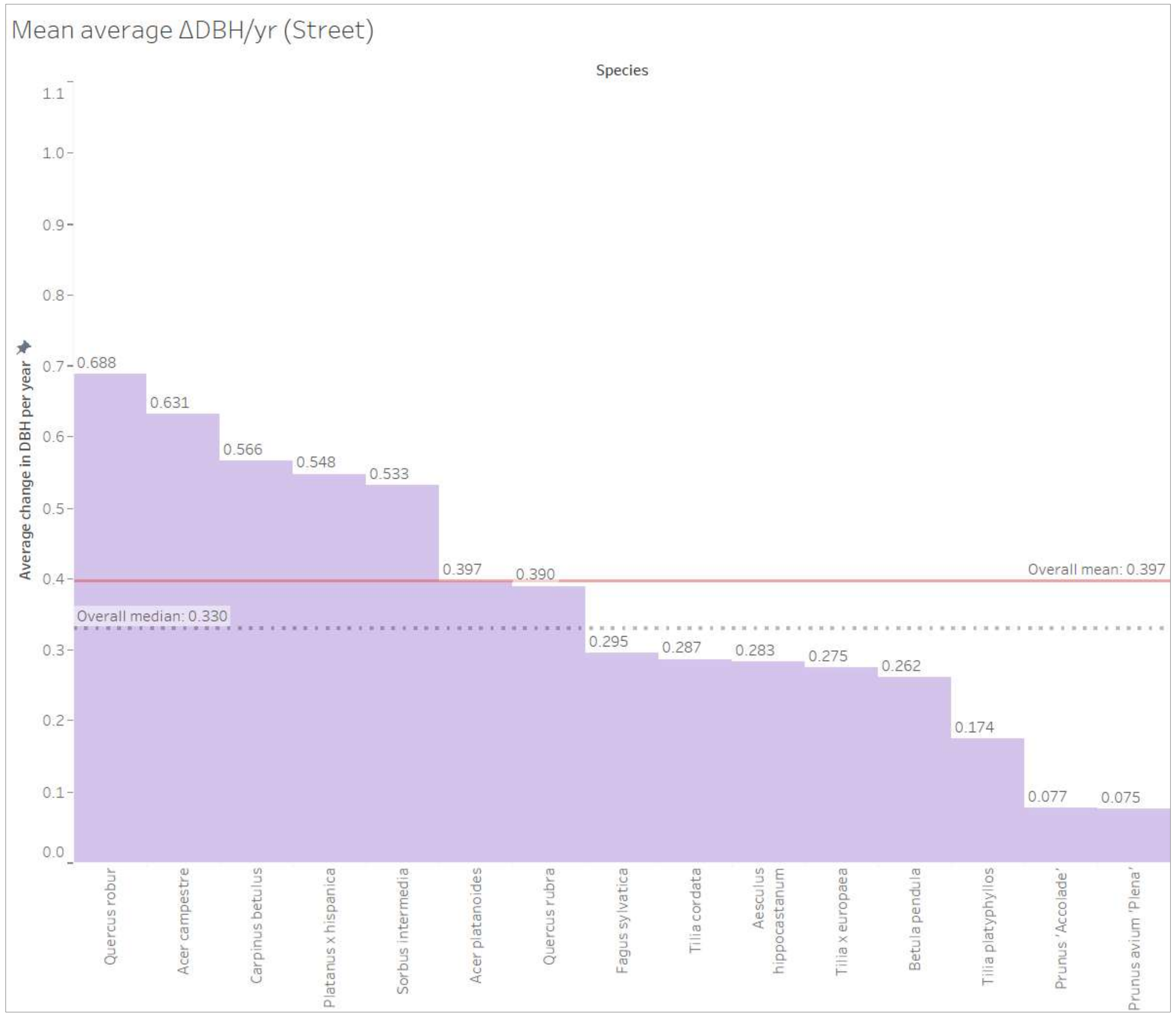


Figure 37: Overall median, overall mean, and per-species mean average change in DBH per year, showing trees recorded as planted in a street environment for each species which has 6 or more trees planted in both park environments and street environments.

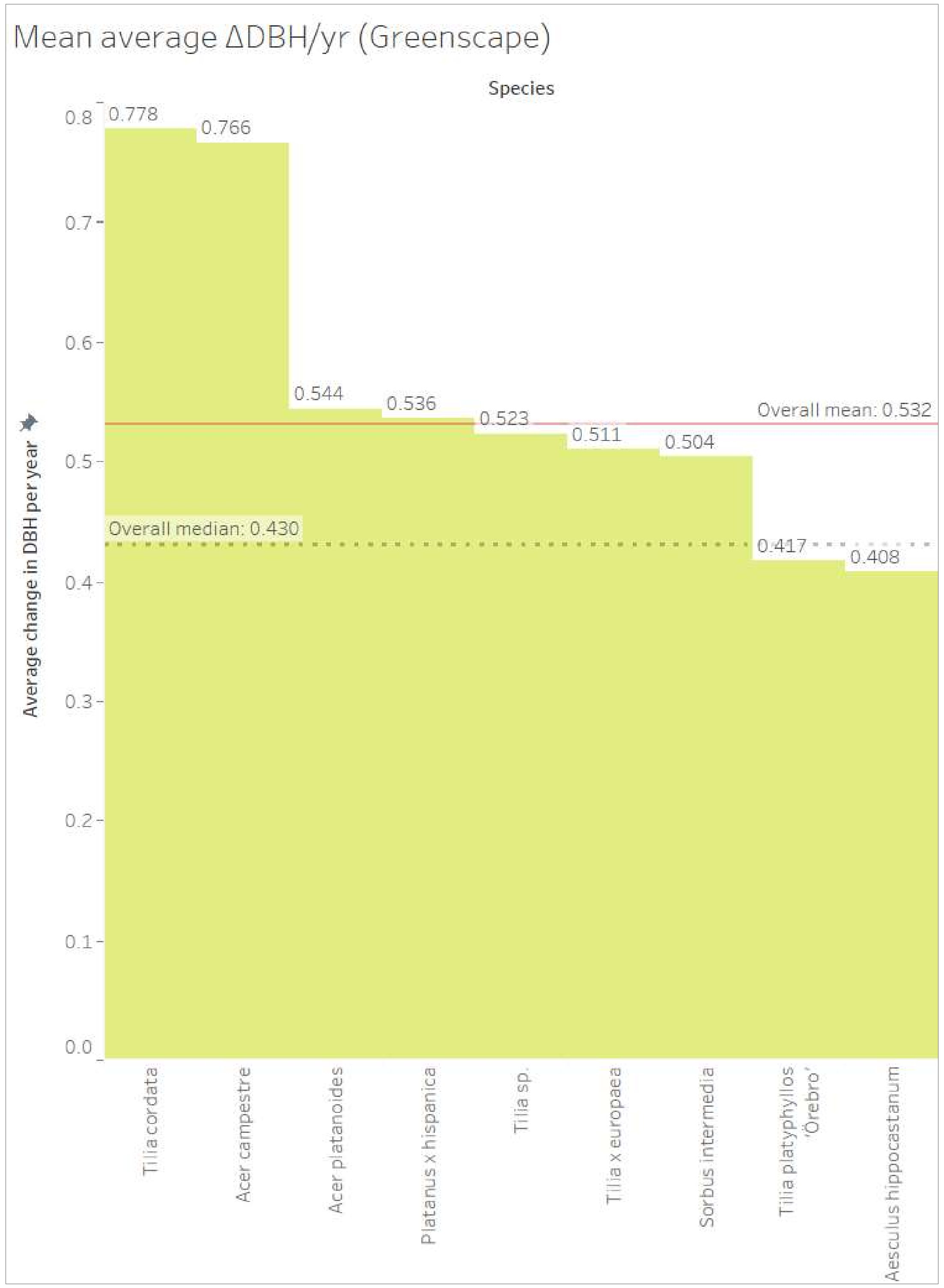


Figure 38: Overall median, overall mean, and per-species mean average change in DBH per year, showing trees recorded as planted in a greenscape groundcover types for each species which has 6 or more trees planted in both greenscape groundcover types and hardscape groundcover types.

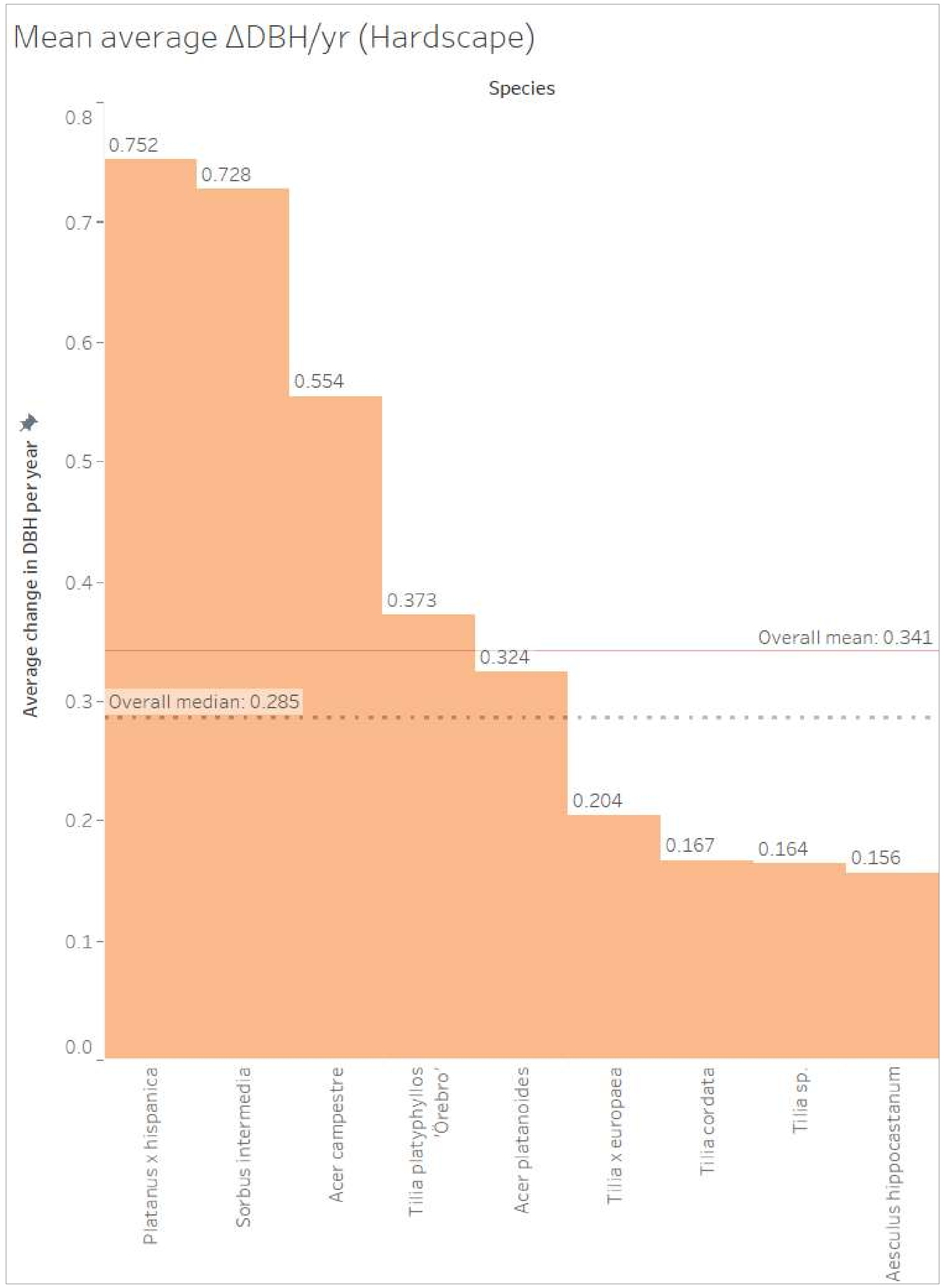


Figure 39: Overall median, overall mean, and per-species mean average change in DBH per year, showing trees recorded as planted in a hardscape groundcover types for each species which has 6 or more trees planted in both greenscape groundcover types and hardscape groundcover types.

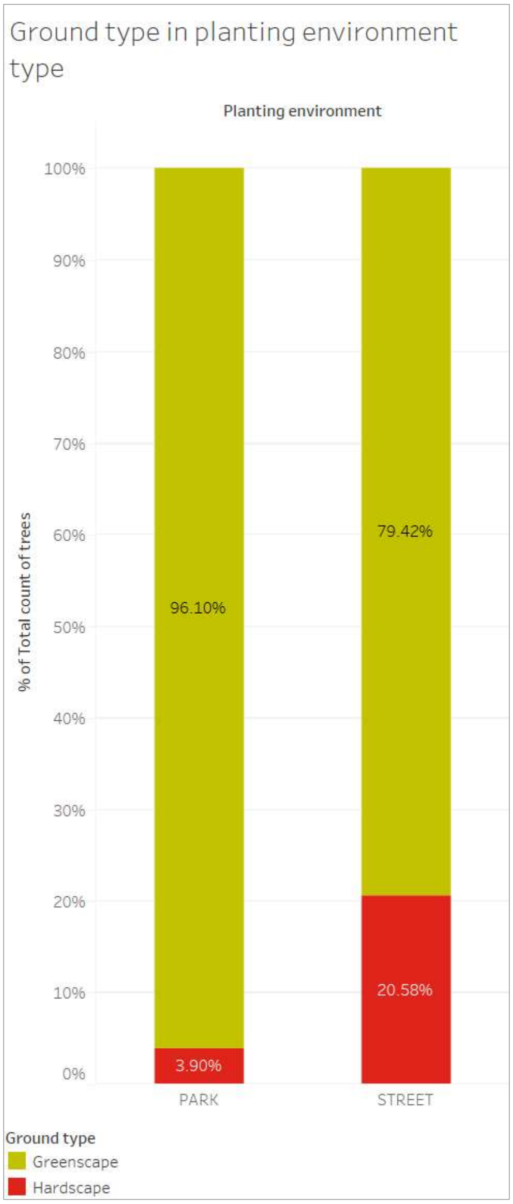


Figure 40: Proportion of groundcover types in planting environments.

6. Discussion

6.1 Comparison of crown diameter and latest DBH

The strong correlation between crown diameter and DBH at latest inventory reinforce the idea that DBH could serve as a reliable proxy for estimating crown diameter without necessitating direct crown diameter measurements. The observed "fan" shape of the data distribution (Figures 18-22) could be attributed to the smaller number of older trees in the dataset, resulting in fewer observations of trees with higher DBH values. However, it is noteworthy that DBH seemed to be a less accurate indicator of crown diameter for trees with a DBH exceeding 100. The relationship appeared most consistent in smaller (younger) trees, becoming less precise as DBH (and age) increased. In future research, analysis could be carried out to obtain a trend line that would have some explanatory power. This could then be used to calculate an estimate of average crown diameter when a tree's DBH is at a given value.

The stronger correlation for park trees and a comparatively weaker correlation for street trees shown in figures 19 and 20 suggest that trees in the park environment grew more quickly than those in a street environment. The same can be said of trees in the groundcover set (Figures 21 & 22), where trees in a greenscape appear to have grown more quickly than trees in a hardscape. In the planting environment set, there were more trees to sample in the park environment than in the street environment. In the groundcover set, there were more trees to analyze in a greenscape than in a hardscape. This uneven distribution between environment sets may be the reason these differences were seen. If more trees were available for analysis in both street and hardscape environments, it is possible a stronger correlation between those trees' DBH and crown diameter could be seen. In future studies of this nature, it would be an improvement to have a more balanced dataset between park and street trees, and greenscape and hardscape trees.

The weaker correlation among street and hardscape trees could be explained by greater variability in conditions affecting the growth of some of these trees in these environments. It is more likely that the crown of a street tree has been pruned to reduce the crown size near roadways or other infrastructure, whereas in a park, severe pruning is less likely to occur. The soil near street trees may become more compacted over time. There may be an increased amount of pollution in some street environments, but not necessarily in all, whereas in a park environment, there is a lesser likelihood of directly adjacent pollution sources. It is important to note, however, that a key finding in a study conducted between 2012 and 2017 (Coombes *et al.*, 2019) concluded that factors such as previous tree pruning and external site conditions, like hard surface coverage over the root area and soil composition, didn't substantially affect the correlation between DBH and crown width, meaning that using DBH as a proxy for tree canopy size is likely still tenable.

There could also be greater variability in species-specific factors that affect growth, such as wind resistance, drought resistance, or differences in root space needs, meaning that certain species may be more sensitive to street or hardscape planting. Because these graphs combine multiple species, it is expected that more environment-indifferent species would follow the normal trend, while more sensitive species would skew the results downward, weakening the correlation.

Although the formation of the new groundcover parameter did give another lens through which to view the data, the newly created parameter of groundcover type is an imperfect way to compare the environments of trees. The categories which were sorted into greenscape and hardscape are not so cut-and-dry as they may seem. For example, a gravel or very fine-particled gravel may not be best categorized as hardscape, as it is highly water-permeable.

6.2 Comparison of tree age at latest inventory and latest DBH

The analysis of the relationship between tree age at latest inventory and DBH at the latest inventory (Figures 23-26) was similar to the analysis done between the crown diameter and DBH at latest inventory. Is showed how closely age and DBH are related. A strong correlation was seen between both age and crown diameter against DBH in both cases. This suggests that DBH may be a fairly reliable substitute for age when age is unknown. However, DBH may already have been used to estimate age for some trees in this dataset, which could also partially explain the correlation.

6.3 Comparison of average change in DBH per year by species

When assessing each species' relative performance in what could be called "more restrictive" (street and hardscape) environments versus "less restrictive" (park and greenscape) environments, the relative performance in different planting environment types for a given species tended to mirror the relative performance in different groundcover types. That is, a species which does relatively better in greenscape compared to hardscape also does relatively better in parks compared to streets. Because of this pattern, these parameters can be discussed simultaneously, while pointing out species which were not present in both planting environment and groundcover sets due to insufficient sample sizes.

The relative performance of each species in both more restrictive and less restrictive environments provides potential insight into the optimal planting environments for various species and their suitability to harsher conditions. Given that more restrictive planting environments, such as streets and hardscapes, generally exert more stress on trees, this data is invaluable to urban tree managers. It allows them to select hardier species that exhibit superior performance under these conditions, particularly pertinent as climate change intensifies stress on urban trees.

In figures 27 and 30, it appears that certain species are especially sensitive to more restrictive planting environments, showing markedly slower growth compared to in less restrictive environments. Species whose median growth rate in one category of planting environment or groundcover environment was less than or equal to the lower extent of the interquartile range of the other category were: *A. hippocastanum, T. cordata,* and *T. europaea,* as well as *F. sylvatica, Prunus* 'Accolade', *Prunus avium* 'Plena', *Q. rubra*, and *T. platyphyllos*, which were only present in the planting environment set, and *Tilia sp.*, which was only present in the groundcover set. *A. platanoides* is also included in this category – its median hardscape growth rate was slightly lower than the bottom of its greenscape interquartile range, while its median street growth rate was very slightly above the bottom of its park interquartile range. These species appear to be best suited to park and greenscape environments.

Of particular interest are *Q. rubra, T. cordata,* and *T. europaea* which showed median growth rates in more restrictive environments which were less than half their growth rates in less restrictive environments. Although they only appeared in the planting environment set, *Prunus* 'Accolade', *Prunus avium* 'Plena', and *T. platyphyllos* were notable for their median growth rate of 0.0 cm per year in street environments. Each of these species did have a handful of trees showing positive growth in the street environment, but overall, they seemed to be exceptionally ill-suited to thrive in street environments. These species did not meet the minimum sample size cut-off for inclusion in the groundcover type set, however, ad hoc analysis of the 24 *Prunus* 'Accolade' planted in greenscape and the three planted in hardscape showed that the median average change in DBH per year was also 0.0 cm in greenscape. This could be because of site-specific conditions and a further step in analysis could be to investigate where these trees are located and what conditions they have been exposed to.

A number of the remaining species had mostly overlapping interquartile ranges for their growth rates, suggesting that they do equally well in less restrictive and more restrictive environments. These species include *A. campestre,* which was present in both the planting environment and groundcover sets, *B. pendula, C. betulus,* and *Q. robur,* which were present only in the planting environment set, and *T. platyphyllos* 'Örebro', which was present only in the groundcover set.

P. hispanica and *S. intermedia* show some promise of being resilient in more restrictive environments. When comparing planting environment types, their median growth rate in street environments was higher than in park environments, although they had overlapping interquartile ranges. When comparing their growth in different groundcover types, their median growth rate was higher in hardscapes than greenscapes, and the hardscape interquartile range was noticeably higher than the greenscape interquartile. It is worth keeping in mind that there is a fairly low sample size of hardscape trees for these species (nine for *P. hispanica* and eight for *S. intermedia*), and there could be elements of survivorship bias at play. For example, with a hypothetical species which does so poorly in a certain planting environment that most younger trees die and are removed before they reach adulthood, only those trees lucky enough to survive would appear in the inventory data. Nevertheless, these species are interesting candidates for further study.

When splitting these categories into trees younger than 40 or trees older than 40 (Figures 28 and 29), it was necessary to focus on species which had sufficient representation in all combinations of age groups and planting environment types: *A. platanoides, A. hippocastanum, S. intermedia, and T. europaea.* The relative performance between park and street trees of each of these four species did not change. Species that, for example, performed relatively better in park environments than street environments did so across age categories. Relative performance in different planting environments is thus more species-dependent than age-dependent. However, caution should be exercised when interpreting differences between age groups. Survivorship bias could be a factor. Also, the 40-year breakpoint may not be appropriate for all species' age distributions and expected growth curves.

6.4 Comparison of average change in DBH per year by vitality class of all trees

As shown in figures 33 through 35, trees with a higher change in DBH per year also had higher vitality overall. Trees in vitality class 1 on average increased DBH more than three times more quickly than trees in vitality class 4. Future research or analysis could be done to see whether growth rate is a leading indicator of later vitality change. This information could be used to identify trees which may be at risk of future vitality degradation.

6.5 Mean average change in DBH per year by planting environment types and groundcover types by species

Figures 36 and 37 compare the overall median, mean, and per-species mean average change in DBH per year within the park environment set, and reinforce the conclusions drawn from the analysis of figures 27 and 30. *C. betulus*, which had the lowest mean avg change in DBH per year of park trees (0.406) was higher than the mean average change in DBH for all species of street trees (0.397) – that is, the worst-performing park tree performed better than all street trees on average. Unsurprisingly, the species which performed better than the overall mean for street trees, *Q. robur, C. betulus, P. hispanica, S. intermedia*, are the same species which were shown to have better relative performance in park versus street planting environments, in addition to *A. campestre*, which had the same relative performance, as shown in figure 27.

Figures 38 and 39 compare the overall median, mean, and per-species mean average change in DBH per year within the groundcover set. Again, *A. hippocastanum*, which had the lowest mean average change in DBH per year of greenscape trees (0.408) was higher than the mean average change in DBH for all species of hardscape trees (0.341). Hardscape trees with growth rates above the overall average were *P. hispanica, S. intermedia, A. campestre,* and *T. platyphyllos* 'Örebro'.

T. cordata and *A. campestre* performed well above the overall mean in greenscape, at 0.778 and 0.776, respectively. *A. campestre* also had above average growth in hardscape (0.554), while *T. cordata* was rather below average with 0.167. A. campestre seemed to be a fast-growing species regardless of groundcover types, whereas T. cordata may be quite sensitive to groundcover conditions, as it grew very quickly in greenscape, and quite poorly in hardscape.

6.6 Proportion of groundcover types in planting environment types

Greater than 95% of all park trees were planted in greenscape, while hardscape groundcover was present in a much higher proportion of street trees; just over 1/5th of street trees were planted in hardscape.

6.7 General discussion

Another dimension of analysis could be digging deeper into expected average growth rates for each species in a given vitality class or age range, for example, which would allow urban forest managers to identify trees which are performing below expectations.

As a further step in the analysis, it would be interesting to see how multiple similar species of *Tilia* perform in these graphs when combined into a single group. *Tilia* is a genus in which it can be difficult to identify a species, especially when inventoried in the winter months when there are no leaves on the tree (Andrianjara *et al.*, 2021). This could also be done with other species in future studies.

Future research could also examine more species-specific age ranges to increase the variety of species available for analysis. For an examination of species age distribution, see appendix 2.

Additional factors, such as modifications to soil composition, could augment the current analysis of planting environment and groundcover type. One particularly challenging aspect of urban forestry is the planting of trees in hard surfaces. This challenge has been addressed through innovative solutions, such as the Malmö model, which employs the use of skeletal soil and pumice in a structural soil mix to facilitate the growth of trees on compacted surfaces. The Malmö model, which has evolved over time and is currently undergoing further refinement, provides an example of how targeted soil amendments can enhance the growth of urban trees (Jensfelt, 2018). The model focuses on allowing tree roots to extend beyond their initial planting pits, ensuring they have access to water and can grow effectively even in challenging urban environments (Bara mineraler, 2020).

It is important to note that while urban tree inventories and long-term monitoring are key for urban forest management, these alone are insufficient to guarantee resilience to climate change. Predictive analysis and future climate simulations are essential for decision-making. Successful management requires combining these tools with projections of urban forest responses to various climate and management scenarios. Currently, the use of these predictive tools in long-term urban forest planning is minimal (Esperon-Rodriguez *et al.*, 2022).

6.8 Limitations

Several limitations were encountered during this study. These limitations highlight areas for improvement and refinement in future research endeavors.

One of these was inconsistency in the recording of inventory parameters in the data set due to the extensive use of free text fields. This allowed for significant variation in spelling, nomenclature, and type of information conveyed, which may have introduced discrepancies in the data.

Another limitation arose from the unclear definitions of the parameters "Street environment" and "Park environment." For example, A tree which on the edge of a street, but within the boundaries of a park is usually recorded being a park tree, whereas a tree which is on the edge of a street, but within what would be considered a residential front lawn, is usually recorded as being a street tree. This is because the "Type" parameter in the inventory data is primarily used by FGK as an indication of how a tree is to be managed, not the environment in which it stands.

The influence of age as a confounding variable was also a significant limitation. In the box and whisker graphs showing average change in DBH per year by species, we look at data points from a wide range of ages, even when they are broken down into over 40 and under 40 categories. Because the expected growth rate varies by age and by species, trying to model age as a co-variant was beyond the scope of this study, but could be explored. Rather than trying to choose a single age break point for all species, it would be interesting to use species-specific expected age to DBH curves to find species-specific age break points, and also to compare performance in different planting environments to species-specific expected DBH averages at a given age.

The accuracy of age records introduced further uncertainty. There were varying levels of certainty in the inventory as to whether the planting year recorded was accurate or an estimate. In many cases, DBH may have been already used to estimate the age. The older the tree is, the more uncertainty there is about its age, but the less it matters because from years 55-60 compared to 60-65 there will not have been as much growth as between years 5-10 or 10-15.

Lastly, the accuracy of DBH measurements was a major limitation. Due to shifting multi-stem measurement standards, a significant number of multi-stemmed trees were excluded from the analysis. There was also a significant number of tree which did not have a recorded DBH at either the original or latest inventory.

7. Conclusion

In order for urban forest managers to provide ecosystem services in a cost-effective and sustainable way, they require tools to enable the selection of species that will thrive in various urban contexts, as well as be resilient against the effects of climate change. This study aimed to assess the feasibility of utilizing DBH measurements gathered in re-inventories as one such decision-making tool for species selection and management. DBH is recognized as an important inventory parameter and, as this and other studies' data show, DBH is a good proxy for crown diameter, which is an indicator of the degree of ecosystem services provided, and high growth rates tend to predict high vitality.

The study showed species-dependent differences in relative performance, as measured by growth rate, between various planting environment types and groundcover types. When urban tree managers are making future species selection decisions, they can use this data to make informed decisions about which species are likely to do well in the planned planting environment. The more restrictive environments of hardscape or street planting environments may be a preview of the increasingly harsh and unpredictable conditions caused by climate change, so, by looking at tree performance in more restrictive planting environments, it may also be possible to predict which species may be resistant to these conditions.

This study employed one way of dividing trees into age categories in order to assess any age-dependent performance difference but found little variation within species between the age groups which were selected. Future research could employ more sophisticated analysis, in particular around species-specific growth curves. Specific attention might be given to analyzing the performance in younger trees, as this would allow urban forest managers to select species which are likely to provide ecosystem services as quickly as possible.

While acknowledging limitations such as variations in measurement standards leading to reduced sample sizes, as well as potential confounding variables like age or unknown site conditions, the findings suggest that DBH measurements are nonetheless a valuable tool for informing species selection. Future re-inventory efforts should continue to prioritize the inclusion of this parameter in order to increase the available data for analysis. By doing so, a more comprehensive understanding of tree populations can be obtained, facilitating informed decision-making and more effective management strategies in the future.

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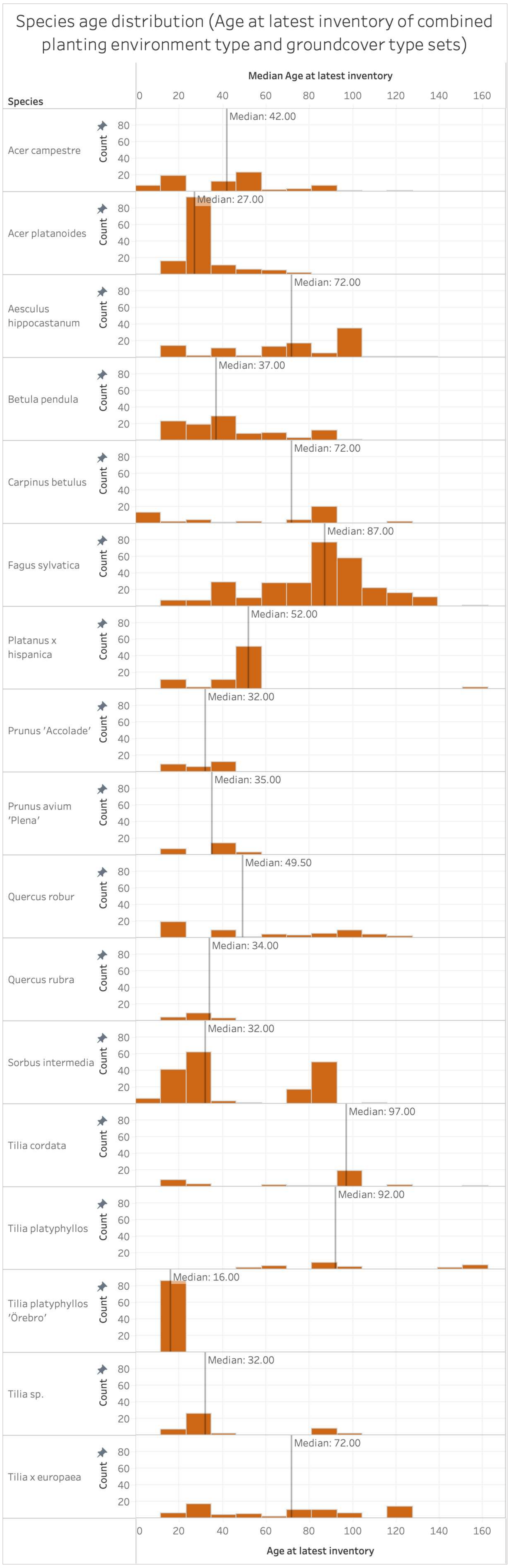
Appendix

***Appendix 1**: Median age of all trees in filtered dataset.*

Median ages (All trees)

Species	
Acer campestre	42.00
Acer campestre 'Green Column'	12.00
Acer negundo	37.00
Acer platanoides	27.00
Acer platanoides 'Globosum'	82.00
Acer pseudoplatanus	62.00
Acer saccharinum 'Pyramidale'	27.00
Aesculus carnea 'Briotii'	13.00
Aesculus hippocastanum	72.00
Alnus cordata	13.00
Alnus glutinosa	17.00
Alnus incana	30.00
Amelanchier x grandiflora 'Robin Hill'	18.00
Betula pendula	37.00
Betula pendula 'Youngii'	32.00
Betula pubescens	77.00
Betula sp.	57.00
Betula utilis	67.00
Carpinus betulus	72.00
Carpinus betulus 'Fastigiata'	24.00
Castanea sativa	37.00
Cedrus atlantica Glauca-Gruppen (syn. C. atlantica 'Glauca')	34.00
Cornus mas	16.00
Corylus colurna	16.00
Crataegus intricata	42.00
Crataegus monogyna	57.00
Crataegus monogyna f. fastigiata	72.00
Crataegus orientalis	94.00
Crataegus punctata 'Aurea'	62.00
Crataegus sp.	78.00
Crataegus x lavallei	13.00
Crataegus x media 'Paul's Scarlet'	77.00
Crataegus x persimilis 'Splendens'	17.00
Fagus orientalis	97.00
Fagus sylvatica	87.00
Fagus sylvatica 'Dawyck'	17.00
Fraxinus angustifolia 'Raywood'	18.00
Fraxinus excelsior	34.50
Fraxinus excelsior 'Pendula'	37.00
Ginkgo biloba	22.00
Juglans cinerea	13.00
Juglans nigra	12.00
Juglans regia	20.50
Larix decidua	92.00
Larix x marschlinsii	17.00
Liriodendron tulipifera	13.00
Magnolia (Liliiflora-Gruppen) 'Susan'	12.00
Magnolia kobus	8.00
Magnolia x soulangeana	32.00
Malus 'Evereste'	12.00
Malus (Purpurapel-Gruppen) 'Eleyi'	32.00
Malus baccata 'Columnaris'	16.00
Malus domestica	36.00
Malus floribunda	27.00
Malus sp.	32.00
Pinus nigra	102.00
Pinus x schwerinii	12.00
Platanus sp.	42.00
Platanus x hispanica	52.00
Populus alba	37.00
Populus nigra 'Plantierensis'	92.00
Populus simonii	49.50
Populus x canadensis 'Robusta'	52.00
Prunus 'Accolade'	32.00
Prunus (Sato-zakura-Gruppen) 'Kanzan'	31.00
Prunus (Sato-zakura-Gruppen) 'Shirotae'	12.00
Prunus avium	28.00
Prunus avium 'Plena'	35.00
Prunus cerasifera	37.00
Prunus cerasus	23.00
Prunus maackii	28.00
Prunus padus	37.00
Prunus sargentii	17.00
Prunus serrula	32.00
Prunus sp.	22.00
Prunus subhirtella 'Autumnalis'	18.00
Pseudotsuga menziesii	79.50
Pterocarya fraxinifolia	26.00
Pyrus communis	92.00
Quercus cerris	13.00
Quercus frainetto	17.00
Quercus petraea	11.00
Quercus robur	49.50
Quercus robur Fastigiata-Gruppen (syn. Quercus robur f. fastigiata)	28.00
Quercus rubra	34.00
Robinia pseudoacacia	36.00
Robinia sp.	62.00
Salix alba	52.00
Salix x fragilis f. vitellina	57.00
Salix x pendulina 'Elegantissima'	37.00
Salix x pendulina f. salmonii 'Chrysocoma' (syn. Salix x sepulcralis 'Chrysocoma')	42.00
Sambucus nigra	32.00
Sequoiadendron giganteum	15.00
Sorbus aria	37.00
Sorbus aucuparia 'Fastigiata'	19.00
Sorbus intermedia	32.00
Sorbus ulleungensis	15.00
Sorbus x thuringiaca 'Fastigiata'	14.00
Styphnolobium japonicum	20.00
Syringa reticulata 'Ivory Silk'	11.00
Taxodium distichum	15.00
Taxus baccata	52.00
Thuja plicata 'Excelsa'	15.00
Tilia cordata	97.00
Tilia platyphyllos	92.00
Tilia platyphyllos 'Örebro'	16.00
Tilia sp.	32.00
Tilia tomentosa	67.00
Tilia x europaea	72.00
Tilia x europaea 'Euchlora'	32.00
Ulmus glabra	72.00
Ulmus minor	36.00
All species	**37.00**

Appendix 2*: Species age distribution for combined planting environment set and groundcover set. Median age of all trees in both sets combined is 42.*



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