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Residential Urban Forest Assessment Methodologies

A Management Perspective

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Residential Urban Forest Assessment Methodologies. A Management Perspective

Abstract

Urban trees provide a wide range of ecosystem services. Many of these are located on private property in residential areas, and are infrequently included in urban forest strategies and plans and for most local governments, the overview of the urban tree population with its potential for supplying ecosystem services is incomplete.

This thesis examined the assessment methodologies of ecosystem services provided by urban trees in the attempt to provide valuable information about residential trees. Various methodological approaches were applied, including: literature study, field work, remote sensing, spatial analysis and questionnaire surveys.

It was found that long-term validation of sampling methods is required for repeated urban forest assessments. While residents reported positive attitudes to trees and benefits they provide, this did not necessarily result in greater tree abundance. Remote sensing could be seen as a reliable and non-invasive way to determine canopy cover in residential areas using publicly available remote sensing imagery.

This thesis addressed the gap in understanding the importance of residential urban trees and the ecosystem services they provide as a part of the urban forest. It provides important contextual information of how residential tree assessments should be utilized to include additional social and spatial variables. This would allow for residential trees to become better integrated into local government, governance structures in order to develop informed management approaches for the entire urban forest.

Keywords: Urban forestry, urban trees, ecosystem services, residential trees, governance, management, canopy cover, remote sensing

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Bedömning av privatägda stadsträd. Förvaltningsperspektiv

Sammandrag

Flertalet stadsträd växer på privat bostadsmark och ingår därför sällan i kommuners och stadsförvaltningars grönplaner eller andra policydokument för stadsträdsförvaltning. De ekosystemtjänster och den dynamik som trädpopulationen i dessa områden erbjuder tas därför inte med i den strategiska planeringen och får inte uppmärksamheten som kan behövas för att säkerställa deras förekomst.

Denna avhandling har studerat metoder för analys av stadsträd i privata bostadsområden för att tillgodose värdefull information till yrkesverksamma inom stadsträdsförvaltning. Den stora mängden träd på individuella tomter prövades gentemot beslutsdrivande variabler utifrån fältanalyser, fjärranalys, platsbesök och granskning av tomters rumsliga uppbyggnad. Trots att boende och husägare uppskattade träd och trädens kvaliteter samt nyttor, så innebar nödvändigtvis inte detta att fler träd växte på dessa tomter. Resultat visar att långsiktig validering av provtagningar (sampling) krävs för en uppföljning av träd i bostadsområden och att fjärranalys kan ses som en tillförlitlig och diskret metod att fastställa trädkronstäckning utifrån officiellt tillgänglig information över bostadsområden.

Arbetet i denna avhandling har bidragit till en större förståelse över träd i bostadsområden och att de behöver ingå i en den större kartläggningen av stadsträd. Ett helhetsgrepp över stadens alla träd, oavsett administrativ gräns, samt hur dessa är kopplade till sociala och rumsliga faktorer blir ett tongivande inslag för att beslutsförhållanden och styrning av framtidens stadsträd verkligen vilar på en holistiskt och välinformerat utgångsläge.

Keywords: Stadsträd, ekosystemtjänster, privatägda träd, governance, förvaltning, krontäckning, fjärranalys

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Dedication

To Euphi and to my family.
For all the support, patience and love over the years.

Contents

List of publications

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

I. Klobucar, B., Östberg, J., Jansson, M. & Randrup, T.B. (2020). Long-term validation and governance role in contemporary urban tree monitoring: A review. *Sustainability* 12, 5589; DOI:10.3390/su12145589

II. Klobucar, B., Sang N. & Randrup, T.B. (2021). Comparing Ground and Remotely Sensed Measurements of Urban Tree Canopy in Private Residential Property. *Trees, Forests & People* [in review.]

III. Klobucar, B., Östberg, J., Jansson, M. & Wiström, B. (2021). Residential urban trees – social and environmental drivers of tree and shrub abundance in the city of Malmö, Sweden. *Urban Forestry & Urban Greening,* DOI: 10.1016/j.ufug.2021.127118.

Papers I-III are reproduced with the permission of the publishers.

The contribution of Blaz Klobucar to the papers included in this thesis was as follows:

I. Corresponding and lead author, with contributions in conceptualisation, visualisation, writing of original draft, reviewing and editing the manuscript

II. Corresponding and lead author, with contributions in methodology, data collection, data curation, writing of original draft, reviewing and editing the manuscript

III. Corresponding and lead author with contributions in methodology, data collection, calculations writing of original draft and editing the manuscript.

1. Introduction

For most of their history, human populations have lived in very low-density rural settings. Prior to 1600, it is estimated that 5% of the world's population lived in cities. The ratio between rural and urban population started to change rapidly during the age of industrialisation, beginning in the 19th century, which fundamentally changed the way we live today. By 2050, it is estimated that more than two-thirds of the global population will live in cities (UN, 2019). This will make the urban environment the primary setting for human lives (Goldewijk *et al.*, 2010) influencing lifestyles, culture and behaviour.

Life in urban settings comes with many benefits. These may take the form of good accessibility and higher quality of basic services, as densification of residents enables more efficient use of resources through use of public transport, cycling and sustainable living. This is in line with the United Nations Sustainable Development Goals, which warn governments that growth of cities should not come at the expense of quality of life (SDG, 2020). Living in an urban environment also comes at a cost, in the form of exposure to negative environmental factors such as noise and air pollution that are less evident in rural areas and have the potential to affect a proportionally higher number of people. For many urban communities, this poses a tremendous challenge to ensuring a high standard of living for a rapidly growing urban population concentrated in a small space (Kabisch *et al.*, 2016; UN, 2014).

There are various ways to address the issues associated with urbanisation, e.g. by providing adequate living space, good healthcare services, access to food and other measures to improve the well-being of inhabitants (EEA, 2015). When it comes to alleviating negative impacts of the urban environment, natural and semi-natural areas, or urban forests or green spaces, integrated within the built environment have been proven to work exceptionally well, supplying a wide array of benefits (Rogers *et al.*, 2017; Gill *et al.*, 2007). As a result of natural and ecological processes, urban forests can help alleviate hazards. Air pollution and noise can be reduced by vegetation, and impacts of extreme weather events (heatwaves, extreme rainfall or flooding) can be mitigated (Norton *et al.*, 2015), thus improving the health (van den Bosch & Ode Sang, 2017) and well-being of urban residents (Bowler *et al.*, 2010; Gill *et al.*, 2007). These combined beneficial effects are commonly called ecosystem services and are integral in shaping global policy for a future sustainable environment (MEA, 2005).

Residential landscapes represent 41% of urban areas globally (UN, 2014). In Sweden, the proportion ranges from 30% in large cities (>100 000 inhabitants) to almost 70% in small cities (<500 inhabitants) (Statistics Sweden, 2015). The function of residential landscape spaces extends past the utilitarian aspect of housing city residents, as these spaces represent connection to nature, closely linked to personal relationships with family and neighbours (Bhatti & Church, 2001). Through natural regeneration or gardening practices, trees are commonly present on residential plots.

Residential trees may represent more than half of all tree canopy cover within a city area, making them a dominant force in providing ecosystem services (McPherson, 1998). The amount of ecosystem services that trees provide is closely related to crown volume and tree species, and can be modelled using allometric equations (Troxel *et al.*, 2013). Based on the calculated amount, the cumulative effects on human well-being and monetary replacement value can been estimated using environmental modelling and projected impacts on human health (Nowak *et al.*, 2013). This approach has been widely used in urban forestry practice and research worldwide.

The benefits of managing and retaining an urban tree population are recognised by local governments world-wide, especially as climate change is expected to exacerbate many of the environmental problems that trees mitigate. The Organisation for Economic Co-operation and Development (OECD) has called for new innovative solutions to minimise the trade-offs between urban growth and environmental priorities (OECD, 2009). Therefore, urban forestry professionals need to be well-versed in multidisciplinary approaches, embracing principles from social and natural sciences, since their profession is positioned at the interface where people meet nature (Miller *et al.*, 2015; Konijnendijk *et al.*, 2006).

Publicly accessible green spaces in urban settings are traditionally the responsibility of a local park, green space or urban forestry department, which manages these green spaces to develop, sustain and maintain public property for the enjoyment of residents (Fongar *et al.*, 2019; Östberg *et al.*, 2018; Randrup *et al.*, 2017; Randrup & Persson, 2009). However, private property is rarely included in the management process and management of privately-owned trees operates independently of public efforts (Jansson & Randrup, 2020; Miller *et al.*, 2015; Konijnendijk *et al.*, 2005). Privately-owned yards are, in their own right, a unique ecological phenomenon of highly maintained and diversely managed ecosystems. They are also the primary setting for a majority of human interactions with the natural environment.

The appearance and condition of residential landscapes and their trees are the outcome of an interplay between many different factors at different scales reflected in the structure and appearance of private properties. Cook *et al.* (2012) illustrated the dynamics of residential landscapes using the model depicted in Figure 1. The model has two main components: human drivers and ecology in residential landscapes. The links between disciplinary perspectives are illustrated as components of a wide framework that form an interconnected system (legal effects and management decisions). Residential properties and the presence of trees make a major contribution to the well-being of urban inhabitants, and possibly constitute the most plentiful source of ecosystem services provided by urban trees across the urban landscape. In Sweden, inclusion of residential trees in planning and management on local government level, which is necessary for a holistic approach to urban forestry management, is currently lacking (Klobucar *et al.*, 2020; Östberg *et al.*, 2018). New inclusive management approaches are needed to manage urban trees comprehensively, as the key to developing sustainable, resilient cities.

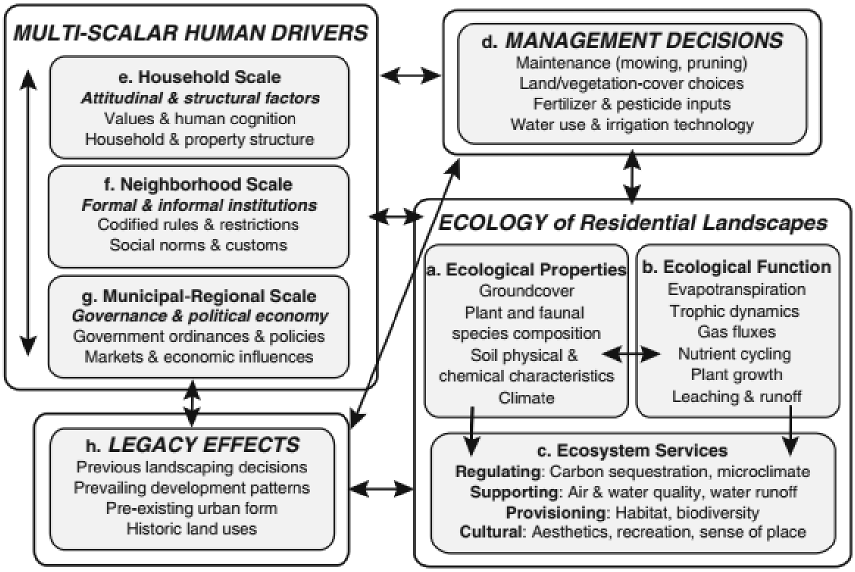

Figure 1 Model of multi-scalar social-ecological interactions in residential landscapes. Source: Cook *et al.* (2009).

As residential landscapes represent a significant part of the total urban area globally (Nowak & Greenfield, 2020), the collective impacts of residents' management decisions have the potential to alter the ecological functioning of the urban landscape. The impacts can be felt throughout the city, as ecosystem services often extend beyond administrative and ownership boundaries. The impact of residents' decisions on the overall ecological footprint of a city is difficult to assess qualitatively and the motives behind specific decisions have proven difficult to predict (Lee *et al.*, 2017; Lowry *et al.*, 2011). Using monitoring predictors of tree abundance in residential landscapes over time, trends can be extrapolated to estimate production of ecosystem services.

According to several contemporary sources, residential landscapes are experiencing an increase in the area of impermeable surfaces (streets, roofs, tiles, patios etc.), at the expense of permeable surfaces, which are more suitable for tree and root growth (Nowak & Greenfield, 2020; Wellmann *et al.*, 2020b). This may be viewed as a concerning trend that can cause long-lasting environmental damage in modern cities and can outweigh the ability of trees in providing sufficient capacity for mitigation of extreme weather events caused by future climate change. Thus integrating residential landscapes into local government management plans and activities could be a major contributing factor to achieving long-term sustainability goals.

The two key components of urban forest resilience are the urban forest as a socio-ecological system and the resilience of urban forest itself (Dobbs *et al.*, 2017). The management behaviour of individual residents has been described as active, fragmented and spontaneous (Conway, 2016). Tree removal can often be associated with poor risk assessment and can lead to removal of healthy trees (Kirkpatrick *et al.*, 2013). Lowry (2011) found that one notable predictor of tree canopy in residential areas is the age of houses, with canopy cover increasing to the peak for houses aged 45-50 years and then beginning to decline. Potential plantable space, as a function of house footprint in relation to plot size, has also been proven to be a predictor of the tree population in residential areas, as it is positively related to canopy cover (Wu *et al.*, 2008).

At the larger scale, measures to increase the urban tree population often include community programmes aimed at encouraging tree planting on residential properties by providing low-cost plant materials and other forms of support to engage the community and raise awareness (Roman *et al.*, 2013). In an effort to retain as much of the existing tree population as possible, some local governments have introduced regulations limiting the ability of property owners to remove trees, with moderate levels of success (Conway & Bang, 2014). A direction that local governments could take is to provide educational activities that promote tree benefits with a clear operational goal in mind, since there is strong evidence of a link between residents' attitudes to trees and individual management actions (Ordóñez & Duinker, 2013). Some studies have classified the attitudes of different groups of residents and their effect on residential tree management, and have found a wide range of opinions among residents that need to be addressed by urban forest managers (Kirkpatrick *et al.*, 2012). These opinions range from tree-averse to pro-tree, depending on perceived benefits/risks associated with trees.

The reason why some residents harbour negative perceptions of, trees leading to their removal, could be that ecosystem disservices are sometimes associated with urban trees. A study in Sweden on written complaints to municipalities found that citizens most often expressed disapproval of trees because of unsuitable growing space, messiness and damage caused to private property (Delshammar *et al.*, 2015).

Urban forest management in Scandinavia includes urban and peri-urban areas and operates at all scales from the entire city to open spaces around buildings and facilities (Randrup & Persson, 2009), but rarely includes private residential trees (Östberg *et al.*, 2018). In Sweden, this means that urban tree management actions and relevant decisions are based on urban tree data for public trees (park and street), based on inventories carried out by a local government department and with emphasis on trees owned and managed by the local government.

However, the approaches described above are not standard practice in Sweden for two specific reasons. First, local government is severely limited in providing planting material to private residents, since it would then need to provide the same opportunity for all residents, due to the legally defined "principle of equality" within municipal law (Likställighetsprincipen). Second, apart from a few exceptions in biodiversity/biotope protection, individual trees are not protected by the laws and regulations in Sweden, essentially giving free rein to residents to express their preferences regarding their private outdoor environment as they see fit (Naturvårdsverket, 2001).

There is thus a need to develop new management approaches supporting inclusion of ecosystem services deriving from private residential trees in local government urban forestry planning and management. This in turn creates a need for finding suitable assessment methods, and potentially also related management approaches, which can enable sustainable urban development in which residential trees and their associated ecosystem services are incorporated.

Residential landscapes are complex ecosystems where ecological outcomes are dictated by human behaviour (Cook *et al.*, 2011). Socio-ecological interactions at the individual property scale result in environmental changes on community scale (Larondelle & Haase, 2013). Therefore, the drivers of management decisions should not be overlooked in an overall ecosystem service provision perspective. In the absence of regulatory measures, the characteristics of individual households and the cognitive characteristics and values of individual householders are the most significant factors in explaining tree mortality (Kirkpatrick *et al.*, 2012).

2. Aim and research questions

Based on the above, this thesis focuses on choosing a *context-appropriate way to assess the residential urban trees.* The aim is to improve the knowledge of the residential tree resource itself, as well as the understanding of relationships between different actors in a way that conclusions could be applied more broadly than the spatially-explicit study site.

The overall aim in this thesis was to study how residential tree assessments can be *designed and performed by local governments in order to provide an understanding of socio-ecological drivers in private residential areas.*

Achieving this required a deeper basic understanding of the *scope*, *small-scale dynamics* and *monitoring* of residential trees on city scale. Therefore, the following three research questions (RQs) were formulated:

RQ 1: Which are the contemporary urban tree assessments methodologies, and how are they these methodologies appropriate for long-term monitoring of residential trees?

RQ 2: Can assessments of privately-owned urban trees be conducted frequently and non-invasively, to provide a complete overview of the urban tree population over time?

RQ3: Which socio – ecological and household-scale parameters explain the variation in provision of regulatory ecosystem services by residential trees?

3. Theoretical approach/framework

3.1 Ecosystem services, green infrastructure and urban forestry

All natural environments on Earth are shaped by human species, directly or indirectly. Humans depend on the capacity of these ecosystems to provide essential ecosystem services, meaning that they function as life-support systems for the planet. The term ‘ecosystem services’ was first coined in the 1970s, in an attempt to bridge the divide between biophysical aspects of ecosystems and human benefits (Westman, 1977). Ecosystem services are broadly divided into four categories that are linked to various components of human well-being (MEA, 2005): provisioning (e.g. food, nutrient cycling), regulating (e.g. flood prevention, climate regulation), support (e.g. habitats, nursery) and cultural (e.g. recreation, aesthetics. Since then, the term has been commonly used in ecosystem assessments worldwide in order to provide an ecological underpinning to valuations of environmental benefits.

Natural and semi-natural areas continue to be present within urban areas to varying degrees and are subject to local environmental planning. To provide planners with a holistic understanding of social-ecological system complexity, the term ‘green infrastructure’ has seen wide use in practice. Within Europe, green infrastructure is defined as a “strategically planned network of natural and semi-natural areas with their environmental features designed and managed to deliver a wide range of ecosystem services” (European Commission, 2013). Several initiatives have been launched to promote this idea in practice (e.g. Hansen, 2017). Residential areas are considered part of urban green infrastructure, as one of the many green space types (Haase *et al.*, 2020). Frequent use of green infrastructure concepts has enabled a clearer articulation in policy regarding management of natural resources, including those within urban areas, but issues still persist, specifically in the quality of information and the risk of institutional failures in mixed-ownership structures (Kumar, 2010).

Trees are a critical component of the Earth's biosphere since, through their photosynthetic activity, they contribute greatly to supporting human welfare and life-support systems (Costanza *et al.*, 1997). This is a result of the biophysical structure and function of the tree population and can be classified as provision of ecosystem services, with a clearly defined beneficiary on the receiving end (Haines-Young *et al.*, 2010). The beneficiary considered in this thesis is people living in urban areas. Rapid urbanisation has made cities a key meeting point between people and (urban) nature, while also increasing the demand for ecosystem services. Climate change will only add to this demand, based on projected rises in temperatures and the frequency of extreme weather effects (IPCC, 2014). Thus, due to their proximity to large numbers of people, trees in urban areas will continue to be important suppliers of ecosystem services.

Trees are particularly well-suited to mitigate the negative environmental impacts of climate change and urbanisation due to their innate ability to remove pollutants from the atmosphere. Compliance with regulations on improved air quality could reduce the number of premature deaths in European cities by more than 50 000 per annum (Khomenko *et al.*, 2021). Trees have been proven to remove pollutants such as ozone, carbon monoxide and sulphur dioxide, and to intercept particulate matter on leaf surfaces (Nowak *et al.*, 2006). In addition to these air improvements, interception and uptake of water by trees dampen peak stormwater flows, and thus lower the risk of flash floods, and reduce the cost of stormwater treatment and pollutant wash-off (Xiao & McPherson, 2002). In warm weather, transpiration of water through leaf surfaces and shading by trees provide a cooling effect that can mitigate the urban heat island effect (Wang & Akbari, 2016). At a larger scale, trees remove carbon from the atmosphere and store it in woody biomass (Nowak & Crane, 2002), contributing to negating greenhouse gas emissions. Studies have shown a great potential for carbon storage and sequestration within residential yards (Ariluoma *et al.*, 2021).

Recognition of the importance of trees in urban environments has resulted in the emergence of urban forestry, a specialist discipline that covers all aspects of urban forest management, ranging from individual trees to urban woods and woodlands (Ferrini *et al.*, 2017; Miller *et al.*, 2015; Konijnendijk *et al.*, 2005; Harris *et al.*, 2004). The practice of urban forestry is dedicated to all aspects of managing individual trees and entire urban forests. This includes an emphasis on addressing social needs and values of urban society, creating a human environment with high levels of comfort and well-being. In practice, urban forestry relies on detailed knowledge among practitioners of the benefits of urban trees and the possibilities to realise these benefits through all four stages of an integrative approach: planning, design, establishment and management (Nilsson *et al.*, 2012). It also relies on practitioners being able to appraise sufficiently the values of all urban trees.

By using an integrative concept, such as ecosystem services, the aims of urban forestry practice are more easily presented to the broader audiences usually involved in decision-making at policy level. In the past few decades, there has been a surge in application of various valuation models to appraise the value of ecosystem services, which has highlighted the importance of urban trees in the wider political discussion. This is due in no small part to the work of the United States Department of Agriculture (USDA) Forest Service, which developed the i-Tree program, the most commonly used set of tools for assessing ecosystem services provided by urban trees in the world today (USDA, 2019).

Generally speaking, urban areas present difficulties for establishment and growth of trees, due to the large number of different stressors and disturbances they contain. Unlike their non-urban counterparts, urban forests are severely limited by the built environment as well as by social structures and organisations. Therefore it is necessary to employ integrated approaches, inclusive of the human component, when managing urban forest (Pickett & Grove, 2009). As most of humanity will spend its life in cities, securing long-term provision of ecosystem services that ensure the well-being of citizens should be a priority for urban communities globally.

3.2 Public management of trees

The urban environment involves a large number of stakeholders and the space required by trees to grow often faces demands from other uses of space. This has long been a strong characteristic of European cities, which have exerted strong control over land use in urban planning throughout history

(Miller *et al.*, 2015). In a European setting, urban forestry is often referred to as urban green space management (Fongar *et al.*, 2019; Randrup *et al.*, 2017) or urban open space management (Jansson & Randrup, 2020). 'Urban open spaces' is a collective term used for diverse types of land cover within urban areas, including green spaces. The term urban green spaces includes, but is not limited to: parks, woodlands, home gardens, lawns and allotment gardens (Haase *et al.*, 2020). In combination, green spaces represent most of the trees and other vegetation found within cities. Residents and users of these green spaces can enjoy a wide range of benefits (Gill *et al.*, 2007). The ecosystem services and associated benefits provided depend on a large number of aspects, such as the amount, size, distribution, internal composition and connectivity of the green spaces. Management processes have a large influence on those benefits, particularly concerning whether and how ecosystem services are provided (Jansson *et al.*, 2019).

The process of development of urban green spaces can be separated into two phases: a place-making phase and a place-keeping phase (Dempsey & Burton, 2012). Place-keeping involves long-term development, implementation of systemic policies and the task of operational maintenance of the spaces (Jansson & Randrup, 2020). The tasks described generally fall within the jurisdiction of local governments (Knuth *et al.*, 2008). In a long-term perspective, urban green spaces can be managed as a resource to fulfil United Nations Sustainable Development Goal 11: "Make cities and human settlements inclusive, safe, resilient and sustainable" (UN, 2015). This goal must entail securing continuity in providing ecosystem services for future generations, including services from privately-owned green spaces and trees.

In order to illustrate the socio-ecological dynamics surrounding management of green spaces with special emphasis on residential urban trees, the Park-User-Organization (PUO) model can be used (see Figure 2) (Randrup & Persson, 2009). The model has three major components or dimensions: "users", "organization" and "parks" with public green spaces (including trees) in a central position. Formal decision-making regarding the management is done within the organization by politicians, administrative staff and operational staff. Users receive ecosystem services provided by the green spaces / trees. The management organization has a continued dialogue with the users, e.g. via the electoral system, or via more or less formal and integrated governance arrangements engaging users in decision making, planning, management or even in operational arrangements (Jansson & Randrup, 2020).

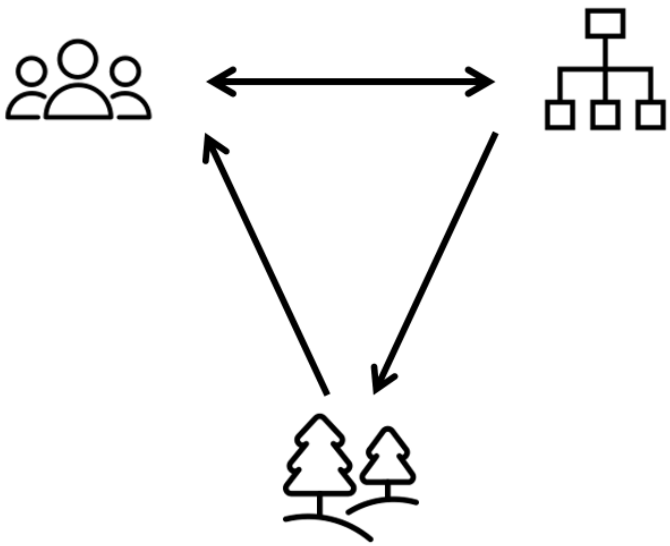

Figure 2: The park-user-organisation (PUO) model. The top left icon represents users (beneficiaries), the top right icon represents the organisation (responsible for planning and management) and the bottom icon signifies parks or trees. Source: Randrup & Persson (2009).

In the context of this thesis, parks are replaced by trees in residential areas and the role of the organisation tasked with the responsibility for making and keeping of green spaces in the PUO model (Dempsey & Smith, 2014) is conducted instead by individual property owners. This follows the rationale whereby in residential landscapes, overall management decisions are made by individual property owners instead of the local park organisation (Cook *et al.*, 2011), resulting in an adjusted model to better represent the object of study. Replacing the organisation with individual property owners and diminishing role of the local park organisation reflected the relationship to the particular green spaces under study. The role of the local park organisation is then reduced to indirect measures, as private property rights take precedent over local government actions. However, there is still sufficient reason to believe that users (or beneficiaries) of the ecosystem services provided by privately-owned trees may be others than individual property owners, since the beneficial effects of ecosystem services are not limited by property boundaries. Through their management actions, individual property owners have the ability to collectively supply the ecosystem services provided by their trees for the benefit of users on city scale. The primary beneficiary, with the closest relationship to residential trees, will always be the individual property owner, but the wider public are secondary beneficiaries of externalities resulting from production of ecosystem services by residential trees.

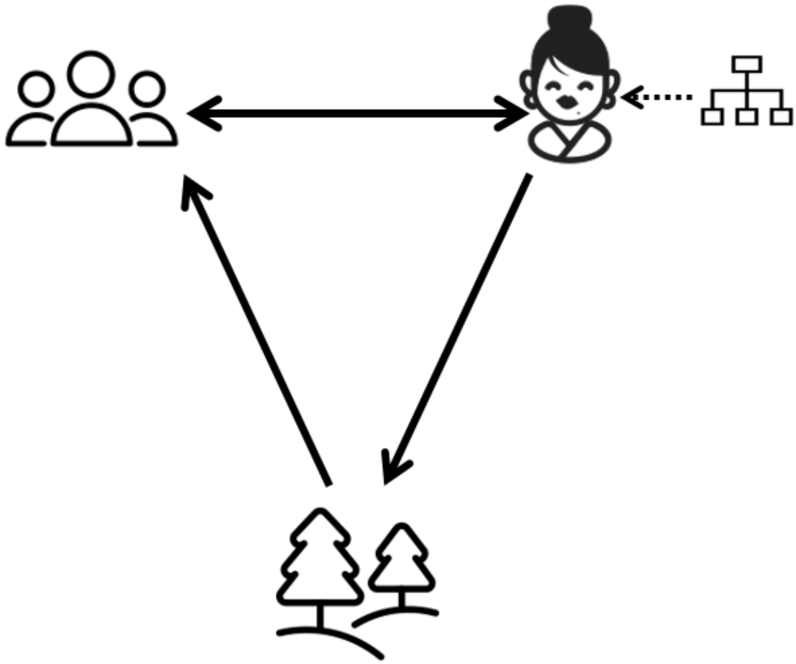

Figure 3: *Adjusted park-user-organisation (PUO) model in which individual property owners take on the role of managing green spaces. Source: adapted version of the PUO model developed by Randrup & Persson (2009)*

The connections and discourses among actors in the social sphere affect the management and consequently the ecological output of the urban forest ecosystem. From the perspective of a local government organisation, working toward sustainable management of urban trees at city scale poses a challenge in terms of including the residential trees in the city (Figure 4). In the strategic organisational effort, the discourse revolves around ecosystem services, sustainable development goals, mitigation of urbanisation and climate change. The dilemma arises when the discourse seen from an individual residential ownership perspective is insular, separated from the city-scale discourse and not recognisant of externalities produced by residential trees and their importance. Individual property owners are seen both as users (beneficiaries) of urban trees in general and as partners in co-creation (making and keeping) of the entire urban forest, by actively contributing to a holistic approach to urban forestry management.

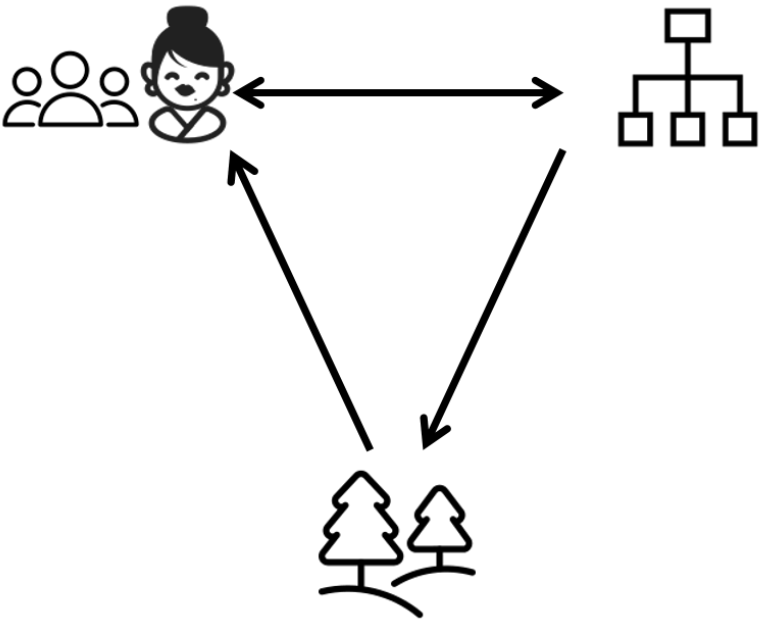

Figure 4: *Adjusted park-user-organisation (PUO) model in which individual property owners are seen from perspective of the local park organisation. Source: adapted version of the PUO model developed by Randrup & Persson (2009).*

The individual configuration of environmental parameters (soil, water, microclimate, vegetation, fauna) varies significantly between different urban areas and within areas, following the urban matrix theory of urban planning and design (Wellmann *et al.*, 2020b). Thus each residential tree owner has a different capacity for decision-making in shaping the outdoor space. This means that the different configurations of environmental parameters are a major factor in explaining the variation in tree abundance between properties and implies that the variation in urban matrix components across residential areas results in formation of distinct hybrids with unique biophysical conditions (Pauleit & Breuste, 2011).

The management decisions and related actions and behaviour of residential tree owners can be related to multi-scalar human drivers, legacy effects and individual values and human cognition (see Figure 1). Thus, in a residential ownership perspective, various aspects of the PUO relationships (see Figure 2) are different from those in a public management perspective. The local government influence is reduced to indirect measures through policy and regulations (Conway & Bang, 2014), but such measures are rarely adopted in Sweden. This means that, due to lack of oversight of privately owned-trees in urban tree inventories (Östberg *et al.*, 2018; Wiström *et al.*, 2016), combined with lack of regulations on tree removal, the role of the public organisation is effectively reduced to that of observer.

Inclusion of private trees in management of the complete extent of the urban forest has frequently been identified as crucial for sustainable management practice (Bell *et al.*, 2005). The first step in facilitating this process is to assess the resource accurately and frequently, bearing in mind both social and ecological aspects and recognising the importance of the discourses between actors. In the next step, critical reflection on the existing governance arrangement could provide valuable insights in efforts to integrate residential trees into overall urban forestry management. Such reflections would be greatly assisted by information from assessments that describe the variety of existing conditions resulting from a multitude of factors (cf. Figure 1).

3.3 Urban forestry and governance

Governance in urban forestry is a developing concept, coinciding with calls for developing new sustainable practices in management of urban green spaces. New governance processes go hand-in-hand with higher democratisation and equal access to environmental benefits for people. Urban forest management focused previously on benefits, technical aspects and maintenance aspects, with governance being very rarely discussed (Lawrence *et al.*, 2013). Increased public interest and increased demand for urban forests have transformed the role of public managers from primarily providing ecological expertise into a cross-disciplinary, socio-ecological role (Randrup & Jansson, 2020; Miller *et al.*, 2015).

Governance is a concept originating from social and political science and has been defined as: "efforts to direct human action towards common goals including private and public actors through setting of common rules that are subsequently applied and enforced" (Konijnendijk van den Bosch, 2014, p. 35). Governance strives towards being non-hierarchical and less formal than conventional ways of enforcing policies through government actions by shifting the decision-making process towards inclusion of a wider variety of stakeholders from multiple decision centres and perspectives, assuming that no single entity holds all the knowledge and answers to solve collective issues (Sehested, 2004). It should not be seen as a replacement of government, but rather as a recognition of a mixture of organisations of various scales and types, operating at the multiple organisational levels required to ensure sustainable resource use in a modern societal context (Jansson *et al.*, 2020). The developments in urban forestry governance have been closely related to the changes in public demand for quality in the urban environment, creating a need for new governance models adapted to various co-development processes (Jansson *et al.*, 2019). Governance approaches can be applied on different scales, ranging from local to national, and may include tactical, operational and strategic levels (Randrup & Persson, 2009). Due to various institutional challenges, residential trees are not included in urban forestry practice to the same degree as e.g. street and park trees. Critical governance analysis can provide important insights into the dynamic relationships between actors in the socio-political structure (Arts *et al.*, 2006). In this thesis, the relationship between local government and individual property owners is described using this approach.

The intention with the work described in this thesis is to obtain more information about residential tree management, with the purpose of finding a suitable governance arrangement necessary for providing better assessments over privately-owned trees. As Figure 5 shows, urban open space exists on a scale from private to public and this scale determines the actors, resources, discourses and rules of the game of the governance structure (Arnouts *et al.*, 2012).

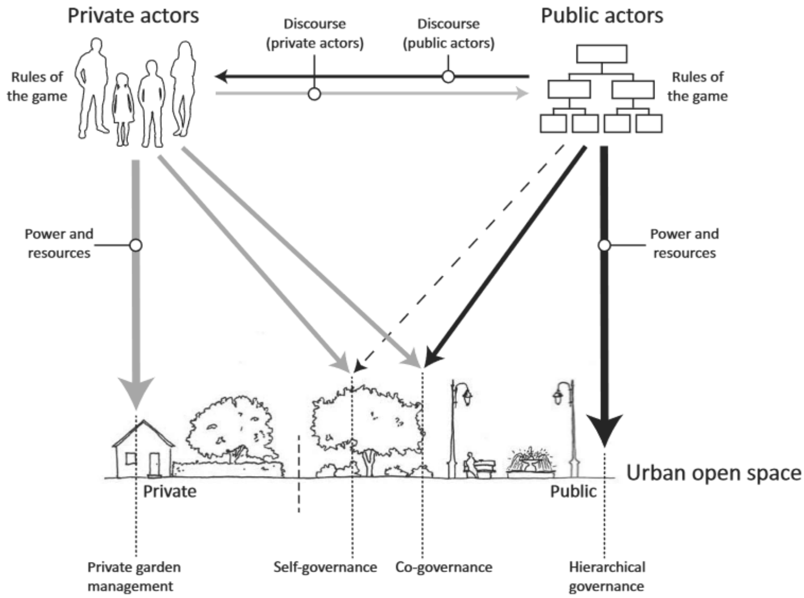

Figure 5: *Model for governance and management of urban open space. Source: Jansson et al. (2019).*

The extent to which local government can impact management decisions in residential areas depends on soft measures (dissemination, community programmes, increasing engagement) and hard measures (laws, bylaws, protective regulations). In some cities, the local government has introduced rules and regulations attempting to direct the behaviour of individuals, using policies and ordinances (Conway & Lue, 2018), but the reception and results of these actions have been varied (Roman *et al.*, 2015; Landry & Pu, 2010). The jurisdiction and enforcement issues surrounding measures that involve restricting behaviour on private property are exceptionally contentious in any context, but especially in the context of democratisation of governance in urban forestry. The crucial challenge lies in finding the right balance between acknowledging the autonomy of individuals and strengthening the social and ecological connectivity between private and public. In the subject area considered in this thesis, the efforts of local managers encounter the obstacle of having to create new policies to enable creation of a well-defined framework of measures related to management of trees on private property. Drafting such policies would require novel, collaborative governance approaches (such as mosaic governance) to achieve the desired ecological effects while engaging politicians, practitioners and individual property owners (Buijs *et al.*, 2016).

From the perspective of a private property owner ('private actors' in Figure 5), the private garden (or the outdoor space) can be seen as a reflection of personal values, beliefs, norms and cognition limited by the property structure, relative wealth and boundaries (Cook *et al.*, 2011). The private garden is a canvas, a nearly unregulated resource (exceptions being exceptionally large trees of important ecological value or biotope protection of tree rows), comprising realised environmental choices with the possibility to cater to personal needs and preferences. This is done with varying amounts of adherence to local social norms and traditions. Overall, residents have autonomous control of their private property, with limited engagement of public actors.

The discourse of public actors (Figure 5) revolves around addressing demands from users as regards public spaces, with private actors (or users) expressing demands through appropriate channels. In elevating urban forestry management from reactionary management to strategic thinking, there is a growing sense of the importance of incorporating all urban trees in providing ecosystem services. This lacks the decision-support systems that are essential for implementation of policy. With respect to private property rights, field assessments of privately-owned vegetation are subject to participation consent and require abundant resources. Access to quality information to evaluate the current status and potential future policy implications is required to harness the political will for implementing new urban forestry practices. The varying discourses between public and private actors is where tree assessments may inform the stakeholders involved regarding not only the status of the resource, but also the incentives for planning and management of the resource. Based on that, appropriate action can be taken to formulate new policies and regulations for desired ecological outcomes.

Comparative studies of urban forest governance arrangements show some major differences in approaches. An analytical framework has been developed in order to increase comparability and identify key concepts (Lawrence *et al.*, 2013). In Table 1, this approach is used in describing the current governance arrangement for public and residential trees.

Table 1: Urban forest governance analysis using an existing analytical framework, seen from Swedish perspective (Lawrence *et al.*, 2013; Arnouts *et al.*, 2012; Jansson *et al.* 2020). Table continues on two pages.

Properties		
Case	**Residential trees in Sweden**	**Public street and park trees**
Type	Urban area within the municipality	Urban area within the municipality
Scale	Private residential property within the urban area, micro-scale with each unit acting independently to at some degree	Meta-scale, with mandate to provide sustainable long-term management
Context	Trees located within private residential property boundaries, with highly fragmented ownership	Trees located on public property, most commonly alongside streets and in parks or other green areas
Rules of the game		
Policies	Sweden's Environment Act	Sweden's Environment Act, municipal comprehensive plan
Planning and regulations	Local detailed planning by the municipality and regionally by the Environmental Protection Agency (Naturvårdsverket)	Detailed development plan
Ownership	Private	Public
Access and use rights	Mostly private property, areas of multi-household dwellings can be accessed and used under right of public access	Public right of access
Actors		
Primary stakeholders	Residents	Local park authority
Other stakeholders	Local government at municipal and regional level, other beneficiaries of the	Users in form of park visitors who can express their preferences

	externalities provided by residential trees	through participation in surveys, correspondence or similar
Power relations	Local government is limited to use of planning regulations to influence resident decisions indirectly. In rare examples, trees are protected through regional agency regulations	
Resources		
Funding	Private	Government-funded
Knowledge and information	Varying degrees of knowledge among residents, local government has knowledge on historical, cultural, social and ecological aspects of the area	High degree of specialisation and training, access to information on the environment, capacity for monitoring and strategic planning
Delivery mechanisms	Residents act independently within the property plot	Through stages of the management model (planning, design, construction and maintenance), there is a continuous, iterative loop for provision of resources
Discourses	Residents see gardening of their property as a pastime, place importance on several aspects of tree benefits	Local government is focused on *e.g.* climate adaptation, long-term provision of ecosystem services.
Participation, engagement, conflict management	Very limited communication between actors, participatory initiatives between local governments and residents are non-existent	
Monitoring and evaluation	Not included in monitoring schemes	Regular monitoring, central database

The governance arrangement provides the context for assessments, meaning that relationships between actors and resources should be reflected in these assessments, especially where multidisciplinary approaches are favoured, to describe the full extent of the topic (Cook *et al.*, 2011). Gathering the same type of information (or in a similar manner) on residential trees as on public trees will not equip practitioners with greater capability to make management decisions with positive ecological outcomes regarding residential trees. More detail in describing drivers of ecological change can only be obtained by adapting assessment methodologies to the underlying governance arrangement and establishing clear governance frameworks (Ordóñez *et al.*, 2019). The future challenge lies in establishing long-term monitoring routines using the actual governance context, as different aspects of assessments change at a different pace and scale. The ability to provide continuous, comparable data is in this sense also dependent on changes in governance arrangements.

3.4 Urban forestry and remote sensing

Respect for the individual autonomy of individuals is an important factor to consider in forming lasting public-private initiatives (Buijs *et al.*, 2016). For public authorities to gain an overview of all residential urban trees, physical access to the property is often required in order to conduct standardised measurements (Östberg *et al.*, 2013). However, field visits for assessments on residential trees can be seen as an invasion of privacy and can jeopardise the relationship between public and private actors, and thus between actors in set collaborative governance arrangements. To conduct such assessments non-invasively, remote sensing technology has emerged as a suitable replacement to field observations (Wellmann *et al.*, 2020a). Access to publicly available, highly detailed data offers the possibility for local government bodies to create a complete overview of the entire urban forest resource within a city and do so relatively cheaply, as the processing capability will only improve over time (Alonzo *et al.*, 2016).

Remote sensing has emerged as the leading observational and analytical tool to assess and manage forests for human well-being (Singh *et al.*, 2018). The scientific discipline of remote sensing involves capture and interpretation of electromagnetic radiation that is reflected or emitted from the observed target and recorded from a distance, as opposed to being in contact with the observed object, thus allowing local governments to assess residential trees without requiring access to private property. The observations of the Earth's surface are recorded by airborne or satellite-borne instruments, in the form of reflectance values from land, ocean and ice surfaces in different light spectra (Mather & Magaly, 2011). With computer processing of the information, it is possible to classify and label properties of the Earth's surface using statistical methods and display them in the form of maps. This offers great potential to deepen knowledge on urban vegetation, with an understanding of ecosystem services and the different categories of these services. The increasing availability of remotely sensed imagery, combined with increased capacity in computer processing, has thus opened up new possibilities to capture, extract, interpret, analyse and visualise information about the physical surface of urban environments. Different types of remote sensing data have characteristics that make them more or less suitable to measure particular attributes of urban forests.

One of the most important (and most commonly used) indices for urban forestry planning is tree canopy cover. Tree canopy cover has been associated with several regulatory ecosystem services, such as temperature regulation (Adams & Smith, 2014), air pollution removal (Jim & Chen, 2008) and runoff mitigation (Giacomoni *et al.*, 2014). Thus monitoring canopy cover development over time is paramount in identifying effects of land conversion on sustainable provision of ecosystem services (Nowak & Greenfield, 2012; Alberti, 2010).

Digital aerial photographs yield good results when estimating the extent of tree canopy with consideration of seasonal changes in interpreting images due to deciduous vegetation. Moreover, sensors can detect light reflectance in multiple spectra, some invisible to the human eye (infra-red and ultra-violet), that are related to vegetative autotrophic activity. Where digital aerial photography provides a spectral form of remote sensing data, LiDAR (light detection and ranging) remote sensing technology provides structural data in the form of three-dimensional (3D) cloud points of distance of observed surfaces from the Earth's surface using light pulses. These light pulses generate 3D information about the Earth's surface and target object, making it possible to create high-quality digital surface models for use in spatial data analysis.

With the help of spectral aerial photography, it is possible to detect photosynthetic activity in plants, as the reflectance values in near-infrared light are higher for surfaces covered with plants. The data can then be used to create maps based on vegetation indices. Normalised Difference Vegetation Index (NDVI) is used commonly to produce maps showing vigorous vegetation over a specified urban area (Wellmann *et al.*, 2020a). It is based on the difference between near-infrared (Sadeh *et al.*) and red (R) spectral bands, calculated using the following formula:

$$NDVI = \frac{NIR - R}{NIR + R}$$

NDVI is used to gain a bird’s-eye perspective on the full extent of urban green spaces, with the focus on vegetation, and potentially to assess the vitality of vegetation. Comparisons of images from the same area using NVDI are facilitated by the fact that the index is less likely to be affected by variations in atmospheric conditions, making NDVI-based assessments very suitable for long-term monitoring of urban tree canopy.

Remote sensing has grea t potential in urban forestry since it can provide a multitude of datasets for a wide array of issues facing urban forests today, regarding the structure, processes and functions of urban vegetation. It can delineate vegetation into forest types, measure characteristics that would be time-consuming to assess in the field and provide new types of information (Singh *et al.*, 2018). In areas where ecological measurements are limited due to private property rights, remote sensing can be considered a convenient and cost-effective alternative. The broad catalogue of high-resolution temporal datasets makes monitoring possible at local or higher scale. In summary, remote sensing provides a vast source of quantitative information for decision-making activities and the technology is becoming increasingly available.

4. Method

The methods employed in this thesis work included various theoretical inputs from practices such as urban forestry and green space management; social science theories related to governance; and natural science approaches such as remote sensing. This wealth of methodological variation was the basis for all the studies described in Papers I-III and is supported by different empirical evidence collected in those studies.

To understand the multifaceted nature of residential urban forests, they were described in this thesis using results from multidisciplinary approaches (Creswell & Plano Clark, 2007). Residential trees and their surrounding dynamics were therefore studied in a nexus of social and natural phenomena, where combining quantitative and qualitative methods in a mixed-method approach was applied to yield useful insights.

The initial analysis of context-independent theory and concept building (Paper I) allowed a gradual transition towards phenomenological, context-dependent studies in the city of Malmö, or rather private residential trees of Malmö, as the object of focus in Papers II and III. The rationale behind this transition was twofold: to position the analysis in closer proximity to the object of study (in order to test assumptions based on available knowledge) and to overcome the difficulty in producing context-independent theory in social science (Flyvbjerg, 2016).

Four different studies (1-4) were performed, as illustrated in Figure 6, covering the study object (residential urban forest) within the broader concept of urban forestry.

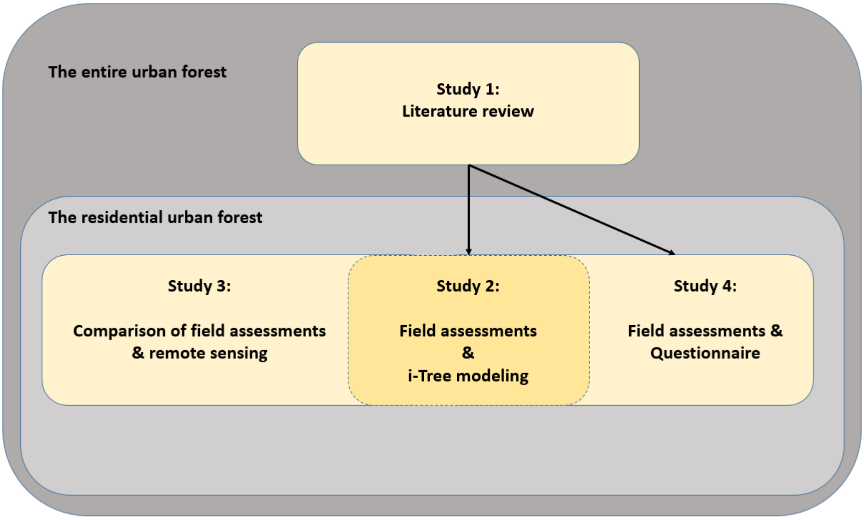

Figure 6: *A multidisciplinary approach was applied in the four studies described in this thesis. The arrows emanating from Study 1 indicate the methodological/theoretical insights gained, which were instrumental in designing studies 2 and 4*.

A literature review of scientific papers on inventories of urban trees was conducted in the first step of the work (Study 1). The research question was formulated based on observed regularities in long-term monitoring of urban trees in a manner consistent with deductive reasoning, while applying a relevant framework for post-hoc analysis of results. In this manner a generalisation was made, as opposed to disproving a hypothesis (Kuhn, 1996).

Study 2 involved collecting quantitative information using field measurements following spatial balanced sampling design (Kermorvant *et al.*, 2019) of urban trees to make estimates for the entire population based on the sample drawn. The representative selection was modelled using allometric equations in i-Tree Eco (Nowak *et al.*, 2006; Nowak & Crane, 2002), providing a detailed description of ecosystem services. These baseline data were utilised in subsequent studies.

In Study 3, a new methodological approach was introduced to the study area by using publicly available remote sensing data to monitor urban tree canopy cover in private residential areas. Following the hypothetico-deductive method, a hypothesis with a testable consequence was formulated (Bunge, 1960). The hypothesis was tested based on the potential correlation between digital remote sensing values and values from field (ground) observations in areas that are not publicly accessible. A null hypothesis was rejected using linear regression between variables, principles consistent of deductive reasoning.

Finally, Study 4 involved statistical analysis of empirical tree data collected using field sampling plots and qualitative analysis (Kvale, 1996) of responses from homeowners in a survey using a structured interview guide in form of a questionnaire. The sampling design and interview guide were formulated through principles of deductive reasoning, based on informed iterative processes from previous steps in the work. The null hypothesis was tested using statistical probability and statistical modelling of probable future scenarios (Yamashita *et al.*, 2007).

4.1 Study site

While the literature review (Paper I/Study 1) was not limited to a specific location, the subsequent stages of research (studies 2-4) were conducted in the city of Malmö, Sweden. Malmö is currently the third largest city in Sweden, with 338 230 inhabitants (Statistics Sweden, 2020), and annual population growth of 1.8%. It is located in the temperate vegetation zone, on the southern Swedish agricultural plains, a region with overall fertile soils and mean precipitation of 600 mm/year (SMHI, 2021). Due to high soil production capacity, the area surrounding the city is deforested, with very few surviving forest remnants and smaller remaining forest patches compared to other cities in the region (Nielsen *et al.*, 2016). With conditions unfavourable for natural regeneration of trees, humans can be considered the main agent in regeneration of trees. Malmö's local government is invested in preserving and managing the trees in the public domain, as evidenced by the large number of well-maintained urban green spaces and several extensive public tree inventories. The local government has a full inventory of around 65 000 street and park trees, with a long list of parameters, and this is updated regularly by field crews recording changes and growth (Sjöman *et al.*, 2012). This is accompanied by active efforts to ensure inclusion of trees in the comprehensive city-wide strategies to mitigate negative environmental effects of climate change and urbanisation, so it is safe to say that Malmö is a good example of urban forestry management practice in the region (Randrup *et al.*, 2017).

Private residential areas of Malmö represent around one-quarter of the total city area (Statistics Sweden, 2015). The extent, distribution and characteristics are a result of socio-economic development through history. The city went through periods of rapid population growth in the industrial age, coinciding with increased demand for labour in factories. During the 19th century, the city became heavily industrialised, with shipbuilding, cement and textile industries in the forefront. With expansion of the population came expansion of the city area, often by annexing outlying smaller settlements and integrating them as city quarters in the urban fabric (Malmö stad, 2021).

As living conditions worsened and economic hardship caused migration waves across the Atlantic throughout the 19th and early 20th century, local and national political movements demanded improvements in living conditions for workers. This led to the establishment of housing loan grants (egnahemslånefond) by the government, providing affordable loans for citizens to purchase property plots in order to build homes to certain specifications. The plots were also intended for small-scale farming, providing basic household sustenance. This policy led to an expansion of residential areas around Malmö and an increase in living space (Malmö stad, 2021).

Decades later, following another rise in demand for housing, a comprehensive housing reform, “Miljonprogrammet” or the million homes programme, was launched in 1965 to provide sufficient living space with improved housing standards. The programme concluded with over 1 million housing units built nationally throughout Sweden. Around 23 000 people in Malmö currently reside in these apartment units, which comprise one-third high-rise multiple household dwellings, one-third low-rise multiple-household dwellings and one-third small housing units (Tykesson, 2001).

These developments have resulted in a diverse structure of residential areas in Malmö, with similarities to other urban developments across Sweden and in neighbouring Nordic countries.

4.2 A review of the literature (Study 1)

As inventories are the basis for informed management (Morgenroth & Östberg, 2017), they can potentially play an important role in the private-public discourse by operating as a communication platform, informing the organisation of the resource characteristics and assisting in identifying management goals. A broad structured search (Yin, 2015) of the literature was performed, in order to obtain a comprehensive overview of scientific articles published on urban forest inventories, for a contemporary perspective in urban forest management.

The search string is explained in detail in Paper 1 and included elements such as location (cities and urban), resource (trees and forests) and approach (sampling, plots, monitoring, inventory). The papers retrieved were categorised depending on the type of ecosystem service assessed (economic, cultural/historical, environmental, and social). A total of 420 articles were reviewed and sorted over two screening processes after consolidation, reducing the number of relevant papers to 82. This sample was categorised based on governance aspects of research initiatives, stakeholder inclusion in discourses and operational scale of the survey. The detailed methodological approach is explained in detail in Paper 1. This literature review provided an overview of urban forest assessment design approaches that were used to inform the next stages of the work.

4.3 Urban tree assessment

Any assessment attempted should be spatially and temporally explicit, so as to acknowledge that ecological function and perceived values are context-, space- and time-dependent (Kumar, 2010). Tree assessment through field measurements is one of the most fundamental disciplines in forest management, dating back to before the emergence of urban forestry as a profession of its own (Jorgensen, 1986). The parameters recorded in particular assessments cater to specific management needs.

Information on the location, structure, condition and physical aspects of trees (*e.g*. trunk diameter, height, crown volume) can be used to estimate regulatory ecosystem service provision (Morgenroth & Östberg, 2017). This is done using allometric equations for leaf biomass in trees, since ecosystem services are provided through photosynthetic activity (Nowak *et al.*, 2013) or deposition of particles on plant canopy surfaces (Nowak *et al.*, 2006). With advances in remote sensing technology and image processing speeds, vegetation indices can be visualised and quantified using computer processing (Mather & Magaly, 2011).

In this thesis, two approaches were used to record tree measurements in order to estimate the ability of trees to produce ecosystem services: i) an on-ground field survey (Study 2), and ii) computer processing of publicly available remotely sensed imagery (Study 3). The results of the two approaches were compared to assess their suitability, advantages/disadvantages and potential management implications in Paper II, and results from the field study were also applied in analysis of interview responses of property owners in Paper III.

4.3.1 Field assessment and i-Tree modelling (Study 2)

Since a full accounting of every individual tree within large areas is in most circumstances not possible due to resource constraints, carefully designed spatial sampling is necessary to acquire representative qualitative data from a limited number of observations. In this thesis, a spatially balanced sample of points across private residential areas of Malmö was selected using software tools (ESRI, 2020). This was done using a simple grid overlaid across the area of interest, in this case the city of Malmö, Sweden, and limiting the number of samples to one per grid cell. Supported by the findings from the literature review, a random selection of points within each grid cell was used. Stratification of the area was avoided, in order to ensure long-term representativeness of the sampling points. Previous studies in urban tree assessments have shown that within a defined area, data from 200 sampling plots in the field will generate a 12% relative standard error in model estimates (Nowak *et al.*, 2015). In the present case, an initial 225 sampling points were selected to account for a non-perfect response rate (Paper III).

In Sweden, private residential property falls into two categories: small housing units (detached or semi-detached housing on an individual privately-owned plot) or multi-household dwellings (apartment buildings) that are operated as housing associations by residents. The point coordinates served as centre-points of sampling plots and were located using GPS device. The residents were notified by regular mail in advance in two waves of notifications, broadly describing the study. The same field crew conducted the assessment throughout the study.

A total of 201 circular plots were assessed during autumn 2018, including measuring any trees present within the designated radius of 5.64 m (100 m2) area. In addition to the circular plot inventory, a full inventory of residential yards was conducted when the plot was located within a small housing unit property boundary.

The tree parameters measured for trees within the sampling plot included: diameter at breast height (DBH), tree crown width, tree crown height, tree species and vitality. All woody species with a DBH above 5 cm were included. If the plant had multiple stems, up to 5 largest stems with DBH above 5 cm were recorded.

The goal was to use the individual tree measurements to determine tree leaf biomass with the i-Tree Eco model, as leaf biomass is the primary indicator of capacity for production of regulatory ecosystem services (Troxel *et al.*, 2013; Nowak *et al.*, 2006; Nowak *et al.*, 2001). i-Tree Eco, a software tool developed by the USDA Forest Service, is the most commonly used model world-wide for assessing structure, threats and benefits provided by urban trees and includes species-specific leaf biomass models. i-Tree Eco uses local weather and pollution databases combined with on-field data to provide locally relevant output of regulatory ecosystem services, and has the ambition to become the leading decision-making support tool in urban forestry (USDA Forest Service, 2019).

Property size and building footprint information was obtained from public records to calculate potential plantable space (PPS) (Statistics Sweden, 2017), using the difference between plot area and building footprint.

4.3.2 Comparison of field assessment and remote sensing (Study 3)

The viability of remote sensing-based assessment using publicly available datasets was tested with ground measurements, to see if computer-assisted interpretation of imagery has the potential to replace field measurements going forward (Paper II).

The crown volume measurements recorded in sampling plots in the previous step were processed with i-Tree Eco, which gave a spatially explicit leaf biomass volume for each tree and plot. With high-resolution ortophoto imagery widely available and the increased use of remote sensing by local governments in urban planning (Wellmann *et al.*, 2020a), ground validation of remotely detected values presents an opportunity to improve the accuracy of estimates. Values obtained from the field survey (Study 2) were compared against values derived by remote sensing using data sources commonly available in Sweden. The Normalised Difference Vegetation Index (NDVI), which indicates photosynthetic activity in land cover, was derived with GIS software, using infra-red and near infra-red spectral bands and with manual calibration of thresholds for optimum contrast between vegetation cover types. Remote multispectral imagery provided by Lantmäteriet dating from 2018 came in 0.25 m resolution including three bands (infrared, red, blue).

A LiDAR dataset dating from 2018 was used to create a digital surface model and a digital elevation model. The elevation difference between the two models contained all above-ground objects, including vegetation. By cross-referencing the aboveground objects to NDVI values from the previous step, a "vegetation window" was created, classified into low and high vegetation. The final result of this process was a comparison of remotely-sensed canopy cover area to the canopy cover area as measured within the plot in Study 2.

4.4 Field assessment and questionnaire survey (Study 4)

Ecological output of residential trees is related to traits of individual property owners, yet few studies have attempted to provide a multidisciplinary perspective on this phenomenon (Cook *et al*., 2011). Moreover, in the absence of regulatory measures, differences in attitudes to trees and tree benefits have been associated with decision-making on tree planting and removal (Conway, 2016; Kirkpatrick *et al*., 2012). In trying to predict these management actions, analysis using classification of attitude groups based on types of preferences and social values is often utilised in similar research (Ives & Kendal, 2014).

Study 4 examined the variation between residential homeowners with possible explanatory variables for planting and removal of trees as a power dynamic between actors and trees as a resource. To assess the importance of individual owner traits, tree assessment results were paired with 99 questionnaire responses by property owners that were recorded.

Owners were notified by mail and visits were individually scheduled upon agreement to participate in the survey. A mix of open-ended and multiple choice questions were formulated around personal preferences and actions concerning trees and vegetation belonging to their property, their responses were recorded using a touchpad at the time of field crew visit.

For tree abundance (which was the response variable in this case), the basal area was used as a proxy for provision of ecosystem services, and the relationships to basal area were tested using a linear regression method. The final model was then tested against a null model using a “Likelihood ratio test” and the assumptions of the model were verified by plotting the residuals from the model.

5. Results

In the following section, the results of the studies are presented in relation to the methodological approaches used to answer the three research questions relating to residential urban forests. The results are described in full in Papers I-III. The outcomes of the i-Tree assessment (Study 2) are presented in form of a table summarising i-Tree Eco v6 model outputs and commentary in this section. The deliverables of the corresponding studies are listed in Figure 7.

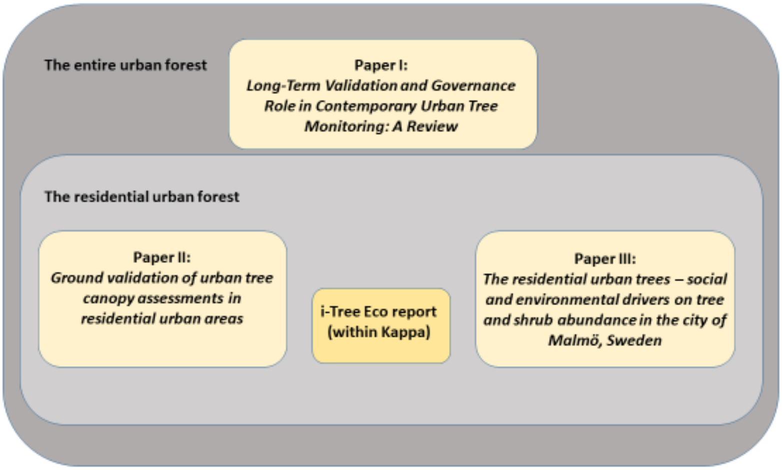

Figure 7: *Visualisation of the content of Papers I-III and themes, providing an overview of the residential tree assessment methodologies applied in this thesis. The literature review (Paper I) included perspectives relevant for creating an overview of the entire urban forest, seen from a management perspective, where Papers II and III focused on the residential part of the urban forest only. The output of i-Tree Eco v6 model are summarised in Table 2 below.*

5.1 Findings in the literature review

The findings from the literature review confirmed the initial assumption that inclusion of residential areas in urban forest inventories is rare. No article focusing exclusively on residential areas was found. Therefore, a set of guidelines was created to assist future research in choosing the most suitable sampling strategy for long-sighted public management approaches.

For public urban forest managers to include residential trees in future sampling, a long-term sampling strategy must be pursued in order to mitigate rapid environmental changes in urban settings. Based on the literature, stratification in sampling design was identified as being detrimental to this purpose, as the division of tree populations introduced additional sources of error over time. A robust design is necessary to provide representativeness of the sampling network for the purpose of repeated measurements and monitoring. Only through monitoring can assumptions on the prevailing dynamic be supported with qualitative data and serve as decision-support for sustainable urban forest management.

Since residents act almost independently in managing their property (Figure 3), inclusion of social parameters in tree inventories could help estimate the ecological output of residential trees. Tree abundance and survivability have been linked to several such social indicators. The literature review examined whether suitable inventory design can facilitate collection of important social factors relevant for management of residential urban forests (Paper I). The results of the literature review are summarised in the following subsections, using the policy arrangement model (Arts *et al.*, 2006) to evaluate key aspects of urban tree inventories.

5.1.1 Application of tree inventories

Tree inventories were found to revolve around capturing specific structures of individual trees that can be interpreted into a tangible ecosystem service using environmental modelling. Ecological aspects dominated the tree inventories, indicating legacy effects due to urban ecology being a relatively new concept (Costanza *et al.*, 1997). This could also be attributed to lack of methodological support capable of assessing economic, social and cultural benefits of urban trees. An academic initiative is currently driving research in the field, which is mostly limited to local, single snapshots of individual research goals.

5.1.2 Sampling design

Despite being a powerful tool for analysis, stratification was found to be less suitable for long-term monitoring, but was commonly used throughout the publications examined in Paper I. Over time it can introduce error in the initial sample. Individual criteria for stratification/strata selection were examined to grade the stratification factor long-term stability (Table 2). The factors were organized according to their type and likelihood of change, here denoted as stability.

Table 2: Types of stratification factors used in the literature and their long-term suitability in monitoring the urban forest (Paper I)

Type of Stratification	Stratification Factor	Stability
Climate	Thermal differences	Medium
Infrastructure	Age of housing	High
	Landscape type	High
	Vicinity to city centre	High
	Land use, land cover	Medium
	Traffic, traffic density	Low
	Pollution	Low
	Specific urban structure	Low
Management	Management units within a city (neighbourhood, homogeneous units within a city)	Medium
Social	Size of a community	Medium
	Index of human interference	Low
	Combination of socio-economic indicators	Low
Vegetation	Urban forest stand structure	Medium
	Vegetation properties	Medium
	Tree cover and other vegetation data	Medium
	Tree species composition	Medium

The infrastructure criteria were rated best in offering a long-term basis for monitoring. Management units are often used as delineators, indicating that inventories continue to have strong operational importance within urban forestry. However, given the relatively young history of urban forest management, these have been adapted and developed as knowledge about the tree population has increased over time. Social stratification seemed least suitable, due to rapid changes in indicators over time. Generally speaking, stratification factors were found to be location-specific, relying on local significance, making them difficult to compare on a larger scale and making it challenging to design a universally-acceptable stratification criteria for management purposes.

5.2 Residential Urban Forest Assessment

The residential urban tree assessments obtained with field measurements of tree parameters in Study 2 were used in Study 3 to compare field data sampling with remotely sensed imagery. In Study 4, the data were used to test hypotheses explaining variation in tree abundance at the individual property scale. Social indicators captured in the questionnaire in Study 4 were included in the analysis of field data assessment results.

5.2.1 Field assessment and i-Tree modelling

This section describes the results of field measurements from sampling plots and the output of the model used to estimate the amount of ecosystem services provided by trees in residential areas. The total number of sampling points was 201, which included both multi-household dwellings and small housing units. The measurements from circular plots in multi-household dwellings were combined with complete inventories of household yards.

Out of 137 small housing units selected in the sampling design, a total of 114 single households (83% success rate) were surveyed, where multi-household dwellings had 100% success rate in surveying of trees. In total, 965 trees were measured, with a mean of 8.05 trees per small housing unit property and mean tree diameter at breast height of 14.22 cm.

The results from the i-Tree Eco model (Table 3) showed the extent of the resource in terms that can be presented to all stakeholders in a simple manner. These results were also paired with the results of a recent i-Tree study conducted in Malmö, to compare differences and assess the relative importance of contributions (see the Discussion section for a detailed comparison).

Table 3: i-Tree Eco v6 model estimates for residential trees in Malmö.

	Malmö residential trees
Survey area	1922 ha
Estimated total number of trees	160 000
Estimated canopy cover	28%
Trees per hectare	83
Annual carbon sequestration (tons/year)	570
Annual avoided runoff (m^3/year)	61 145
Removal of pollutants (tons/year)	
O_3	4 278
NO_2	17 751
PM2.5	1 589
SO_2	647

5.2.2 Comparison of field assessment and remote sensing

Within the Malmö city area, private residential property is included in frequent high-resolution aerial ortophotography. This includes the infra-red light spectrum associated with vegetation activity. Locations of plots that were visited on the ground were recorded and visualised by concentric rings using computer software (Figure 8).

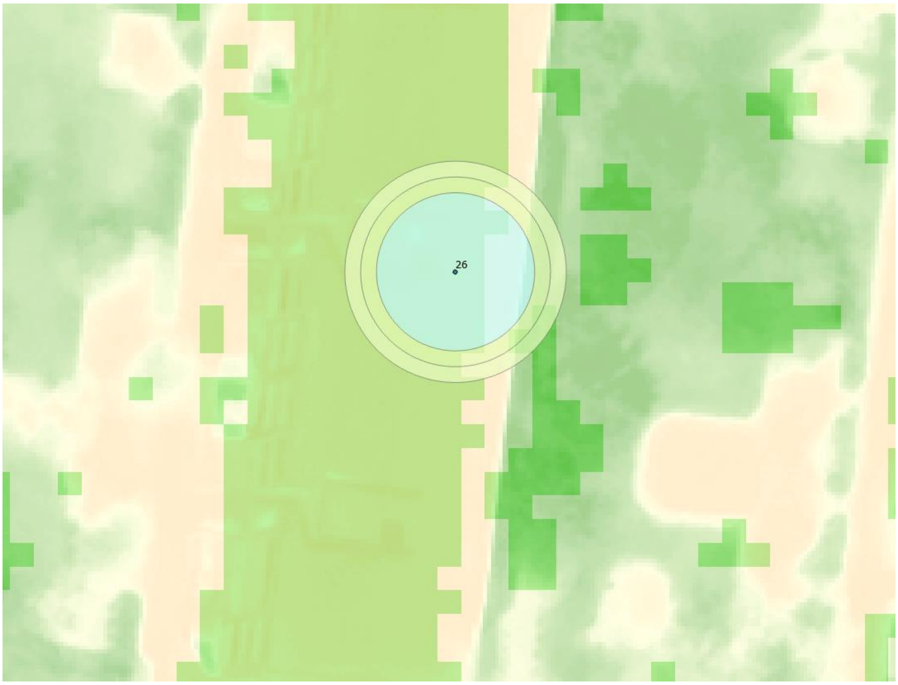

Figure 8: *Raster cells indicating presence of vegetation within plot area, which were counted to get an estimate of canopy cover area. The value was compared against values from same locations obtained using field measurements. Use of concentric plots for remote sensing was due to potential overlapping canopies*

The results of linear regression analysis indicated that aerial very high resolution (VHR) ortophotography, in combination with LiDAR, showed a high correlation to ground measurements in residential areas (Table 4). This relationship shows that, even in urban areas with high fragmentation and diversity, the proposed workflow in remote sensing can be a substitute for extensive field work. When type of vegetation (deciduous, coniferous, mixed) was also used in the explanatory mixed model, this added variable did not improve the significance in the relationship with canopy area or leaf biomass as a response.

Table 4: Results of linear regression analysis of canopy area estimated using remote sensing to ground measurements. Use of concentric plots for remote sensing was due to potential overlapping canopies. The asterisks denote level of significance (as represented by the P value) in the relationship between variables (* P ≤ 0.05, ** P ≤ 0.01)

	Coefficients		ANOVA table Type II test	
Variable	Estimate	StdError	t-value	Pr(>t)
Plot1	0.6541	0.2260	2.895	0.00579**
Plot + 1SD	0.4607	0.1775	2.596	0.0126*
Plot + 2SD	0.3187	0.1399	2.278	0.0274*

The results indicated a few instances of overlapping canopies in residential areas, since the total canopy area rarely exceeded plot area. The output for surveyed plots in terms of total canopy area showed an interesting pattern, with one outlier that strengthened the overall trend (Figure 9).

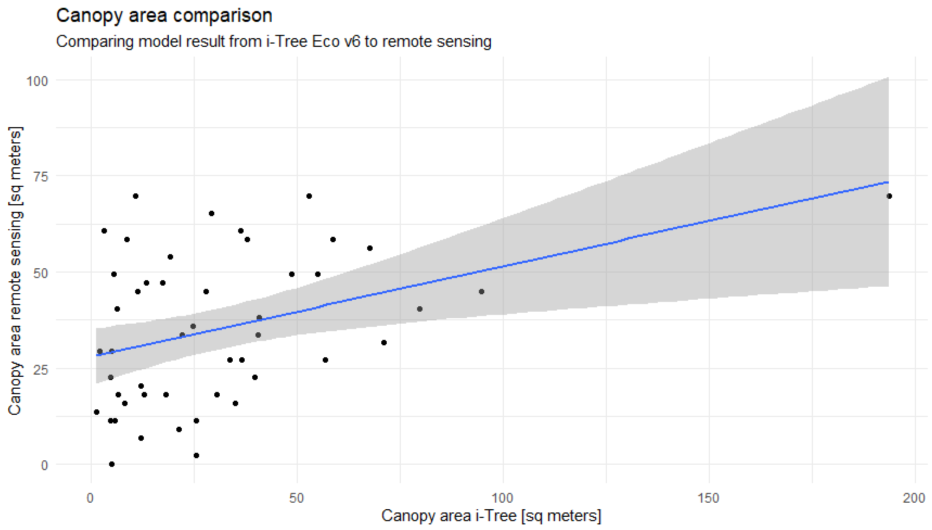

Figure 9: *Ground validation of remotely sensed values to remote sensing values. Each point shown in the diagram represents a surveyed plot on the ground with the corresponding remotely-sensed value*

5.2.3 Results from field assessment and questionnaire

Residents were grouped into four responder types, based on an answer to the open-ended question: What benefits do you associate with trees? The field crew was careful not to reveal any prior agenda or suggest any potential replies before this question was posed, and potential benefits of trees were not discussed before this point. If respondents could not list any benefits (or simply did not want to answer the question) the answer field was left blank. The four responder groups formulated based on the responses were:

- Utilitarian (respondents who mentioned utilitarian benefits provided by trees).
- Aesthetic (respondents who mentioned aesthetic benefits of trees).
- Mixed (respondents who mentioned utilitarian and aesthetic benefits of trees).
- None (respondents who gave no answer and possibly do not associate trees with any benefits).

Apart from this particular question, a total of 21 questions were listed, including general information (length of residence, gender, age, education level and house age), preferred outdoor space use, management actions regarding trees (future and past planting or removal), likelihood of adding other features to the outdoor space and interactions with the local community. The complete results and significant findings are published in Paper III.

Survey answers were recorded at the time of visit, with a 72.3% response rate. The results showed that the majority of residential property owners belonged to the Utilitarian group (43%) (Table 5). A further 23% were in the Mixed group and 34% in the None group. Only 3% of property owners fell into the Aesthetic group (Table 5).

Table 5: Respondent types based on perceived ecosystem services associated with trees, mean house age, and mean years of residence. Years of residence indicates how many years have passed since they purchased the property.

Respondent type	**(Response to the question: "What benefits do you associate with trees?")**	**Percentage of total respondents (n=99)**	**Mean house age (years)**	**Mean years of residence**
Aesthetic	Colour richness, lush appearance, blossoming, beautification, enjoyment, aesthetically appealing, decorative purpose, natural appearance.	3%	84.33	29
Utilitarian	Oxygen production, carbon storage, water uptake, pollinator species, shading, fruit production, animal habitat, compost production, pollution removal, counteracting climate change, clean air, noise dampening, sight concealment, weather protection, wind protection, sheltering.	43%	61	24.83
Mixed	Benefits from both the aesthetics and utilitarian categories.	20%	68.40	12.20
None	No benefits listed or questions left unanswered.	34%	64	17.03
	Total	**100%**	**64.35**	**19.78**

According to statistical analysis, the differences between the different groups did not explain the variation in tree abundance at individual property level, but even the “tree-positive attitude” did not result in greater tree abundance. On the other hand, house age and potential plantable space (PPS) proved to be a statistically significant predictor of tree abundance according to the mixed model regression. Figure 10 shows a visualisation of PPS in surveyed plots in relation to basal area and house age. A decrease in tree abundance at age 70-100 years could point to tree mortality due to maturity of trees in the plot, with 47% of respondents reporting that they had removed trees during the previous five years. No significant model or explanatory variable was found to be associated with tree removal. Including all respondents, 38% reported having planted a tree in the past five years and length of residence was negatively related to the likelihood of tree planting, as shown in Figure 11.

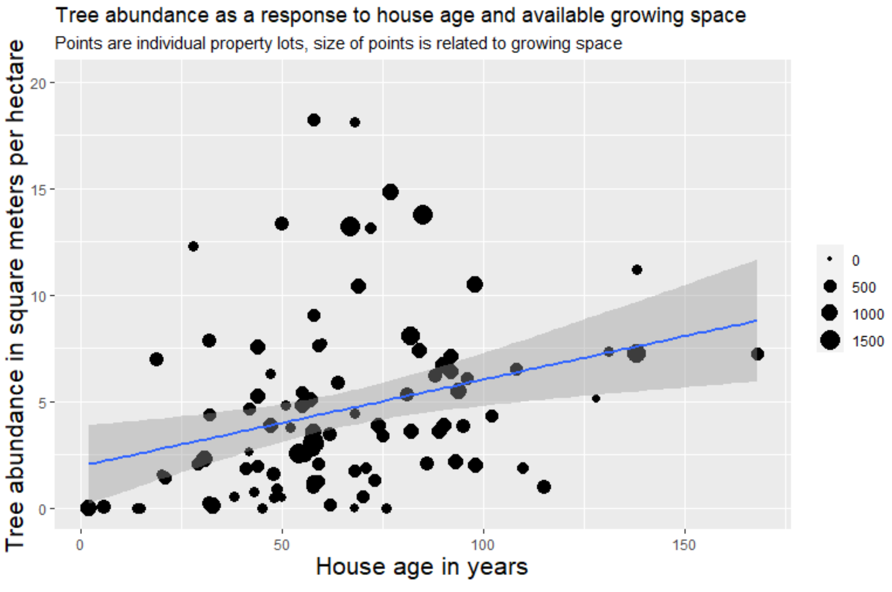

Figure 10: Basal area per hectare as an indicator of tree abundance on the individual property plot. Points represent individual households, size of the point corresponds to potential plantable space (PPS in m^2). Both house age and PPS were statistically correlated to basal area.

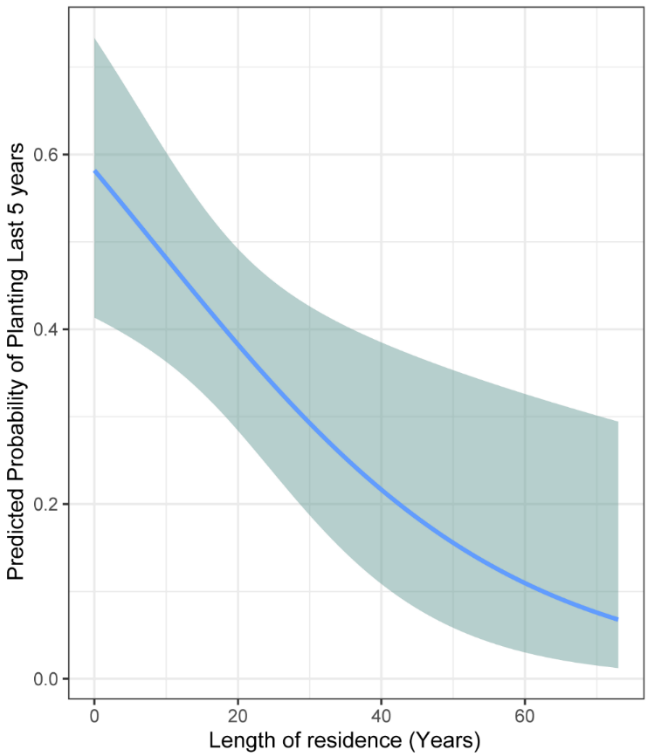

Figure 11: Predicted probability of tree planting by residential property owners in relation to years of residence. Negative relationship between the variables is indicated.

6. Discussion

On a global scale, cities are experiencing a loss of urban tree canopy cover (Nowak & Greenfield, 2020), leading to a bleak outlook for the quality of future life in cities. Trees in urban environments are essential for the well-being of urbanites, by mitigating negative impacts of climate change (Ferrini *et al.*, 2017; Nowak *et al.*, 2006). The contributions of residential urban trees are significant for urban areas (Wolff & Haase, 2019), but descriptions of this resource currently lack detail. Local government authorities in Sweden are left with the question of how to manage areas they do not own. This is exemplified in lack of knowledge on how to assess this resource and provide the contextual information necessary for decision-support. This thesis provided initial structural information about the extent of the residential urban forest for a city in Sweden and its relative contribution to providing ecosystem services across that city. It also provided new insights on relevant socio-ecological interactions within urban green spaces.

Studies 2-4 in this thesis work were spatially explicit, i.e. the city of Malmö was chosen as the study site. In urban forest governance analysis (Table 1) and description of the study site, the aim was to provide specific context on where the findings in this thesis can be generalised and applied in practice for the purpose of developing context-sensitive residential tree assessments. Several cities in the Nordic countries follow similar governance structures (Randrup & Persson, 2009) and thus the findings presented here could prove valuable for Nordic researchers and practitioners alike.

6.1 Contemporary urban tree inventories

Residential urban forest assessment approaches in the literature focus on either social aspects (Engebretson *et al.*, 2020; Conway & Lue, 2018; Conway, 2016; Ives & Kendal, 2014; Cook *et al.*, 2011) or ecological aspects (Lee *et al.*, 2017; Kabisch & Haase, 2013; Schmitt-Harsh *et al.*, 2013). A few previous studies have combined both disciplines in linking tree abundance to sociological factors while focusing on diversity (Avolio *et al.*, 2015) or vegetation cover (Boone *et al.*, 2009), providing relevant information for informing local urban forestry practice. The long-term provision of ecosystem services is dependent on accurate assessments of both social and ecological aspects, in order to link management practices to desired outcomes. Findings from the literature review confirmed the initial assumption that inclusion of private residential areas in urban forest inventories is uncommon, with no articles exclusively focusing on residential areas (Paper I). However, the literature search was limited to scientific publications in the English language, so Paper I was unable to confirm previous statements on the non-existence of such inventories.

In Paper I, the inventory design methodology applied in the papers reviewed was often found to be sub-optimal for long-term monitoring, due to common use of stratification. Studies were found to be socially and locally explicit, while the temporal aspect of the representative sample was not as frequently considered. Such methodological choices are not ideal for long-term monitoring, since stratification can introduce error over time if the boundaries of the strata change. The majority of the studies reviewed described short-term research projects, while monitoring of urban tree populations appeared to be less routinely described in scientific papers, perhaps due to the fact that local governments, not research institutions are usually responsible for monitoring of urban trees.

One of the issues encountered in selecting a search string was the apparent interchangeability in usage of the terms ‘inventory’ and ‘assessment’ within urban forestry. According to many authors of the publications reviewed, the term inventory refers to an incomplete list of items, contradicting the dictionary definition. The term ‘urban tree survey’ was also often ambiguously used, referring to a mail survey, questionnaire survey or field measurements. This can create confusion among urban forestry practitioners, so harmonisation of term usage in scientific literature would be beneficial.

The likelihood of finding additional relevant information on such inventories would have been improved if grey literature had been included in the review, but this would have made comparisons to scientific papers difficult as regards the governance analysis approach. Moreover, grey literature methodology often references scientific publications as the framework for design of inventories or instruction manuals of commonly-used practices. A broader methodological discussion on monitoring strategies and on the terminology used by the urban forestry community could assist with repeated measurements and replicability of many single-trial experiments.

6.2 Field assessments of residential trees in Malmö

Sweden is well on its way to adopting i-Tree as the go-to model for urban forestry planning at municipal and organisational level, with e.g. a recently concluded nation-wide i-Tree project (Deak Sjöman & Östberg, 2020). The i-Tree assessment based on plot measurements collected in this thesis provided novel insights and structural information on the residential urban forest in Malmö, and is the first such assessment in Sweden. The results showed the volume and capacity to mitigate negative environmental effects using ecosystem services provided by residential trees.

As the city of Malmö has conducted a similar assessment using i-Tree Eco model, comparisons of the results are merited, but it is important to consider differences between the two approaches beforehand, to better understand the contrasting results produced by i-Tree Eco. First, the population area for the municipal survey was bounded by the highway ring, whereas the study in this thesis used the so-called urban (tätort/agglomeration) boundary designated by Statistics Bureau of Sweden (Statistics Sweden, 2017). Both studies used circular sampling plots that were selected using a location of a random point within a grid, but the municipal study did not differentiate between different ownership types. Another important distinction was that municipal study did not record all woody species above DBH threshold, only tree species. This means that it ran a risk of underestimating the number of smaller-stature trees, which are very common in residential areas (Schmitt-Harsh *et al.*, 2013). Lastly, there were several different field crews involved in data collection with the municipal study, whereas the same crew was employed throughout the data collection process in the residential tree study, which could potentially influence the consistency of measurements.

Table 6: Comparison of the i-Tree Eco v6 model output estimates (the relative standard error of outputs is estimated at 12% by the model authors) for Malmö's residential urban forest, and for the entire urban forest in Malmö according to a report by Deak Sjöman & Östberg (2020)

	Malmö residential trees	**Relative contribution of residential trees**	**Malmö tree survey of the entire city (Deak Sjöman & Östberg, 2020)**
Survey area	1922 ha	22.6% of total area	8500 ha
Canopy cover	26-28%		18-22%
Sampling plots surveyed	201		300
Trees per hectare	83		22
Annual carbon sequestration (tons/year)	570	26%	2 198
Annual avoided runoff (m^3/year)	61 145	30%	204 493
Removal of pollutants (tons/year)			
O_3	4 278	35%	12 091
NO_2	17 751	32%	54 941
PM2.5	1 589	42%	3 790
SO_2	647	30%	2 112

Comparison of the i-Tree Eco results from the two studies (Table 6) showed that the relative contribution was proportionally greater than the relative area represented. Overall, residential areas had higher estimated canopy cover ratio (28%, compared with 18-21% for Malmö on average). The difference in tree density indicates, as previously stated, the difference in methodology in field measurements.

In relation to the perceived benefits listed by residents in Table 5, i-Tree Eco managed to quantify carbon storage, water uptake, pollution removal and air improvement, temperature regulation and oxygen production. It did not allow for assessments of habitat quality, fruit production, compost production, noise dampening, sight concealment, wind protection and sheltering. Thus, using i-Tree to quantify the total contribution of ecosystem services of residential trees was still inadequate. Combining biodiversity valuation methods with these types of assessments (Kumar, 2010) could perhaps provide additional context and significance in the future. However, the future in residential tree assessments lies with remote sensing (Alonzo *et al.*, 2016) and, more importantly, the capability of local governments to utilise smart technologies (Galle *et al.*, 2019) to gain a better understanding of how urban ecosystems operate in the age of digitalisation.

6.3 Remote sensing

As mentioned previously, remote sensing holds many strategic advantages for cost-effective and convenient assessment of the ecosystem services provided by residential trees. Most notably, it provides a non-invasive way to assess urban tree canopy based on publicly available high-resolution imagery-derived vegetation indices (Baines *et al.*, 2020; Gascon *et al.*, 2016). In addition, the availability of temporal data makes monitoring a clear possibility. The data for such image analysis are readily accessible for urban areas in Sweden and in many other countries, but such an approach is not necessarily relevant to places where no such data, or only lower-resolution data, are available. This introduces limitations in wider applicability of the findings in this thesis. Spectral imagery of urban areas is susceptible to many sources of error (seasonal differences in vegetation, shadowing due to vicinity of buildings) and has poor capability for species recognition or detecting vitality signs. Thus even with availability of high-quality data, complex interpretation techniques require extensive training for practitioners and impose limitations on smaller urban communities (Sang, 2020), which lack the resources required to create a comprehensive urban forest monitoring plan.

To summarise, residential urban trees represent a major source of ecosystem services at city scale. Therefore, local governments should try to find a suitable governance arrangement in order to optimise ecological outcomes and sustainable supply of ecosystem services. One such approach is described in mosaic governance: a step towards delivering environmental, social and institutional resilience by recognising the interdependencies that vary by type of green space relying on active citizenship (Buijs *et al.*, 2016).

Adopting a multi-disciplinary perspective at single-household scale would enable practitioners to get a new perspective in formulating policies with beneficial environmental outcomes. This includes reconsidering how they assess residential urban forest, in order to address the complexity of socio-ecological interactions described in this thesis and how best to harness the new knowledge for future management.

6.4 Residential trees as a socio-ecological phenomenon

Ordinances and policies are instruments used by local government to indirectly shape the ecology of residential landscapes by influencing individual management decisions by residents (Conway & Bang, 2014; Landry & Pu, 2010). This can be done e.g. by mandating tree replacement, setting favourable area-to-floor ratios or demanding individual protection of trees of great ecological importance. Such protective measures tend to protect tree removal based on exaggerated risks (Clark *et al.*, 2020; Kirkpatrick *et al.*, 2013). On the other hand, tree retention is associated with high cost of removal despite the presence of government regulations and by-laws, as e.g. local planning acts emphasise the value of trees (Guo *et al.*, 2019). In the absence of direct measures at the household scale; human values, cognition and property structure are key to shaping residential landscapes (Ko *et al.*, 2015; Kirkpatrick *et al.*, 2012).

Formulation of resident attitude groups was performed in this thesis using a simplified methodology, by categorising respondents depending on whether they prefer utilitarian or aesthetic aspects of tree benefits. Other studies have used more complex classifications based on e.g. residents' perceptions, values and behaviours, with information mainly obtained using mail surveys (Guo *et al.*, 2019; Almas & Conway, 2017; Conway & Bang, 2014; Kirkpatrick *et al.*, 2013; Kirkpatrick *et al.*, 2012). Such methodology is based on a much larger sample size, e.g. Conway (2016) obtained over 600 survey responses, and conducted over 40 interviews, while over 650 questionnaires were analysed by Kirkpatrick *et al.* (2012), which provides greater statistical power for drawing clearer divisions between attitude types. However, the crude simplification applied in this thesis still allowed for some interesting comparisons.

"Grass-root" collaborative neighbourhood initiatives for tree planting are commonplace in North America (Breger *et al.*, 2019; Roman *et al.*, 2014; Roman *et al.*, 2013), but such programmes lack the support of local governments in Sweden, passing the responsibility to individual residents. For the case of Malmö, this thesis showed that even socially favourable views of trees and tree benefits among residents do not necessarily entail better ecological outcomes in ecosystem service provision, making tree variation difficult to predict based on social factors. However, some research indicates that favourable views can mean better receptiveness to management activities (Ives & Kendal, 2014). The thesis also showed that, while the public in Malmö has been receptive to messaging on the environmental benefits of trees, there are other limitations that are more restrictive to supporting abundance of trees on individual privately-owned plots, most likely related to property constraints. Residents in Malmö were aware of the direct small-scale implications of maintaining trees (Table 5), but were perhaps unaware of the "bigger picture" in sustainable provision of ecosystem services at city scale. With increased awareness of externalities in ecosystem service appropriation, higher support for community-organised efforts could result in better citizen engagement or demand for action by local government. The same applies to hard preventative measures, e.g. introducing new legislation on tree removals, which would require coordinated efforts from local government park organisations, political will and support from residents. This thesis did not gauge the support for such measures, which has been done elsewhere (Clark *et al.*, 2020; Conway & Bang, 2014), but it would be reasonable to do so in future research.

In focusing on social aspects of urban forest assessment, this thesis revealed the importance of local governments capitalising on specific opportunities to include information on residential trees in their overall management. The results showed that residents are aware of beneficial effects of trees (Paper III), yet perhaps lack the knowledge to maintain trees and often opt to remove healthy trees based on improper site selection. Soft preventive measures by local government to prevent this problem could include reaching out and offering practical advice at key moments, e.g. at a change of property ownership as indicated in Paper III, in order to focus on better residential site/species selection when planting new trees and better protection of existing trees through including residential trees of high ecological importance in the existing inventory. This could ultimately lead to higher residential tree survivability, for optimisation of ecosystem service delivery across the entire urban forest.

Planting prediction modelling for the particular example studied in this thesis showed that assessments based only on tree measurements cannot predict the changes in population dynamics due to seemingly random tree removals over time. No significant predictors were found, but there were indications that the probability of tree planting decreased over time with age of residence (Figure 11). This suggests that a change in property ownership, differences in housing age or other built environment characteristics play a much greater role in urban tree population dynamics, confirming findings in other studies (Lee *et al.*, 2017; Conway, 2016; Lowry *et al.*, 2011; Landry & Pu, 2010; Larson *et al.*, 2010).

Despite the deterring factor of stratification in long-term monitoring, groupings based on house age and potential plantable space make sense in formulating single-event studies, as these are defining characteristics of the capacity for maintaining and planting trees. A well-designed monitoring system can provide both an overall perspective and detail on the dynamics of sub-groups formulated on criteria validated in Papers I and III in this thesis. As reported previously (Lowry *et al.*, 2011), residential development age could be used as a starting point in monitoring, since the residential landscape of Malmö has been subjected to many large-scale housing reforms over time.

Current modelling and monitoring of the ecosystem services provided by urban vegetation places much emphasis on woody vegetation exceeding a specified DBH size threshold (Morgenroth & Östberg, 2017; Nowak *et al.*, 2013). Much less emphasis is given to vegetation that does not, by arbitrary definition, pass as a tree. However, there is an abundance of shrubs and hedges present in residential landscapes that provide multiple benefits for residents in terms of sight concealment, coloration or scent, based on their survey responses. Despite the lack of normalised quantitative evaluation methods, non-regulatory (cultural, provisional, supporting) ecosystem services are still an important contributing factor to human well-being. This topic merits further consideration in future research aimed at developing tools that can quantify such contributions for management purposes.

7. Conclusions

Based on the findings in this thesis, residential urban forest should be seen as being inseparably linked to the individual socio-ecological unit in the urban landscape, i.e. individual property owners. In practice, this means that assessments of residential urban forests need to be formulated around this premise, addressing the social, natural and built environment characteristics. A multidisciplinary approach was used here to develop a blueprint for how such assessments should be designed, following trends in contemporary tree inventory methodology (Paper I), contemporary remote sensing capability and accessibility (Paper II) and contemporary governance approaches (Paper III).

The thesis enabled clear, context-independent recommendations regarding long-term monitoring of urban trees regarding validation of stratification factors. It also provided generalisable findings regarding socio-ecological processes at an individual level: the impact (or lack thereof) of resident attitudes to tree abundance, the importance of available planting space and temporal likelihood of planting new trees. Finally, it gives recommendation in using a remote sensing model, constructed from data sources freely available to urban communities in Sweden, to estimate and monitor canopy cover changes in residential areas.

Small-scale social environment characteristics are often an overlooked aspect in urban tree assessments and it is safe to assume that this leads to formulation of suboptimal assumptions in efforts to achieve sustainable management of the urban forest as a cohesive unit. Residential urban forest assessment is not only a tool for gathering relevant information, but also a facilitator for new governance approaches based on co-creation of urban open spaces through active citizenship and improved tree stewardship. Cities are increasingly adopting new technologies and integrative approaches aimed at improving the urban environment, so the findings in this thesis could lead to better-quality models for locating or predicting spatial-temporal events that are responsible for declines in the urban tree population. The findings described in this thesis can assist practitioners in developing their own optimal assessment routines and lead to better management outcomes of urban trees.

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Popular science summary

Urban trees provide many environmental benefits for the people living in cities. Many of urban trees are located on private property in private residential areas, but they are rarely included in urban forest inventories and management plans. For most cities, the contributions of residential trees are unknown.

This thesis examined the different methods used for assessing residential trees in the attempt to provide valuable information for urban forestry managers. Mixed methodology was applied, including field work, remote sensing, questionnaires and spatial property information.

It was found that long-term of validation of sampling methods is required for monitoring of urban trees. With the advancements in technology, remote sensing could be seen as a reliable and non-invasive way to determine canopy cover using publicly available information in residential areas. Our results also showed that while residents reported positive attitudes to trees and benefits, this did not necessarily result in greater tree abundance on individual properties, instead available planting space has proven decisive in this.

This thesis improved understanding of residential urban trees, their assessments as part of the urban forest. These assessment should include social and spatial variables influencing their development to allow residential trees to become integrated into city efforts to develop informed management approaches for the entire urban forest.

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What is written in this thesis, and how, is much indicative of my path in life. I find myself very often faced with the task to connect several contrasting, seemingly incompatible aspects; very often against better judgement of my rational self or people around me. Trees and People. Private and Public. Individual and Collective. Natural and Social Science. North and South. East and West. I've come to embrace such diversity over years, despite the toll it takes on trying to keep things in reasonable shape.

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Review

Long-Term Validation and Governance Role in Contemporary Urban Tree Monitoring: A Review

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Abstract: Urban trees provide important ecosystem services, across ownership and governance structures, and tree inventories are an important tool enabling urban foresters and green space managers to monitor and perform the sustainable management of urban trees. For optimal management of urban trees, a better understanding is needed concerning how urban tree inventories can provide long-term monitoring overviews across administrative borders, and how inventory protocols should be adapted to address specific practitioner issues. In this review, 98 articles on urban tree inventories were examined, the primary focus being sampling design. A governance arrangement approach was applied to identify the policy-making arrangements behind the inventories. Stratification is commonly used in the sampling design, despite being problematic for long-term representativeness. Only 10% of the stratification sampling designs identified were considered as having long-term validity. The studies frequently relied on an individual sampling design aimed at a particular issue, as opposed to using an existing longitudinal sampling network. Although private trees can constitute over 50% of the urban tree population, 41% of the studies reviewed did not include private trees at all. Urban tree inventories focused primarily on tree data on a local scale. Users or private tree owners are commonly not included in these studies, and limited attention is paid to economic, cultural or social factors. A long-term validation of sampling methods in urban areas, and a multi-lateral approach to tree inventories, are needed to maintain long-term operational value for local managers in securing ecosystem service provisions for entire urban forests.

Keywords: urban forestry; urban trees; governance analysis; tree inventories

1. Introduction

Urban areas are undergoing transformation, with climate change and increased urbanization being two of many contemporary challenges [1]. Successful adaptation to climate change will hinge on the measures taken in urban areas, where the majority of the world's population resides [2]. Thus, cities are being forced to adopt long-term perspectives in the planning and management of their resources. Urban forest inventories should reflect this dynamic in order to anchor the role and relevance of urban trees. The multifunctional beneficial contributions of urban forests are well documented, and considerable effort is being devoted to making these benefits accessible to a wide range of urban residents [3–6].

Urban forests have been identified as key in delivering ecosystem services in urban environments, and as an indispensable resource in shaping resilient future cities [7]. However, residential developments can cause a 1% loss in urban tree canopy per year due to the construction of impermeable surfaces [8]. Despite this, urban forestry programs (management of urban trees and green spaces) are often limited to publicly-owned spaces, omitting privately-owned property [9,10].

The main responsibility for the management of urban forests lies at the local government level [11]. Thus, inventories of urban trees are often used by local governments as a tool to assess and manage their urban tree resources, despite multiple ownership forms and areas of administrative responsibility. The local government structure can be divided into three levels of activity: operational, tactical and policy [9]. Urban forest inventories are generally performed on the tactical level, using the data to inform policy and operations. Inventories are the basis for sustainable resource management, providing data for decision-making in urban forestry, while repeated measurements over time (monitoring) inform managers about trends and enhance their ability to identify potential threats [12]. Failing to recognize potential threats can lead to a significant decline in the provision of environmental benefits and, since trees are not easily replaced, a long delay before the supply of ecosystem services is returned to pre-disturbance levels. Many public managers struggle with a lack of available funds, knowledge or time to conduct or maintain an urban tree monitoring program [13,14], resulting in a worrying level of preparedness for an event of the loss of urban tree vegetation.

Existing urban tree inventories and monitoring schemes are based on spatial sampling assessment techniques that generally follow guidelines set by forest management and ecology specialists [3]. The sampling design applied in these methods offers much in terms of variability, but critical analysis is needed to identify approaches suitable for long-term monitoring in urban settings [15]. Sampling inventories can also make it possible to estimate the state of privately owned trees [16]. However, there are many potential pitfalls when setting up a new monitoring system. Over time, some methods can impede the unbiased representation of the population, and give an inaccurate description of the resource. This is due to the inherent variabilities and dynamics of the urban space, and the changing boundaries, land use and development driven by the high rates of urbanization and changes in land ownership [17]. The common approach of using spatial groupings within urban boundaries (stratification) can be problematic, since urban land is often re-classified, re-developed or re-purposed. Groupings based on spatial features can encompass a wider array of factors in forming urban forest ecosystem units in order to differentiate between sites with different conditions [18]. The stratification factor used for the grouping (land use, normalized difference vegetation index, socio-economic factor, etc.) can change over time, making comparisons of repeated measurements (e.g., permanent plot networks) problematic.

Spatial stratification continues to be commonly employed to obtain better estimates of urban forest sub-populations. For example, the i-Tree Eco program developed by the USDA Forest Service is one of the most frequently used urban forestry analysis and benefit assessment tools, used globally, with over 300,000 unique users [19]. The user's manual describes how the sampling design can be stratified when collecting field data [19].

Approximately 50% of what is often considered to be urban open space is privately owned [20,21], yet may still be accessible, physically or visually, and contribute much to the public in various ways, through providing amenity and ecosystem services. In truth, private households are a very important actor in urban tree management [22], as they sometimes own more than 50% of the urban tree cover [23]. Thus, it is relevant to consider a scale from private to public when defining or dealing with the management of urban trees [24]. There is great variation in the regulatory measures between countries (as well as between different local governments within a country) [25,26] regarding privately-owned trees, causing local practices to rely on stewardship networks to improve the survival of trees [27]. Small-scale variations in stewardship could be partially explained by the differences in attitudes that people exhibit towards trees, yet not many inventories include this type of surveying [28].

In order to provide holistic, overarching measures to manage all of the urban forest, inclusive governance structures need to be applied, since the private component of urban forests is dependent in large part on measures supported by local governments [2]. This involves appropriate frameworks to plan and manage key ecosystem services, regardless of whether these services are derived from public, semi-public or private land. To deal with the rising pace of urbanization and maximize environmental outcomes, active citizenship needs to be stimulated by enhancing relationships between communities.

However, from a public management perspective, residential area developments and trees owned by private individuals are inherently difficult/complex to monitor, and pose many dilemmas in relation to overviewing, recording, monitoring and data gathering. Only 2.4% of Swedish municipalities that run a tree monitoring program include private trees [29], which means that the majority of the information which guides decision-making on a local scale is based solely on data gathered from public, park and street trees. Further research is required on how to successfully integrate privately-owned trees into city-wide urban planning and management, beyond the current scope of incentives and regulations [25,26]. We suggest that using inventories as instruments to introduce inclusive governance is the way towards a holistic understanding of urban tree dynamics.

Field inventories based on spatial sampling remain the most common approach to assessing the structure of urban forests. Accurate inventories are the basis of good natural resource management practice [30], and the use of urban tree inventories is a thoroughly researched topic. However, a critical evaluation, applying a long-term perspective to the sampling design, seems to be lacking, raising questions about the viability of contemporary methods. Against this background, we considered the research question of how to design a long-term monitoring system for comprehensive and inclusive urban forest management. In order to address this question, we studied:

- Common sampling design techniques used in urban tree inventories;
- the policy arrangement context in relation to urban tree inventories.

2. Materials and Methods

2.1. Urban Tree Sampling Terms and Definitions

Urban tree inventories are widely recognized as being key to creating an urban forest monitoring framework [31–33]. An inventory can be defined as "a written list of all the objects, furniture, etc. in a particular building" [34]. The colloquial use of the term in forestry research most commonly refers to inventories as assessments based on incomplete data, as opposed to a full record of the resource [16]. For example, national forest inventories worldwide do not draw up a complete list of all trees or forests within a particular area, but instead make estimates based on data collected from sampling plots. In this review, an inventory is defined as an assessment of a tree resource in a particular area, which is not necessarily based on a complete list of trees.

Single event inventories provide a snapshot of the current state of the trees in an urban forest, while repeated inventories (monitoring) provide an understanding of how tree populations change over time, and offer better information for policy and decision making with respect to urban forest management [16]. It is imperative that all subsequent inventory repetitions follow the same design and form, allowing the direct comparison of different snapshots and enabling the local government to draw correct assumptions.

Whenever an incomplete number of trees is selected to represent the urban forest in an area, the estimates contain inherent sampling errors [35], and aggregated data are reported in confidence intervals. However, the sampling error can be minimized by increasing the number of samples, or in other ways [36]. Different strategies have been developed to obtain more accurate estimates from sampled data in an effort to be representative of the urban forest as a whole. These include random, systematic, cluster and stratified sampling [37], all of which are dependent on the set inventory goals and objectives.

The use of stratification is widespread in sampling, the main benefit being the powerful analysis options it provides. The stratification method entails dividing the population into sub-populations (strata) using delineation criteria called stratification factors. With populations divided, sampling occurs at uneven densities between strata. Some common stratification factors applied in urban forestry include land use and local management units or other geographical units, such as ownership [18].

2.2. Structured Search and Bibliographic Overview

We performed a broad structured search of the literature in order to get a comprehensive overview of scientific articles published on sample urban forest inventories. The search included literature from 2001 onwards. In December 2019, the following search string was applied to Web of Science and Scopus: (cit* OR urban*) AND forest* AND tree* AND (monitor* OR invent*) AND (sampl* OR plot*). The search string components were location (cities and urban), population (trees and forests) and method (sampling, plots, monitoring, inventory), representing the frame of tree population and method used. Only publications written in English and only peer-reviewed articles published in international journals were included.

All the articles were reviewed and sorted via two screening processes (Figure 1). After consolidating results from both databases, 420 unique articles were identified. The first screening of these was based on abstract and title relevancy, the second screening was based on reviewing the body of the text for each individual entry. The end result was a final number of 98 articles. The criteria for excluding irrelevant articles were non-tree inventories, inventories in non-urban environments or articles not pertinent to the topic of urban forestry. The final 98 articles all included a tree inventory described in the methods section.

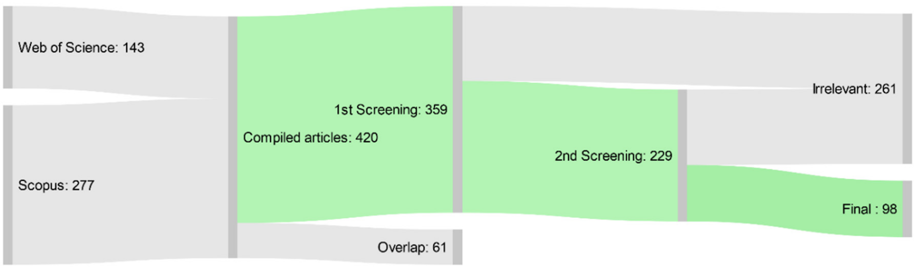

Figure 1. Sankey diagram demonstrating the literature review process and its iterations.

2.3. Validating Contemporary Sampling Methods for Long-Term Monitoring

The 98 articles were categorized based on: (i) stratification factor, (ii) possibility for long-term monitoring, and (iii) sampling method. The categorization also included information on the use of existing frameworks (e.g., the USDA Forest Service's Forest Inventories and Analysis, National Forest Inventory) or when the study used a new design.

The stratification factors were ranked on the basis of their susceptibility to change over time, based on the Urban Forest Ecosystem Classification framework [18]:

1. High stability. The basis for stratification has a low probability of changing over the coming 30 years, based on housing development age, infrastructure, and set distances from a specific point;
2. Medium stability. The basis for stratification has a low to medium probability of changing over the coming 30 years, based on human demographics (e.g., population) and urban vegetation structure;
3. Low stability. The basis for stratification has a high probability of changing over the coming 30 years, based on, e.g., socioeconomics and pollution rates.

2.4. Policy Arrangement Analysis

Governance factors were analyzed using the policy arrangement model (PAM), a conceptual framework developed in environmental policy studies to assist in understanding content and organization in a policy domain. According to Arts et al. [38], a policy arrangement is the state in which the interaction between four profoundly interconnected dimensions, namely actors, resources, rules of the game and discourses, solidifies into institutionalization. This is an unstable construct that will be forced to readjust as the interdependency of the dimensions changes. Here, the four dimensions all provided insights into how an urban forest inventory may be organized within any political framework. The 98 articles were categorized according to the PAM model and its four dimensions, defined as:

Actors. Actors and coalitions. The initiative for an inventory was classified as the origin of the idea that led to the inventory being conducted. Actors were differentiated into public, private and academic. Inventories that had a pronounced official public role were classified as public initiatives, and cases when private individuals or organizations were the driving force were classified as private initiatives. Academic initiatives were defined as inventories formulated for the purpose of answering a scientific question;

Resources. The benefits derived from trees (or ecosystem services) that were mentioned in the individual studies were categorized into economic, cultural/historical, environmental and social categories.

Rules of the game. Formal rules and boundaries related to the inventories were interpreted as the organizational level at which the inventory operated. Three different scales of inventory were differentiated, namely, local, national and international, as defined by the boundaries of the area surveyed. Local scale was classified as scaling from site to multi-regional inventories;

Discourses. Views and narratives of the actors presented in the discussion and application of the data compiled in the inventory were used to distinguish discourses. Special focus was given to articles that involved views other than those of the actors themselves, and that speculated on the potential implications of the results. The actors involved in the inventory were then categorized as politicians, public servants, academics, private owners or end-users. In this context, the end-users are beneficiaries of ecosystem services provided by trees, e.g., a park visitor that is only indirectly involved in managing processes.

For each of the four policy arrangement dimensions, multiple aspects were included per category in cases where joint involvement was described in the methodology, such as shared initiative between academic and public actors in the experiment design.

3. Results

3.1. Bibliographic Overview

We found an uneven, but gradually increasing, number of published articles during the selected study period (2001–June 2019), with 2011 being the first year in which more than three articles within this subject were published (Figure 2). A relatively low number of articles was published in 2015, but this was followed by a substantial increase from 2016 onwards. The publications primarily originated from North America and Europe, accounting for 43% and 31%, respectively, of the total number of publications, compared with 2% from Australia and 1% from Africa (Figure 2).

We identified 30 studies (31% of the total) that used remote sensing data. This is in accordance with reports in the literature of an increasing trend of using remote sensing [39,40], or testing remote sensing accuracy against other types of inventories [41,42].

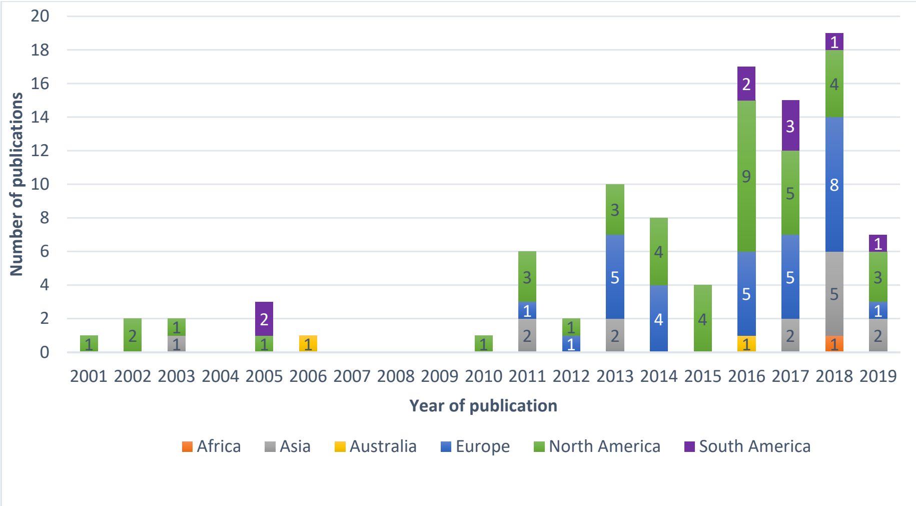

Figure 2. Number of publications per year in different regions, the full list of articles with bibliographic information is available as supplementary materials online.

3.2. Validating Contemporary Sampling Methods for Long-Term Monitoring

We identified 14 different stratification factors, all of which could be classified according to a framework for urban forest ecosystems [18]. In total, we distinguished five types of factors: climate, infrastructure, management, social and vegetation. In Table 1, these stratification factors are listed in relation to the respective stratification types. For each stratification factor, we assessed the stability for long-term studies (low, medium or high) and the chosen sampling method.

A total of 39 of the articles (40%) described the use of a type of stratification in their sampling design. In some cases, post-stratification was applied [43,44]. The stratification factors varied in relation to stability, and were primarily based on infrastructure, vegetation or social factors (Table 1).

Of the 39 studies that applied stratification, 20 were designed as long-term trials. None discussed the validation of stratification factors or the likelihood of change in these factors over different time scales. To better illustrate examples when validating stratification factors, Figure 3 outlines our interpretation of different decision-making scenarios that occur during sampling design, related to the necessity for validation.

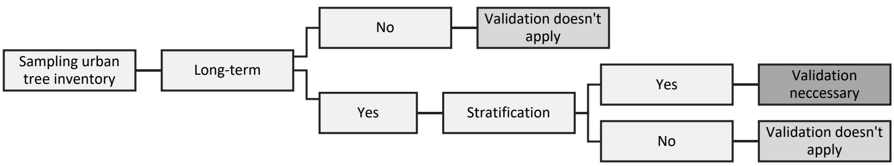

Figure 3. Diagram illustrating when validation of stratification factors is necessary for future representativeness.

Only one type of stratification (infrastructure) yielded stratification factors that were categorized as providing longitudinal stability and reliability to create a long-term network (Age of housing, Proximity to city center, Landscape type). Only one article reported a systematic stratified sampling method [45], while all others used a random stratified approach.

Table 1. Full list of articles that used stratification in their sampling design, grouped by type of stratification factor. Systematic stratified selection used set distances between sampling points, whereas random stratified selection uses a randomly selected point within the strata.

Type of Stratification	Stratification Factor	Stability	Sampling Method	References from the Literature Studied in This Article
Climate	Thermal differences	Medium	Stratified systematic	[45]
Infrastructure	Age of housing	High	Stratified random	[46]
	Landscape type	High	Stratified random	[46]
	Vicinity to city center	High	Stratified random	[47]
	Land use, land cover	Medium	Stratified random	[48–51]
	Traffic, traffic density	Low	Stratified random	[52,53]
	Pollution	Low	Stratified random	[54]
	Specific urban structure	Low	Stratified random	[52]
Management	Management units within a city (neighborhood, homogenous units within a city)	Medium	Stratified random	[21,43,55–59]
Social	Size of a community	Medium	Stratified random	[60]
	Index of human interference	Low	Stratified random	[61]
	Combination of socio-economic indicators	Low	Stratified random	[39,62]
Vegetation	Urban forest stand structure	Medium	Stratified random	[56,57,63]
	Vegetation properties	Medium	Stratified random	[64,65]
	Tree cover and other vegetation data	Medium	Stratified random	[40,44,65–69]
	Tree species composition	Medium	Stratified random	[70,71]

We found a varying degree of stability within the five types of stratification factors, the exceptions being the climate and management categories. We rated infrastructure as offering the best basis for monitoring. Management units are often utilized as delineators, indicating that inventories continue to have strong operational importance within urban forestry, yet given the relatively young history of urban forest management, these have been adapted as knowledge about urban trees has changed over time [72].

Social factors were graded as the least stable, due to rapidly changing global demographics [73], and they were featured in only four articles in our review. Generally speaking, stratification factors were found to be location-specific; even when different authors used a similar approach in stratifying their population, they used different methodologies to determine essentially the same factors. For example: tree species composition was determined using the broadleaves to conifers ratio index in one case [71], and individual species mixture in another [70]. This indicates large a difference in applications between regions, and makes determining a set of universal stratification factors challenging.

3.3. Governance Analysis

A total of 98 studies were initiated by academics, and 37 of these studies also included public perspectives (municipalities or government agencies) in the research topic, primarily by discussing the results from a public management perspective. A small proportion (5 out of 98) mentioned a private stakeholder inclusion/initiative in the conception of the study. The majority of the studies were conducted on the local government scale (92), some also applying the methodology to the national scale [41,44,74,75], but only one study [33] set its findings within an international perspective.

All studies highlighted the ecological aspects of trees in the urban environment. Economic impact was featured eight times and the social aspect four times, while only one article referred to the cultural values of urban trees. Only five studies involved joint initiation with private actors [58,59,76–78], which mirrors the fact that only eight studies [21,46,48,58,76,79–81] included private tree owners.

The results of the qualitative governance analysis are summarized in Table 2. According to the results, contemporary urban forest inventories are based on an academic (scientific) initiative and approach, with the focus being on local environmental perspectives. In studies that included multiple actors, we detected a higher potential for management application [49,61,82].

Table 2. Results of governance analysis according to the four dimensions of the policy arrangement model (PAM).

Actors	Resource	Rules of the Game	Discourses
Academic (98) Public (37) Private (5)	Economic (8) Environmental (98) Social (4) Cultural (1)	Local (92) National (11) International (2)	Academic (98) Public servants (24) Private owners (8) Users (4) Politicians (0)
Multiple categories * (38)	Multiple categories * (12)	Multiple categories * (7)	Multiple categories * (27)

* Multiple categories row indicates how many of the articles in each separate aspect category (column) had joint perspectives.

4. Discussion

Inventories and monitoring are key components in the planning and management of any resource [3,16]. Urban forestry is largely based on tree inventories [14], and the importance of continuous long-term monitoring of urban tree stocks is gaining attention. Despite this, only 10% of the stratification factors identified in this review were rated as having high stability, i.e., allowing for long-term studies. Infrastructure is frequently used as a stratification factor. However, numerous articles use low stability factors, such as traffic density and pollution levels related to traffic. Likewise, social factors with low stability, such as socio-economic indicators, are used. Such factors fluctuate over time, and therefore cannot be recommended from a long-term monitoring perspective. Vegetation factors, such as stand structure, tree cover and species composition, also fluctuate over time, but have medium stability from a long-term perspective. Too often, factors are selected based on current focus areas, with over-reliance on delineations that are less suitable for time-frames greater than a couple of years. Even though we cannot expect every trial to prioritize broad timescales, we believe that this contemporary trend is concerning, as it indicates that research on urban tree inventories is not sufficiently addressing the needs of the practice. In an urban forestry and green space management context, a transition from single inventories (a snapshot of the urban forest at a specific time) to long-term monitoring seem critical. This is especially relevant in instances where a new monitoring system is put into place by urban forestry managers in growing cities [67]. From a research perspective, these snapshots also limit the possibility for longitudinal studies, which is crucial for studies of long-term processes.

In line with Nielsen et al. [13] and Ordóñez et al. [83], we found that European and North American publications dominate the field of urban forestry in the study period, with a gradual increasing trend in the number of publications since 2010. This also reinforces the notion of the modest contributions to tree sampling and urban tree inventories in other regions [84], as well as the limited focus on the non-environmental benefits of urban trees. As reported previously, we can see that the geographical scope of scientific studies has expanded from being primarily North American during the early 2000s, and now spans all continents. The dominance of North American research up until 2018 reflects the overall expansion in the field of urban forestry, which developed in North America during the 1960s as an integrative, multidisciplinary approach to the planning and management of all forest and tree resources in and near urban areas [10]. This can be partially explained by the fact that it was not until the mid-1990s that the concept was adopted in Europe and elsewhere, following pioneering work by the US Forest Service on quantifying and modelling urban forest benefits in the Chicago Urban Forest Climate Project [10]. This late adoption is still evident in scales and scopes when comparing studies by region of origin; North American studies represent more than half of the studies that involved private stakeholders in discourses (5 out of 8), and they were most likely to involve the economic aspects of tree benefits (also 5 out of 8 studies). The scope of these studies was also more likely to include the social aspects of urban tree benefits (4 out of 4), which was most evident in recent studies.

Few articles represented more than just a single environmental aspect, which may be appropriate from a strictly scientific perspective, but it comes with the risk of restricting urban forest studies to environmental science, which accounted for 70% of the studies, instead of the multi-disciplinary field called for by many researchers and high level politicians [72,85,86]. Even if scientific studies often have the need to focus on a single perspective, we found a surprising lack of studies focusing on the aspects of social, cultural and economic value. Given the importance of these aspects, we would expect more studies focusing on the broader aspects of tree benefits. We can assume that the field of urban forestry is in a phase wherein new ways to interpret human–nature interactions are needed to better inform policymakers. With future studies being more conscious of the multidisciplinary nature of urban forestry research, trees can become better integrated in urban planning, as their contribution would be better translated across operational fields.

Since the study was restricted to articles written in English and published in peer-reviewed scientific journals, it is not surprising that all studies were driven by academics. However, tree inventory methods and findings at the local or national level may also be published as reports, guidelines and 'grey' literature, and thus a number of studies in which urban tree inventory methods are described and/or used as data sources may have been overlooked. By expanding the scope of further studies, it might be possible to get an even deeper understanding of the methods used when inventorying and monitoring the urban forest. We therefore encourage further studies to go beyond the scientific literature, and to also include other publications and languages.

The same applies for the geographically narrow focus in the literature reviewed. Only two studies adopted an international perspective, even though urban forestry is a highly international field [33,83]. More international meta-studies could improve the understanding of international urban forest inventories and methods, which could lead to the greater harmonization of inventory methods between countries and cultures, enabling them to combine efforts and share data-based experiences dealing with global issues. We also see a need for access to detailed data on the entire urban forest, as the existing information and documentation of the effects of urbanization on the actual tree resource seems scattered and varied in its conclusions.

When looking at the background of performing the tree inventories, none of the studies focused on policy implication, while only four focused on users and eight on private owners. This lack of inclusiveness risks limiting urban forest monitoring to being an academic exercise, without connecting the results or the research field of urban forestry to either policymaking or practice. The potential for using tree data as the background for policymaking is inevitable, and it seems to have a great potential in the future [87], just as the omission of private owners needs to be addressed by future research, as data concerning the contribution of residential trees to the total amount of the urban forest is a prerequisite for the creation of a total overview of the urban forest. Without long-term and stable monitoring systems, local governments will face challenges in creating suitable frameworks to ensure sustainable management. So far, the academic literature within the field does not explore how the full potential of the urban forest as a resource can be fulfilled.

5. Conclusions

This review shows how contemporary urban tree monitoring data have limited concern for long-term stability and longitudinal perspectives. This approach leads to urban forest management based on a disproportional part of the urban tree population, and long-term strategies are exposed to a higher risk of failure.

Urban forestry research has a long tradition with the applied science approach to aiding management organizations in coping with future challenges. These different methods have their advantages and disadvantages, dependent on the basis and use. We found that the relation between the research basis and the actual use, expressed via (lack of) public perspectives, was significant.

The predominant use of sampling different strata at different densities can be the best approach to resolving immediate and short-term management issues. However, unless the stratification factors possess long-term stability, this approach will not provide representative longitudinal data. In order to achieve reliable long-term trials and monitoring systems, stratification should be implemented after careful consideration of stratification factor(s) and their likelihood of changing over the given time-frame. As each city is different, the choice of stratification factors should be fitted to its local context. We suggest using rigid, local infrastructure delineations related to city characteristics (age of buildings, proximity to city center) that, unlike socio-economic indicators, population density and vegetation composition, will endure the test of time, and not significantly impact the representability. In order to make individual inventories comparable, and to increase the likelihood of international perspectives being applied to local inventories, we propose using a thorough validation process to certify each suggested factor, instead of relying on preset factors.

Non-stratification is advisable. However, a grid-based sample seems least suitable, since it easily introduces a systematic sampling bias due to the frequent use of grids in urban design.

The majority of inventories did not acknowledge the potential involved in engaging a broader range of local (and private) actors in order to secure a broader image of the urban forest data, as well as ensuring shared ownership of the inventory and its results. The involvement of multiple actors could be extended to private–public collaborations between local government and private residents. As the latter own a large proportion of the trees in a city, this form of inventory design has a higher likelihood of involving privately owned trees, and can help raise awareness and stewardship of the entire urban forest population.

Remote sensing could solve issues of access to private property, but some of the variables that it is essential to monitor in urban forest environment (pathogens, species, tree condition) continue to be hard to assess when relying solely on remote imagery.

Human–environment interaction differs a lot over the urban landscape, and in order to manage for positive ecological outcomes in the long-term future, the way we assess the tree population needs to be frequently revisited, from a methodological as well as a paradigmatic standpoint. Researchers and practitioners need to internalize the interdisciplinary nature of urban forestry, and consider building in the capacity to collect such relevant data when designing monitoring systems.

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II

Comparing Ground and Remotely Sensed Measurements of Urban Tree Canopy in Private Residential Property

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Abstract

Private residential areas represent a large portion of urban tree canopy and provide a significant amount of ecosystem services for mitigation of negative environmental impacts. With densification, in-sealing of permeable surfaces, loss of plantable space and urban tree canopy loss, communities are facing a potential degradation of urban environment and loss of living quality. Monitoring urban tree canopy change with repeated assessments over time is key for supplying information for management decisions.

We examined how remote sensing has been used in the past assessments of urban tree canopy area, the public availability and quality of geodata sources and grey literature examples. Field measurements of tree canopy area were collected in private residential property of Malmö, Sweden and compared to estimates of canopy area using publicly available data sources in remote sensing. The remote sensing model was derived using normalized difference in vegetation (NDVI) and LiDAR.

Most Swedish municipalities conduct urban tree monitoring schemes only on street and park trees. Our results show a correlation in remotely sensed tree canopy area and field measurements, suggesting that monitoring of private residential areas can be conducted frequently and non-invasively using publicly accessible geodata even in communities across Sweden and elsewhere where information of similar quality is publicly available.

Keywords: Urban forestry; urban tree canopy; remote sensing; monitoring; urban trees

Introduction

Urban forests has been defined as consisting of individual trees, stands of trees, and urban woodlands near or within urban areas (Konijnendijk *et al.*., 2006). The value of urban forests for human life and well-being has been widely documented and described (WHO, 2016). It provides a wide array of ecosystem services (UN, 2014), including mitigation of negative impacts associated with climate change by removal of pollutants, carbon sequestration, and water uptake (Gill *et al.*., 2007; Nowak *et al.*., 2006).

The spatial configuration of urban areas, with numerous different land uses, can involve half the land area being dedicated to housing, also referred to as residential land use (UN, 2014). Trends in European cities in past decades have resulted in an increase in residential areas, making them the most common setting for daily human-nature interactions (Kabisch and Haase, 2013). Residential areas are made up of different forms of housing, but most of the area belongs to private individuals or housing associations. Therefore private residential property not only provides housing amenities, but is also a large component of green infrastructure (GI), a term used to describe a wide range of natural features located at different scales and all forming an interconnected ecological network. For example, a single tree in a residential area is part of the overall GI, contributing key local environmental values (EC, 2013).

Urban forests on public land is most often planned and managed by local governments (de Magalhães and Carmona, 2009; Jansson and Randrup, 2020). However, very few local governments include assessments of privately-owned trees and vegetation in their urban forest inventories (Östberg *et al.*., 2018). Trees growing in private residential areas are vulnerable to removal, e.g., a study of single-family residential neighbourhoods in Los Angeles County found a 1.2% annual decrease in tree/shrub cover (Lee *et al.*., 2017). When a substantial part of the urban forest is not included in assessment, there is a risk of significant contributions of ecosystem services from the total urban forest being overlooked. Additionally, future planning and management is at risk of omitting valuable inputs in terms of location and specific ecosystem services provided by trees on private residential plots. This may lead to inadequate operational management and policymaking. To evaluate the complete volume of ecosystem services provided by urban trees across the urban landscape, privately owned vegetation needs to be included in assessments of urban forest (Cook *et al.*., 2011).

Recording work on urban trees by local governments broadly falls into two categories: on-site approaches using field work and on-ground measurements, or top-down approaches using remote sensing imagery (satellite or aircraft-mounted cameras) to detect the extent of vegetation in an area. A central argument for not applying bottom-up approaches to include residential trees in public tree databases is the private rights to the property and the related restriction on physical access by local government staff for monitoring and data collection. Top-down approaches, on the other hand, can be used to detect the total urban forest composition via canopy cover assessment. Its limitations in urban areas lie in determining tree species, vitality, and site conditions for individual trees (Huang *et al.*., 2019; Johnson *et al.*., 2015). Due to regular image-generating observations and relatively simple access, the cost of obtaining high-resolution imagery has considerably decreased in recent years, simplifying the data-gathering process and driving transition of tree management to a digital future (Galle *et al.*., 2019). For the same reason, remote sensing is recognized as an important tool for assessing sudden changes in tree cover caused by development, diseases, or similar underlying reasons (Kangas and Maltamo, 2006).

This study compared data on trees in private residential property obtained in manual field surveys with data obtained using Normalized Difference Vegetation Index (NDVI) and Light Detection and Ranging (LiDAR) classified remote sensing imagery. The aim was to test whether remote sensing can be used to complement canopy information from field surveys in private residential areas. The specific objective was to evaluate whether statistical extrapolations from field data align with those from remote sensing, and thus whether ecosystem services assessment can be improved using this additional data source, given its low invasive nature and potentially frequent update. The terms 'assessment', 'monitoring', and 'inventory' are often used inconsistently in the literature. For clarity, we delimited the analysis to 'assessment', as in 'assessing the extent or amount of', since both inventory and measurement might imply a degree of completeness inappropriate to a sampled approach. Monitoring implies some sustainable longer-term consistency in data collection, which must be left to future work once the more limited aim of potential for assessment is investigated. However, due to the ambiguity and overlap in terms, we employ other authors' choice of term when citing other work.

Similarly, the term "validation" is often used to mean validation of the classified products from remote sensing (e.g., by pixel-level confusion matrix). The stated objective in this study required a different test; not the proportion of pixels validly classified, but whether canopy area estimated from remote sensing is comparable to area measured in field assessments for domestic gardens. We did not consider either the field or image dataset to be the "absolute truth", but were simply interested in whether the two methods produce similar estimates.

Remote sensing in assessment of tree canopy cover

In managing trees, there is a long history of using remote sensing as a means to monitor and assess tree canopy coverage, starting with manual assessment of aerial photographs in the forestry industry and for land-cover mapping (Heller, 1964). The introduction of multi-spectral imaging greatly improved the accuracy of automated assessments, in particular NDVI (Pettorelli, 2015), which uses infra-red absorption to distinguish plant life (specifically chlorophyll) from other green land cover (see Pettorelli ibid. for development of the principle). NVDI was first proposed in the early 1970s (Rouse, 1974), and has proven useful in a wide array of application areas where vegetation plays a role (e.g., mapping urban heat islands, landslides, soil erosion, epidemiology, psychology, and hedonic property pricing), at a wide range of scales from individual gardens to global maps. This section represents a selected overview of key themes within context of urban forestry, based on a structured literature search which found well over 4000 journal papers referencing the technique in an urban Space does not allow for a complete literature review, but only to present a brief overview.

In urban areas, until relatively recently satellite resolution for freely available multi-spectral imagery was limited at around 20-30 m (e.g., Landsat TM, SPOT) in terms of satellites with affordable global coverage. Consequently application to urban areas remained complex, with various attempts to extract greater thematic detail such as pixel un-mixing (Liu and Yang, 2013) and panchromatic texture analysis (Ozkan *et al.*., 2016) to improve estimated total area of different types of vegetation per pixel. These lacked sufficient geometric precision to reveal the contribution of scattered trees in complex environments. trees. Distinguishing between the urban forest and other elements of the urban GI was further hampered by lack of sufficient Digital Surface Models (DSM) in nationally collected datasets. Until 2000, a typical DSM had 25 m resolution, with building data possibly added in the form of 3D models but often without vegetation height data. The advent of LiDAR provided the possibility to automatically identify 3D structures such as canopy edges and individual tree crowns for the first time (Meng *et al.*., 2018) (for a review in urban forestry see Wang *et al.*., 2019).

In theory, LiDAR can work to almost arbitrarily detailed resolution, data size, and collection mode. However, collection over large areas and national data are usually limited to around 2 m resolution for urban areas. Thus while many studies have used very high resolution (VHR) LiDAR to identify and classify individual trees, resolution of 10 cm or 25 cm cannot be assumed to be generally available. Earth observation satellite missions Sentinel 2A and 2B, launched in 2015 and 2017 respectively, increased the available resolution of freely available multi-spectral data to 10 m and in doing so crossed a threshold for utility in urban areas in general (Baines *et al.*., 2020; Moreno *et al.*., 2020). This, plus the dramatic expansion of GIS and data science use in the public sector (Svännel *et al.*., 2020), has led to growing use of remote sensing to assess residential green space and its importance for various aspects of human wellbeing (Singh *et al.*., 2018).

Resolution is not the only reason why it is challenging to use NDVI to assess urban areas. It also requires use of indicators such as soil type and vegetation density (Sadeh *et al.*., 2021). This has led to some concern that NDVI might locally underestimate urban GI in general (Gascon *et al.*., 2016), and in the development of indices to address this (e.g. EVI, SAVI) (Pettorelli, (2015). The urban tree canopy is arguably less vulnerable to such underestimation than other constituents of the urban GI, since canopies are relatively dense and elevated above the background surface. LiDAR data on elevation can be used to distinguish larger trees from other land covers, although a resolution of 10 m still requires spectral un-mixing to extract information about smaller tree crowns. Although not freely available, VHR imagery can remove this size barrier, but there are problems associated with VHR due to spectral diversity across the tree crown (Ardila *et al.*., 2012). This has been described as a 'salt and pepper effect' which, if not separable from the surrounding space by other variables (i.e., height), might necessitate more complex object-based (Ardila *et al.*., 2012) and artificial intelligence (AI) approaches (Chouhan *et al.*., 2019; Timilsina *et al.*., 2020) to tree crown identification. This includes attempting to identify likely species from hyperspectral imagery or multispectral LiDAR (Dai *et al.*., 2018).

Swedish local authorities now often have access to VHR imagery at sub-30 cm resolution and LiDAR at resolution of 1-2 m. However, despite increasing use of unmanned aerial vehicles (UAV) in the forestry sector (Baek and Hong, 2017), t. Object, texture, and AI approaches to identify individual tree crowns are at the forefront of current knowledge, but are probably of most use when attempting to identify the characteristics of individual trees within a multi-tree stand, i.e., when canopy height does not suffice to distinguish the cover of interest. When the task is simply one of measuring canopy extent, there are practical reasons for attempting to do so using as simple and standardized approaches as possible.

The standard NDVI/LiDAR combination approach to assess tree canopy in private gardens is limited by lack of ground data, since: "Although inventory measurements are locally comprehensive, they can be sparse in a heterogeneous urban landscape, laborious and time-consuming to measure" (Baines *et al.*., 2020). On the one hand, wide experience of use of the NDVI-LiDAR method for urban canopy assessment in general (Parmehr *et al.*., 2016) and successful application in studies within residential areas as a whole (Gernes *et al.*., 2019; Peng *et al.*., 2020; Sadeh *et al.*., 2021) give reason for confidence. On the other hand, specific characteristics of private gardens might give reason to expect confounding issues. For example:

- A relatively high proportion of residential property plots is needed for buildings. Compared with parks and streets, trees in private gardens are often close to buildings, meaning that off nadir shadow formation (i.e. areas where the lidar signal is occluded) sand resolution might interfere with the signal.
- Private gardens are likely to have a diverse, unusual mix of tree species, particularly with more fruit trees and non-native tree species, which might have different spectral responses (Avolio *et al.*., 2015).
- In private gardens, there are fewer large stands of trees and a higher proportion of younger, smaller trees compared with in parks and streets (Grove *et al.*., 2006).
- In private gardens there are suboptimal management practices (e.g., cutting branches off at a property boundary), which may compromise estimation (Miller *et al.*., 2015).

Ardila *et al.*. (2012), showed that when attempting to map tree crowns from VHR images there were "false negative errors concentrated on small trees and false positive errors in private gardens". Thus, both forms of error may be a particular issue in private gardens, since smaller trees can also be expected in smaller plots.

Urban tree canopy assessments by local governments

Urban tree canopy assessments provide a systematic overview of the urban tree resource, to better assess that resource. The history of local government monitoring of urban trees stretches back over a century (Morgenroth and Östberg, 2017), and predates formalization of urban forestry as a discipline. In a review of contemporary urban tree inventory methods used to monitor data at single-tree level, Nielsen *et al*.. (2014) found only six studies using remote sensing out of 57 (11%). More recently, (Klobucar *et al.*., 2020) found that only 31% of papers they reviewed reported use of remote sensing in urban tree inventories. Tree assessment methods are subject to traditions from adjacent disciplines, e.g., monitoring of "trees outside forest" often includes urban areas in national forest inventories, applying identical methodologies with sparse networks of plots (Schnell *et al.*., 2015), meaning that more detailed urban tree canopy assessments are conducted at the local government level.

There are several examples in which remote sensing methodologies have been applied to monitor urban trees in practice. The United States Forest Service (USFS) provides important methodological descriptions for practice (USDA, 2019b). Its guidelines touch upon using LiDAR mapping, high-resolution imagery, and spectral imagery for assessments of urban tree canopy. LiDAR is described as necessary to improve the accuracy based solely on imagery, especially in distinguishing vegetation from other features. In its report, the USFS also suggests that practitioners take advantage of the potential to monitor tree canopy changes using remote sensing tools and not merely offer single "point-in-time" assessments for local planning bodies (USDA, 2019b). The (brief) report does not mention any potential issues related to the specificity of residential areas. It also directs practitioners towards use of i-Tree Canopy (a Google Earth-based tool for sampling assessment of tree canopy) and i-Tree Landscape (a web-based geographic database of Landsat imagery and demographic information) (USDA, 2019b).

A good example of monitoring practice is the Tree Canopy Assessment by the city of Philadelphia, where a combination of aerial photography and LiDAR, acquired through government agencies, was used for obtaining fundamental information about the urban tree canopy (O'Neil-Dunne, 2019). The local government goal of obtaining 30% cover in each neighbourhood was repeatedly evaluated for implementation of necessary policies. The findings provided information on land cover change, loss of canopy cover, potential plantable space, and more. The greatest change was recorded in residential area, but the analysis encountered issues when comparing datasets from different years, due to differences in sensors and time of acquisition (O'Neil-Dunne, 2019). They not discuss the specific sources of error for residential areas or the vegetation indices used for mapping change (O'Neil-Dunne, 2019). Using a combination of aerial photography and LiDAR to assess (and monitor) urban tree canopy seems to be widely accepted method by communities worldwide. In a literature search restricted to English language sources, we found reports on use of this method by local governments in London, New York, Baltimore, Seattle, and Toronto.

In Sweden, 26 municipalities and organizations collaborated in a recent project assessing ecosystem services provided by urban trees at national level using i-Tree Eco v6 (Deak Sjöman and Östberg, 2020). Canopy assessments were made using field measurements and primarily on public property. The University of Gothenburg has used LiDAR to successfully map trees at city level using high-resolution LiDAR point clouds with highly accurate tree models (Lindberg, 2013). To date, no report on urban canopy assessment based on aerial photography and LiDAR has been published in Sweden. Instead, local governments rely on collaborations with research institutions and mixtures of methods to assess urban tree canopy.

Overall, a divergent picture emerges on the use of RS in general, and Lidar-NDVI in particular within urban forestry. It is a well-documented method with studies as to method and accuracy for monitoring urban forestry at larger spatial extents, particularly as to canopy and larger individual trees in public spaces. However it is still not standard practice internationally (as demonstrated by the case of Sweden which certainly has the technical and financial capacity) particularly outside major conurbations. The specific context of private gardens has also been studied but less conclusively as to accuracy at the pixel level but perhaps more importantly, as to comparability between remote sensing and field assessment at plot level. Indeed there are some reasons why, prima facie, one might expect site and remotely sensed plot data to diverge.

Method

This study applied a case study approach, using one city (Malmö, Sweden) as a detailed examination of a single case (Flyvbjerg, 2016). The city of Malmö (55°36′21″N 13°02′09″E) is the third most populous city in Sweden, with 338 230 inhabitants (SCB, 2020). It is located in the temperate vegetation zone, on the southern Swedish agricultural plains, a region with overall fertile soils and mean precipitation of 600 mm/year (SMHI, 2021). The urban area extends to 8105 ha, with 1877 ha of this (23%) classified as private residential area. The city government has been proactive in using urban trees as part of overall strategies for mitigation of climate change, and has a full inventory of street and park trees (Sjöman *et al.*., 2012). As a result, a "tree plan" strategy for long-term development of urban vegetation has been repeatedly updated and developed (2017).

Plot Definition and Canopy Extent

Whether the circular plot is used or the whole garden, both face a definitional problem for comparison with areal imagery; the canopy above a plot does not necessarily grow from a stem located within that plot. In the case of i-Tree, the aim is to measure that which grows from the plot (regardless of whether it then hangs beyond the plot). In the case of the imagery, the aim is to measure what covers that plot, regardless of where its tree grows from. Not only do these (literally) a ground up and top down approaches mismatch conceptually, they might also be expected to operate with antithetical effect as regards estimation of canopy cover within that space. The ground up may systematically over estimate canopy within the plot (since it includes that which hangs outward) the top down systematically over estimate that which grows in the plot (since it includes that which hang inward).

The only way these two methods will record the same total canopy for a plot is if in the ground based approach that "gained" on one stem is "lost" at another, while for the top down approach that "gained" from outside is "lost" from stems inside with crowns which hang beyond the boundary. Furthermore these losses and gains but a balance out in equal measure between the two approaches. Whether that happens depends on spatial pattern at a higher scale. Comparability between ground based (plot based) and area based (image based) canopy extent assessment is therefore not a simple question of whether pixel classification is sufficiently accurate to map urban canopy, or even whether it is sufficient to map this in private gardens. Rather it is a question of whether the two methods converge statistically at all and if so under what conditions of plot size, scale, urban morphology, extent and so on. First and foremost this method aims to answer only whether the methods converge, but since the i-Tree plot samples stem position not canopy, some slight alternative plot diameters are also tested.

Another potential confounding factor is that canopy may overlap, which the ground level assessment would include but the aerial view does not (at least in simple 2D extent). Again, the significance or otherwise of this for comparability of the two methods in private gardens depends on how often it happens in private gardens. While of course overlap does occur, there are structural reasons to expect it may be not particularly significant e.g. plot size, tree age and the fact that most trees are planted with some forethought as to how much space their canopy will need (or are managed/removed subsequently). So while, in terms of RS classification, gardens may present some additional challenges at the pixel level, other characteristics could prove advantageous for statistical comparability with ground survey assessment.

Field data

Field work was conducted in autumn 2018. In urban tree assessments, a sampling design with 200 sampling plots gives ~12% relative standard error in estimating tree populations (Nowak *et al.*., 2015). Within the 1877 ha of private residential areas in the city of Malmö, we therefore selected 225 spatially-balanced sampling points to compensate for potential refusal rate. Residents were notified by mail, and visits were individually scheduled after agreement to participate. At each sampling point, a 100 m2 circular plot was outlined and surveyed for trees.

For tree stems with diameter at breast height (DBH) above 5 cm present within the plot, the following measurements were taken:

- Azimuth and distance of tree stem from plot centre
- Tree species
- Stem DBH
- Crown width in two perpendicular directions
- Tree height

Tree canopy measurements were made ignoring residential plot boundaries.

Regulating ecosystem services supplied by trees are generated through photosynthesis, where the capacity to produce CO2 is closely related to leaf biomass. These can be calculated using allometric equations (Nowak *et al.*., 2013). The data were entered into the i-Tree Eco model (USDA, 2019a) for each plot individually and, as a result, canopy area and total leaf biomass were available for each plot. Individual plots were also classified by type of vegetation, divided into three categories: deciduous, coniferous or mixed, based on the tree species. In total, 200 plots were surveyed, since not all plots were accessible due to residents not consenting to participate in the study.

Orthophoto imagery and NDVI classification

The plot aggregate was used to compare field measurements to remote sensing imagery. Cadaster maps of real estate records, which include shape and size of private property with building footprint, were acquired through public freedom of information. Coordinates of sampling points from the field measurements were buffered to create digital surfaces of the sampling plots.

LiDAR and orthophoto geodata products were procured through Lantmäteriet, the Swedish mapping, cadastral, and land registration authority (Lantmäteriet, 2020). Geodata on property borders was requested from City of Malmö through right of access to public information (Table 1). The remote multispectral imagery product used for the analysis was IRF in 0.25 m resolution, which comes in three bands (infrared, red, and blue). Out of all available years (2011, 2012, 2014, 2016, 2018), the imagery from 2016 was most suitable, since the images for 2018 (year of field measurements) were taken in the early spring, when most of the local deciduous vegetation was not in full leaf, and were therefore less suitable for NDVI calculations. Raster mosaic tiles were combined to a single raster layer and values were normalized by the built-in mosaic function. NDVI was derived by ArcGIS Pro 2.6.3. software (ESRI, 2020) using infra-red (IR) and near infra-red

(Sadeh *et al.*.) spectral bands included in the product, with manual calibration of thresholds for optimum contrast, calculated as:

$$NDVI = \frac{NIR - R}{NIR + R}$$

The output of this operation was a raster map of NDVI values across the city, which was subsequently extracted to the field plot areas. In order to consider the potential effect of instances where tree canopy extended across the circular plot boundary, two additional sets of areas were extracted for larger radii at one and two standard deviations (SD) of the mean individual tree canopy radius, as recorded in the field. Thus we created three concentric circles for the purpose of assessment of the remote sensing values, with radius 5.64 m, 6.72 m, and 7.8 m (Plot1; Plot + 1 SD; Plot + 2SD, respectively), as shown in Figure 1.

LiDAR vegetation surface model

Low vegetation (lawns and small shrubs) is difficult to distinguish from trees using only NDVI values. Therefore the LiDAR dataset obtained from Lantmäteriet was used to create a raster Digital Surface Model (DSM) from first return point cloud and a Digital Terrain Model (DTM) from ground points. The resolution of the two raster layers was based on the density of available points (0.5-1 point per m2) and set at 1.5 m. The height difference between surface and elevation models represented all aboveground objects. Our field measurements for canopy height ranged from 16.5 m to 1.3 m, providing a vertical "vegetation window". The re-sampled NDVI classified imagery from the previous steps was then overlain to segment the surface into canopy and non-canopy.

Regression analysis

The LiDAR surface model, overlaid with NDVI-classified images, was used to count the total number of pixels within each of the three concentric plots for each plot site. To determine total canopy area, the total count of pixels was multiplied by pixel area size. The result was then compared to canopy area estimated from field measurements, where the two perpendicular radius measurements were used to calculate canopy area of trees present within the plot. The resulting dataset thus consisted of 48 observations of both field-based estimates and remotely sensed estimates of canopy area for three concentric areas (Table 2).

Results

Table 2 shows the results of the three linear regressions, for each of which the field estimate of canopy was the dependent variable against each of the respective plot sizes.

While all three covariates tested were significant for canopy area, the smallest size plot (100 m^2) showed greatest significance (Figure 2). This suggests that the relationship with field measurements was strongest for the original plot area and that canopy extending beyond the plot was not a confounding feature. The obvious outlier was a case where multiple canopies overlapped, which strengthened the significance but not critically so as the correlation remained significant when the outlier was removed. Additionally, using plot categorized by type of vegetation (deciduous, coniferous, mixed) as a factor in a mixed effect model did not improve significance in the relationship with canopy area, and no subgroup had a significant correlation by itself.

Discussion

This study was conducted at a single location (Malmö, Sweden). The surrounding area is deforested arable plains and most woody vegetation on private property is planted by human hand, with higher frequency of solitary trees and rare forest stand-like conditions with multi-layered tree canopies. This is perhaps less frequently the case for urban development that are encroaching into forested areas, which is potentially problematic from the perspective of generalizing the results found here, given that NDVI analysis does not detect multi-layered canopy. As indicated by the outlier in Figure 2, there was some overlapping of canopies that resembled forested landscape. In this particular inclusion of outlier improved the statistical significance of the relationship between remotely sensed values and field measurements. The outlier example of stand-like conditions in Malmö is quite possibly a frequent occurrence in private residential areas of cities surrounded by forested landscape, where natural regeneration is the leading form of tree regeneration in residential areas (Nowak and Greenfield, 2012). This indicates that surrounding landscape characteristics are an important factor in ability to remotely detect canopy area. A further caveat is that Malmö is a comparatively spacious city. Urban form may affect the suitability of plot shape and size used in field work, and the severity of potential issues from shadowing by adjacent built structures in remote sensing work. The relationship found and the appropriateness of the spatial sample are likely to be scale- and spatial unit-dependent (Openshaw, 1984), which poses a potential challenge to consistent long-term monitoring as urban form evolves. However, mapping potential disturbances affecting provision of ecosystem services, especially regulating ecosystem services as studied here, long-term monitoring is important in providing representative longitudinal data (Klobucar *et al.*., 2020). The results in this study indicate that remote sensing could also be a valuable resource in designing a monitoring system for urban forest.

We found that annual high-resolution spectral orthophoto imagery in Sweden is not collected consistently during the season when trees are in leaf. Full flushing of leaves also occurs at different times during the spring-early summer for different species, making NDVI-based analysis difficult to compare between years, which is an important limitation. Consistent routines in data collection would greatly assist monitoring of urban vegetation development and should be developed in future research. Such routines should take into consideration the vegetation zone diversity in Sweden. Type of regulating ecosystem services provided and seasonal changes in these are dependent on tree species (Alonzo *et al.*., 2016). Our methodology used a broad generalization for the entire canopy cover, due to sampling design choices for field work. For more detailed information on different types of canopy cover (deciduous, coniferous, and mixed), a different design would yield important information for improving remote sensing detection of different canopy types, so that seasonal variation and species-dependent provision of ecosystem services could be observed. Currently, the LiDAR point density publicly available for Swedish urban communities ranges from 0.5 to 1 point per m2 and is unsuitable for species recognition based on crown shape. The accuracy of using LiDAR and spectral aerial photography could be improved using vegetation indices.

Surprisingly, in a review of grey literature on application of similar methodology in practice, we found that assessments of urban tree canopy often did not include NDVI as an ancillary information source for assessing urban tree canopy. Instead, the local governments concerned relied on interpretation of aerial imagery without infrared light reflectance.

Much research has shown increasing interest among private stakeholders in being heard and even engaging in urban forestry applications (see e.g., (Fors *et al.*., 2015; Mattijssen *et al.*., 2017). Remote sensing could be utilized as a methodology to overcome the major obstacle of gaining access to private gardens for monitoring. Klobucar *et al.*. (2020) found that a majority of urban forest inventories performed by local governments did not acknowledge the potential of engaging private residents in collecting urban forest data. The issue of access to private gardens proved relevant in the present study too. Public participation is frequently described as a sampling approach (citizen science) relevant for urban forestry, but may not prove to be efficient or of sufficient accuracy for large sampling areas, e.g., entire city areas (see e.g., (Foster *et al.*., 2017; Roman *et al.*., 2017). If simple field-based indices such as perpendicular axial estimation of canopy area can be reliably cross-referenced with remote sensing sources, as done in this work, then options exist to address both accuracy and coverage issues. In this context, our findings may prove to be valuable for future planning and management of entire urban forests in an efficient manner, without overlooking the important relation to the owners of trees actually assessed. A potentially interesting further step would be to use the extensive coverage provided by remote sensing to investigate the wider social relevance of privately managed (and largely ungoverned) urban canopy.

Conclusion

A strong relationship was found between remotely-sensed canopy area estimates and canopy area measured on the ground. Using the approach described, remote sensing could provide valuable information in evaluating provision of ecosystem services, specifically where high-resolution data are easily accessible. Remote sensing of public trees and private trees in residential areas could be utilized in cases where gaining access for monitoring on private land is challenging. As most local governments manage only public trees, use of remote sensing would improve knowledge about the complete urban forest, including information on site condition, vitality, and other data that can influence the survival of trees on residential property.

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Tables and Figures

Table 1*: Geodata sources used in this study with respective metadata.*

Geodata	**Date**	**Projection**	**Collecting agency**	**Resolution/Density**	**Raster/Vector/Other**
LiDAR dataset	2018-03-01	SWEREF99	Lantmäteriet	0.25-1 points per m^2	Point cloud
Orthophoto	2016-05-09	SWEREF99	Lantmäteriet	0.25 m^2/pixel	Raster
Cadaster data	2019-04-19	SWEREF99	Malmö FGK[1]		Vector

Table 2: Canopy area estimated by field measurements compared with remote sensing. A significant correlation was found for all three variables, with the smallest plot showing the strongest relationship.

	Coefficients		**ANOVA table Type II test**		
Variable	Estimate	StdError	t-value	Pr(>t)	
100 m^2 plot	0.6541	0.2260	2.895	0.00579	**
Plot + 1SD	0.4607	0.1775	2.596	0.0126	*
Plot + 2SD	0.3187	0.1399	2.278	0.0274	*

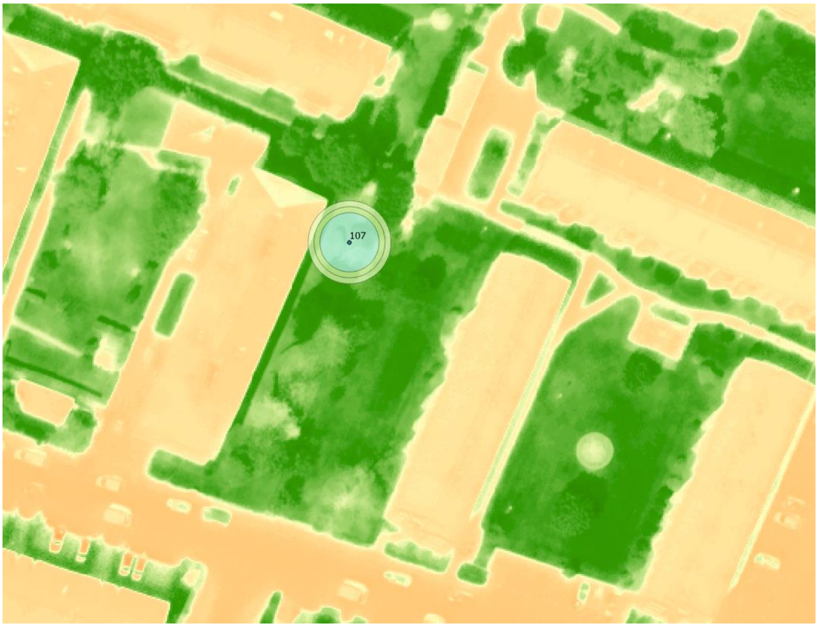

Figure 1: NDVI-classified high resolution aerial image of sampling point "107", with green color representing high reflectance values (vegetation) and orange color representing low reflectance values (non-vegetation). The concentric circles (from smallest to largest) represent: 1) Sampling plot area (100 m^2), 2) sampling plot radius increased by one standard deviation (1.08 m) of average crown radius, and 3) sampling plot radius increased by two standard deviations (2.16 m) of average crown radius.

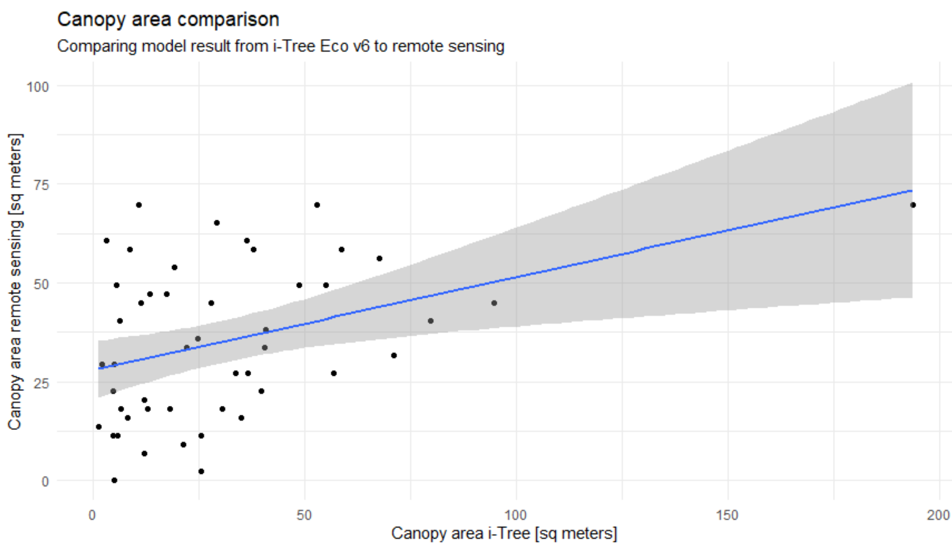

Figure 2: Validation of ground-measured canopy values to remote sensing values. Each point shown represents a 100 m^2 circular plot on the ground.

III

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Original article

Residential urban trees – socio-ecological factors affecting tree and shrub abundance in the city of Malmö, Sweden

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ABSTRACT

Trees and large shrubs in urban environments provide a wide array of ecosystem services, enhancing the well-being of urban residents. Public trees in Sweden are managed by local governments, but private-owned urban trees, which represent a large proportion of the total urban tree population, are managed by residential property owners. Residential urban trees are therefore generally not included in urban forest management plans. This study examined property-level characteristics that could lead to better management decisions by property owners on residential trees in Malmö, Sweden.

Using spatial sampling, 99 properties were inventoried to determine tree basal area (m 2 /ha), as a measure of woody plant abundance. In parallel, residents were surveyed about their attitudes to trees, and information on background variables on their properties was collected using GIS. Statistical modelling was used to determine relationships between key socio-ecological variables and tree abundance as well as reasons for planting and removal of trees.

The results showed that positively perceived benefits of trees to property owners did not necessarily result in greater tree and shrub abundance on individual properties.

Instead, house age and potential plantable space were the variables positively correlated with tree and shrub abundance. Years of residence had a negative correlation with probability of planting. The primary reason for tree removal was improper growing site, which indicates that providing practical information on appropriate site/species selection could reduce the risk of healthy urban tree removal.

Using spatial sampling, 99 properties were inventoried to determine tree basal area (m 2 /ha), as a measure of woody plant abundance. In parallel, residents were surveyed about their attitudes to trees, and information on background variables on their properties was collected using GIS. Statistical modelling was used to determine relationships between key socio-ecological variables and tree abundance, and find a set of variables explaining the variation in tree occurrence between residential properties.

The results showed that positively perceived benefits of trees to property owners did not necessarily result in greater tree and shrub abundance on individual properties.

Instead, house age and potential plantable space were the variables positively correlated with tree and shrub abundance. Years of residence had a negative correlation with probability of planting. The primary reason for tree removal was poor planting site selection. Thus local efforts should focus on improving site and species selection for residential areas, in order to increase urban tree survivability and tree stewardship in the absence of regulatory measures.

1. Introduction

With the current rapid pace of urbanisation, increasing numbers of city dwellers are frequently being confronted by a wide array of challenges related to climate change, e.g. heat waves, urban flooding and air pollution (Nowak et al., 2006; Xiao and McPherson, 2002). Research clearly shows the value of trees and large shrubs in mitigating these challenges and making cities more liveable (Bowler et al., 2010; Gill et al., 2007; Grahn and Stigsdotter, 2003; Jones, 2008; Norton et al., 2015; Tyrväinen et al., 2007). The urban forest consists of a mosaic of different owners and management types, e.g. municipal arborists (Randrup and Persson, 2009; Östberg et al., 2018), institutions

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(Konijnendijk et al., 2005) and individual citizens (Buijs et al., 2016). In order to increase understanding of the urban forest, it is crucial to study how these different ownership groups regard urban green spaces, and the trees and shrubs grown on land under different ownership forms (EEA, 2015).

Residential landscapes make up over 40 % of urban landscapes (UN, 2014), so residential landowners play a key part in provision of ecosystem services at the global scale (Shakeel and Conway, 2014). The ecological outcomes of residential landscapes in the form of ecosystem services are a result of interactions between human drivers, legacy effects and management decisions by individuals (Cook et al., 2011). Decision-making by private individuals has been examined in several studies assessing the importance of urban residents' social values in environmental management (Ives and Kendal, 2014). Management decisions made by residential tree owners have been described as active, fragmented and spontaneous (Conway, 2016). Tree removal is often associated with poor risk assessment and can lead to removal of healthy trees (Kirkpatrick et al., 2013). Studies have shown that residents tend to exhibit risk-averse behaviour when it comes to trees and tree care, not fully recognising the positive benefits of owning trees (Kirkpatrick et al., 2013). This results in a trend for removal of healthy trees based on perceived risks to personal property and injuries. Recent trends in residential development often result in expansion of hardscapes, which has led to urban tree canopy loss (Lee et al., 2017), potentially exposing residential areas to environmental risks due to a decline in ecosystem services. On the other hand, tree retention is associated with high cost of removal and of non-compliance with government regulations and by-laws (Guo et al., 2019). Some urban residents clearly harbour negative perceptions of trees, leading to their removal, which could be explained by perceived or real ecosystem disservices associated with urban trees, e.g. fear of trees causing structural damage, unsuitable growing space and messiness (Delshammar et al., 2015).

Management of urban trees and green spaces in Sweden is predominantly the responsibility of local municipalities (Konijnendijk et al., 2006; Randrup and Persson, 2009), but their area of responsibility is limited to management of public spaces populated with park and street trees. Local municipalities have direct control over these spaces, but this control does not extend across private property boundaries. As a result, privately-owned trees are rarely included in urban tree inventories. A recent survey in Sweden found that only 2% of all local governments that conduct urban tree inventories include private trees (Wiström et al., 2016). Against this background, privately owned trees and large shrubs can be assumed to be a largely unknown and overlooked source of urban ecosystem services from a local government perspective, in Sweden and elsewhere (Wiström et al., 2016; Ordóñez-Barona et al., 2021).

Retention and survival of urban trees on privately owned land can be affected by direct or indirect incentives implemented by local governments. For example, tree ordinance and zoning regulations have been shown to have a positive impact on preserving the urban tree canopy (Hill et al., 2010). There are few ordinances in place to protect trees on private property in Sweden and the factors influencing woody species abundance in residential areas, including the extent of residential vegetation, are largely unknown (Östberg et al., 2018).

One of the approaches that local governments can adopt is to carry out educational activities highlighting the benefits of trees, but with a clear operational goal in mind (Ordóñez and Duinker, 2013). Among past attempts to establish trees in cities using tree planting initiatives aimed at residents, the most successful programmes have emphasised stewardship, species and site selection, and involvement of skilled volunteers (Roman et al., 2015). Some studies have identified different groups of residents based on their attitudes and approaches to tree management, suggesting that there is a wide range of opinions among residents. This needs to be addressed by practitioners (Kirkpatrick et al., 2012), as functional traits of urban tree communities have been shown to be dependent on residents' preferences and perceptions (Avolio et al., 2015). However, previous studies report mixed results regarding the role of residents' attitudes in decision-making on urban trees (Conway, 2016; Kirkpatrick et al., 2012; Larson et al., 2010). Based on the assumption that positive associations result in positive outcomes, social and pro-environment values are frequently incorporated in the framing of management activities for ecological systems, to minimise conflicts between stakeholders (Ives and Kendal, 2014). In a study by Guo et al. (2019), aesthetics were identified as the main driving force behind individual tree management actions, with increased tree retention linked to recognition of ecosystem services, while tree removal was linked to perceived disservices (Kirkpatrick et al., 2012). In a Swedish context, one study addressing why trees on public land are felled (Wiström et al., 2016) and one study on complaints about public trees to municipalities (Delshammar et al., 2015) have been published, but no previous study has focused on private residential land and the management decisions being made by these tree owners. Since few regulations influencing privately owned trees are in place in Sweden (Mebus, 2014), the relationship between resident preferences, perceptions and ecological outcomes is arguably the key factor in tree survivability and retention at individual property scale (Grove et al., 2006). In order to understand the management actions needed to promote sustainable urban forest management in Sweden, the connection between tree abundance and residential property owners' attitudes needs to be better explored.

In assessing tree abundance on private property, several parameters and their interactions need to be considered. Potential plantable space (PPS), i.e. the difference between total area of a private residential property and the building footprint, has been shown to be positively correlated with total tree canopy, as it reflects the capacity for potential urban canopy cover (Wu et al., 2008). When trees are introduced on new residential plots, they require time to mature and to reach peak production of ecosystem services. This in turn means that house age might be a factor that is positively correlated to tree abundance, while new developments and changes in ownership might have a negative impact on canopy cover. However, all of these aspects could also be affected by owners' individual decisions and views on trees.

The link between socio-ecological drivers and environmental outcomes of management decisions is a rapidly growing field of research, with recent publications (e.g.:Avolio et al., 2015; Engebretson et al., 2020; Padullés Cubino et al., 2020; Schmitt-Harsh and Mincey, 2020). However, the majority of these studies are within a North American or Australian context, within specific urban forestry management traditions and residential development legacies. Our study was specifically interested in the regional residential development context and in linking tree abundance to individual attitudes or preferences instead of vegetation diversity.

Based on this background, the aim of the present study was to develop a better understanding of factors related to existing tree and shrub abundance, and factors influencing tree plantings and removal on urban residential land in Sweden. Using examples from extensive research in socio-ecological dynamics in other regions, the following research question was addressed:

- How do physical properties, in the form of potential plantable space, house age and length of residence, together with residential property owners' perceptions of the ecosystem services supplied by trees, affect the abundance of trees on privately owned land? And which factors influence the tree owner's decision to remove or plant trees?

2. Methods

2.1. Study site and sampling method

The city of Malmö (55°36′21″N 13°02′09″E) is the third largest city in Sweden, with 338 230 inhabitants (SCB, 2020). It is located in the temperate vegetation zone, on the southern Swedish agricultural plains, a region with overall fertile soils and mean precipitation of 600 mm/year (SMHI, 2020). The city occupies an area of 8105 ha, of which

1133 ha are classified as *small housing units*, the term used in national statistics for detached or semi-detached single-household units (Statistics Sweden, 2019).

Using publicly available property information provided by Malmö city authority, small housing units in the city were identified for this study (Fig. 1). The sampling design used a fishnet grid with 290m × 290m cell dimensions. Within each cell grid, a random point was selected using ESRI ArcMap 10.8 (ESRI, 2020). From the total residential area, 137 points representing small housing units were selected (Fig. 2). None of the properties included in the survey were vacant or leased to tenants, providing a basis for establishing a direct relationship between the individual owners and their management actions regarding residential urban trees.

The 137 selected households were twice notified in advance, in order to gain their consent or record their refusal to participate in the study. The first communication introduced respondents to the study and gave an estimated date for a visit with a tree inventory and questionnaire-based survey. The second communication specified the date and time of the visit and gave additional details, including contact information for re-scheduling if necessary.

2.2. Tree inventory

In September and November 2018, the residential properties included in the study were visited. All trees and woody plants present on the property were recorded, trunk diameter at breast height (DBH) was measured with a tape measure and the plant species present were identified. The DBH threshold for the inventory was set at 5 cm. If a tree or shrub had multiple stems and the point of pith separation was above ground, DBH measurements were made on up to five branches per tree (i-Tree User's manual, 2020). The measured DBH values, along with date and point identification number, were recorded in a plot inventory paper form and later transcribed into an Excel spreadsheet (Microsoft Excel, 2016).

2.3. Property owner survey

During the visits, a survey was conducted of the residential property owners to identify the ecosystem services they associated with trees and their management decisions on their own trees. A total of 21 questions were included in the survey, covering: general information (years of residence, gender, age, education level and house age); management actions regarding trees (future and past planting or removal); likelihood of adding other features to the outdoor space; and tree-related interactions with the local government. Survey answers were recorded by the owner using a tablet computer, or via an online form (Google form) sent later to the owner. The field staff verbally confirmed that all the respondents were property owners (or co-owners).

In total, 99 surveys paired with full inventories of residential plots were completed, out of a total of 137 households invited to participate in the study, giving a response rate of 72.3 %.

2.3.1. Tree benefits

To assess the property owner's understanding of ecosystem services, we used the open-end survey question: *What benefits do you associate with trees?* Before this question was posed, respondents received no

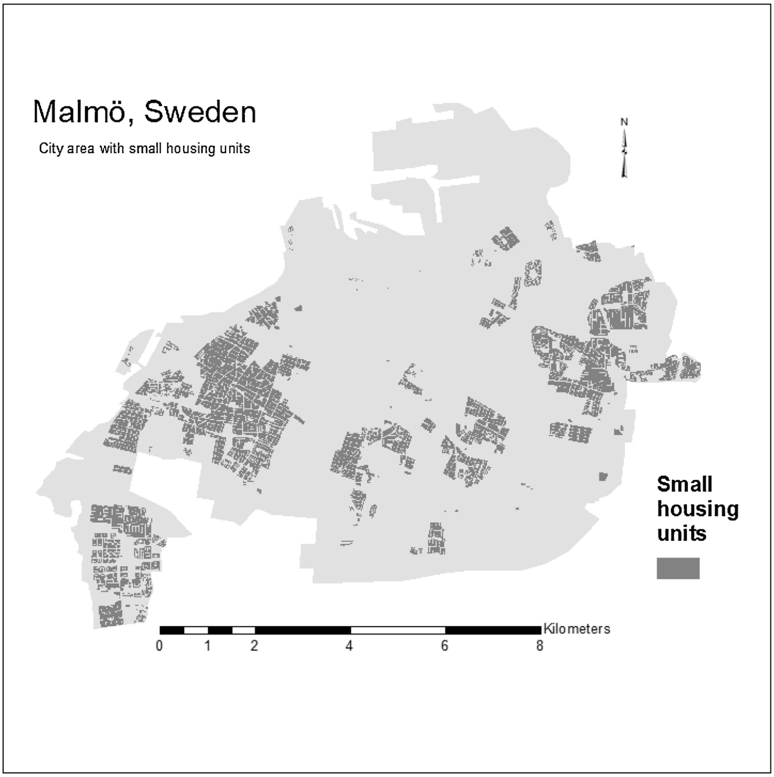

Fig. 1. Map of the study site, the city of Malmö, Sweden, showing total city area and the small housing units surveyed in this study.

Fig. 2. Example of a point in satellite imagery that coincided with a small housing unit within the borders of the city of Malmö.

indication of the purpose of the survey and potential benefits of trees were not discussed. If respondents could not list any benefits (or simply did not want to answer the question), the answer field was left blank.

Based on the responses received to this question, we classified the participating residential property owners into four different groups:

1 Utilitarian (respondents who mentioned utilitarian benefits provided by trees).
2 Aesthetic (respondents who mentioned aesthetic benefits of trees).
3 Mixed (respondents who mentioned utilitarian and aesthetic benefits of trees).
4 None (respondents who gave no answer and possibly do not associate trees with any benefits).

2.3.2. *Tree removal and tree planting*

As a part of the survey, the following two questions on tree removal and tree planting were posed:

- Have you planted any trees in the past five years? (yes/no)
- Have you removed any trees in the past five years? (yes/no).

If the answer to the latter question was yes, the respondent was asked to select the reason for removal from among pre-listed alternatives or state it in a free text field. The reason for providing pre-listed alternatives was to enable comparison of the results with those in previous studies by e.g. Wiström et al. (2016), (Hauer and Peterson, 2016) and Delshammar et al. (2015). The alternatives provided were:

- Tree mortality
- Lack of maintenance
- Neighbour complaint
- Poor vitality
- Improper growing site
- Risk
- Disease
- Infrastructure damage
- Traffic damage
- Shading
- Wind damage.
- Other (in free text format).*

*The authors reviewed the responses and all four answers could be classified as inappropriate growing site, since they included statements such as: "the tree was too large" and "the trees were planted too densely".

2.4. *Analysis and modelling*

All statistical analyses were performed in R (RStudio, 2020), using the packages "MASS", "dplyr", "car" and "tidyverse", with a significance level of $p < 0.05$. Missing values were treated by dropping observations in modelling. Descriptive statistics were calculated for the survey responses (basal area, PPS) using R and Excel. Statistical modelling was performed using the main measured parameters as response and explanatory variables.

2.4.1. *Response variables in statistical modelling*

The extent of regulating ecosystem services provided by trees (e.g. carbon storage, water uptake, air pollution removal) is positively related to tree size or, more accurately, leaf biomass per unit tree crown volume (Nowak et al., 2006, 2013). Studies have found a strong relationship between diameter at breast height (DBH) and crown volume (Troxel et al., 2013; Pretzsch et al., 2015). Indicators of tree abundance at areal unit are therefore better expressed as a function of DBH, rather than number of individual trees, since there is large variation between individual trees in their ability to produce ecosystem services. Basing tree abundance indicator on the number of trees would overestimate production of ecosystem services in residential plots with a large number of small trees. Urban forestry models based on allometric equations are available to predict growth of urban trees for management and maintenance and can estimate the provision of regulating ecosystem services (Nowak et al., 2001). These equations are widely used by local governments and individuals. In this study, basal area of the trees and shrubs was used as a proxy for the amount of ecosystem services provided. To map changes in the private tree population, survey responses to the questions of whether trees had been planted or removed during the past five years were used as binary response variables.

The basal area of trees (m^2/ha) in each residential plot was calculated as the sum of area occupied by tree stems per unit area of the property. Potential plantable space (PPS) was calculated as residential plot area minus building footprint.

2.4.2. Explanatory variables in statistical modelling

Information on the spatial geometry and building footprint of residential plots in Sweden is in the public domain and was obtained from the city department for property and streets. Although there were some constraints for individual properties, PPS was derived using publicly available information from the city of Malmö geodatabase, by deducting building footprint from individual residential plot area using ArcMap (ESRI, 2020). Tree age is strongly related to time since property construction (Lowry et al., 2011), and was determined from the questionnaire responses, as were house age and years of residence at the property. These three factors were later used as explanatory variables for tree abundance. Only three of the four groups of property owners classified in terms of perceived tree benefit types were included in the analysis (*Utilitarian*, *Mixed* and *None*), as the *Aesthetics* group was very small (n = 3) and was included in the *Mixed* group. Running the models without the Aesthetics groups did not affect final model selections and their goodness of fit.

2.4.3. Modelling approach

To find the best model describing the relationship between basal area, removal of trees, planting of trees and our explanatory variables of interest (including their two-way interactions), the following approach was used: First, we used stepwise variable selection with minimisation of Akaike information criterion with both forward and backward selection. Prior to model inclusion, explanatory variables were tested for inter-correlations, to avoid model inflation or strongly skewed groupings in relation to class variables. Since the automated stepwise procedure can in some cases create spurious results, manual model selection following a top-down strategy (Zuur et al., 2009) was used in parallel, starting with a full beyond-optimal model and then dropping non-significant explanatory variables. If the approaches gave different final models, these were compared using likelihood ratio tests. The final model was then tested against a null model using a likelihood ratio test and the assumptions in the model were verified by plotting the residuals from the model following the approach of Zuur et al. (2009). The final model was used to obtain estimated variables and related Type II ANOVA and deviance tables.

2.4.4. Modelling basal area

Basal area in m^2/ha was used as a numerical response variable in general linear modelling, using the *lm* function in R (RStudio, 2020). Explanatory variables were potential planting space (numerical), house age (numerical), years of residence (numerical) and perceived tree benefit type (class with three levels), including their two-way interactions.

2.4.5. Modelling tree planting and removal

Survey responses on tree planting and removal in the past five years were modelled as binary responses using a generalised linear model with logit as link function, using the function "glm". Explanatory variables were potential planting space (numerical), house age (numerical), years of residence (numerical) and perceived tree benefit type (class with three levels), including their two-way interactions. In addition to plotting residuals to check assumptions, the final models were tested for over-dispersion.

3. Results

3.1. Descriptive summary of respondents

The mean age of the respondents was 58 years, which is similar to the average age of homeowners in Malmö (55 years) (SCB, 2020). In total, 70.8 % of the respondents had tertiary education (university degree). Mean duration of residence at the property was 19.8 years (range 0–73, SD = 16.2), while mean house age was 64.3 years (range 2–168, SD = 30.3) and mean PPS was 579.7 m^2 (range 101.2 to 1818.1 m^2, SD = 323.7).

3.1.1. Association of trees with ecosystem services

It was found that the majority of residents belonged to the *Utilitarian* group (43 %). A further 23 % were in the *Mixed* group and 34 % in the *None* group. Only 3% of property owners fell into the *Aesthetic* group. Table 1 shown all responses obtained translated from Swedish language.

3.2. Correlations to tree basal area

The final model for tree basal area included PPS, house age, respondent type (*Utilitarian*, *Mixed*, *None*) and the interaction between PPS and respondent attitude type. PPS and house age were found to be positively correlated with basal area, while respondent type as an individual variable did not show any significant correlations (Table 2). However, there was a significant interaction between PPS and respondent type. Re-running the analysis with only two groups, i.e. those associating benefits with trees (*Utilitarian* + *Mixed*) and the no answer group (*None*), or including the number of benefits mentioned per house owner as an explanatory variable in the model did not change the main results of the analysis. Thus, there was little evidence to suggest that property owners associating benefits with trees had more tree basal area on their property.

3.3. Correlations to tree planting and removal

Among the 99 respondents, 38 % reported having planted a tree in the past five years. The final model (Chisq = 6.9224, p = 0.009) explaining tree planting included years of residence and no other explanatory variable tested (e.g. PPS, perceived benefits group, house

Table 1
Respondent types based on perceived ecosystem services associated with trees, categorised into four attitude types. Examples of responses and how they were classified together are shown, with the total number and percentages of each respondent type.

Respondent type	Response to the question: "What benefits do you associate with trees?"	Number and percentage of total respondents (n = 99)
Aesthetic	Colour richness, lush appearance, blossoming, beautification, enjoyment, aesthetically appealing, decorative purpose, natural appearance.	3 (3%)
Utilitarian	Oxygen production, carbon storage, water uptake, pollinator species, shading, fruit production, animal habitat, compost production, pollution removal, counteracting climate change, clean air, noise dampening, sight concealment, weather protection, wind protection, sheltering.	43 (43 %)
Mixed	Benefits from both the aesthetics and utilitarian categories.	20 (20 %)
None	No benefits listed or question left unanswered.	34 (34 %)
	Total	99 (100 %)

Table 2
Explanatory variables for basal area, where PPS is potential plantable space and residential property owners (n = 99) are grouped, based on perceived benefits of trees, as Mixed (M), None (N) and Utilitarian U).

	Coefficients		ANOVA table Type II test				
Variable	Estimate	StdError	SumSq	Df	F-value	Pr(>F)	
PPS	0.0015	0.0027	81.58	1	5.7023	0.0191	*
House age	0.0367	0.0130	113.96	1	7.9657	0.0059	**
Mixed group (M)			6.70	2	0.2343	0.7916	ns
No answer group (N)	3.0986	2.2564					
Utilitarian group (U)	1.5929	2.1553					
PPS x (M)			125.05	2	4.3705	0.0155	*
PPS x (N)	0.0063	0.0034					
PPS x (U)	0.0022	0.0034					
Residuals			1244.67	87			

age). This gave the following final model, with SE in brackets: logit (Planting) = 0.2781(0.340) - 0.0369(0.015) x Years of residence. Since log odds are less intuitive than probabilities, the negative relationship between planting trees in the past five years and years of residence is visualised in Fig. 3 using predicted probabilities derived from the final model including 95 % confidence intervals. As an example, after 20 years of residence the predicted probability of planting was significantly below 0.5, while after 70 years of residence it was below 0.3 (Fig. 3).

Among the 99 respondents, 47 % reported that they had removed tree/s during the past five years. No significant model or explanatory variable was found to be associated with tree removal. When comparing the reasons for removal with those identified in three previous studies (Delshammar et al., 2015; Hauer and Peterson, 2016; Wiström et al., 2016), some similarities were found. For example, a tree showing poor vitality or dying was a common reason for removal in both the present survey of residential property owners (cited by 18.6 %), and in Swedish municipalities (Wiström et al., 2016) (26.7 %) and in the survey by Hauer & Peterson (2014) (46 %). The results were also similar for risk, disease and lack of maintenance as reasons for tree removal. However, there was a discrepancy for the parameter *Inappropriate growing site*, which 20.3 % of our respondents and 22 % of respondents in Wiström et al. (2016) cited as a reason for tree removal, but which was not mentioned in complaints to municipalities analysed by Delshammar et al. (2015). Receiving complaints was not cited as a reason for tree removal in the present study, compared with 6% in Wiström et al. (2016) (Table 3).

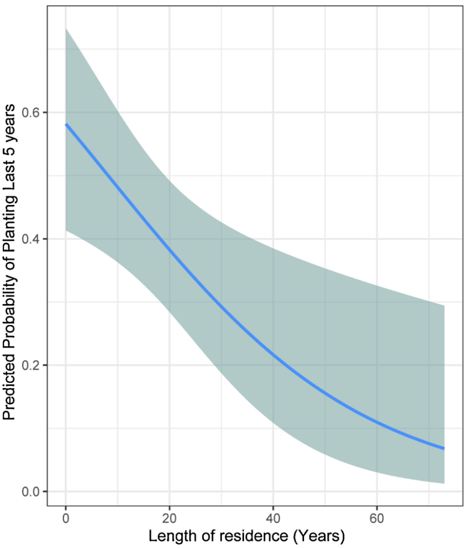

Fig. 3. Predicted probability, with 95 % confidence intervals, of tree planting by residential property owners in the past five years in relation to years of residence at the property Values shown are predicted from the logistic model of planting.

4. Discussion

As part of wider international efforts aligned with the United Nations Sustainable Development Goals (SDGs) in order to make urban areas more liveable (UN, 2014), the city of Malmö has a tree management plan with goals and objectives related to urban tree population specifically aimed at enhancement of regulating ecosystem services (2017). To achieve the desired goals and objectives, the actions taken by the city need to extend to the private tree population, as residential trees represent a significant proportion of the total urban tree population (Conway, 2016). Since ecosystem services materialise decades after tree planting (Maco and McPherson, 2003), understanding the small-scale dynamics in tree planting and removal in the private tree population is essential for creating a sustainable and liveable city. The results of the present study provide a better understanding of the link between tree

Table 3
Reasons cited for removal of residential urban trees in this study and in previous studies by Wiström et al. (2016) (based on a survey of Swedish local municipalities and answered by public servants), Delshammar et al. (2015) (compiled from complaints from residents received by various Swedish local governments regarding urban trees) and Hauer & Peterson (2014 (based on a survey of US communities and answered by public servants).

Reason for removal	This study	Wiström et al. (2016)[a]	Delshammar et al. (2015)	Hauer and Peterson (2016)
Complaint from resident	0	6%		
Lack of maintenance	1.0 %	1.2 %		
Poor vitality or dead	18.3 %	26.7 %		46.0 %
Inappropriate growing site	20.3 %[b]	0.0 %	22 %[c]	
Construction	4.1 %	5.0 %		8.6 %[d]
Risk	8.3 %	13.0 %	5%	12.3 %
Disease	7.1 %	11.8 %	10 %	11.9 %
Infrastructure damage	5.1 %	0.6 %	5%	5.0 %
Wind damage	5.1 %	11.2 %		9.1 %[e]
Damage to traffic	0.0 %	0.6 %		
Other	1.0 %	0.0 %		
Shading	3.1 %		3%	

[a] Listed as 'very common reasons for tree removal'.
[b] Too large, too close together etc.
[c] Obstructing roads and pavements, concealing traffic signs etc.
[d] Damage to sidewalk.
[e] Storm damage.

and shrub abundance on private residential properties and the attitudes, actions and resources of the property owners. By assessing potential relationships between tree abundance and various property-level factors, we were able to identify areas where urban tree management efforts should be focused in order to achieve sustainability goals in tree management for the city of Malmö. We also examined some general factors behind residential tree management actions.

There were no statistically significant differences between the different groups of residential property owners identified based on their perceptions of trees. Tree abundance for the group that associated trees with utilitarian benefits did not improve with increasing PPS, showing that tree-positive views did not lead to higher tree abundance. Our results thereby differ from those of Ives and Kendal (2014), who found that that positive associations resulted in positive outcomes, and Guo et al. (2019), who identified aesthetics as the main driving force behind individual tree management actions. Additionally, the combination of selected social variables with biophysical variables did not result in better prediction of tree abundance in the studied case, in contrast to previous research (Luck et al., 2009). However, our results are in line with findings by Kirkpatrick et al. (2012) that even people described as "tree-haters" do not live in a tree-averse way when comparing the amount of trees on their property. Similar findings have been made in a study in Scotland, where differences in attitudes were not reflected in degree of garden care or structural complexity of gardens (Hitchmough and Bonugli, 1997).

The strongest positive predictor of tree and shrub abundance was found to be house age, reflecting empirically the natural fact that trees need time to mature and reach peak production of ecosystem services (Lowry et al., 2011). Similarly to previous research (Boone et al., 2009), we found that current urban vegetation characteristics are partly reflected by past residents. What makes our findings interesting is that the changes over time occurred with little to no interference from local government, apart from urban planning decisions in the initial construction phase. By now, the trees present at these properties have matured and are more susceptible to pathogens and declining vitality. We suggest that future residential development plans for urban infill and re-development should place particular emphasis on retaining existing trees, as opposed to relying on replacement of trees by residents themselves. Local detailed plans already allow for special protection of trees within biotope protection measures, but we recommend that this be expanded to include a larger proportion of the older tree population.

The other significant factor for tree and shrub abundance was PPS, indicating the need for allowing space for residential property owners to plant trees. Previous studies using remote sensing technology to identify potential tree planting sites found that, unsurprisingly, the majority of suitable sites were in predominantly residential areas (Wu et al., 2008). With increased home size and other home extensions, individual households can severely limit the potential future tree canopy cover (Lee et al., 2017), replacing it with impermeable surfaces. Implementing tree protection ordinances and limiting the building footprint per plot through local planning legislation are possible measures to consider, especially since public support for such policies is reported to be high (Conway and Bang, 2014). However, these measures, although logical, are still somewhat problematic for the city of Malmö, which has strongly opted for densification instead of urban sprawl (2020). Densification may have some environmental advantages, but it limits the amount of trees that can be grown in a city, as clearly shown in this study.

Based on the finding that around 38 % of respondents had planted a tree in the past five years, the best-fitting explanatory model for predicted planting was years of residence, while none of the other explanatory variables (e.g. PPS, perceived benefits group, house age, age of residents) showed any significant correlation with tree planting (Table 2). The predicted probability of tree planting during the past five years decreased with years of residence at the property across all other aspects (Fig. 3). While this was surprising, some factors may influence why trees are primarily planted during the first years of an owner's residence in a house. For example, property owners might show a higher likelihood to invest in their newly acquired property in order to improve the appearance or the neighbourhood (Guo et al., 2019). With the passage of time, property owners might become less interested in committing to planting a new tree, which generally requires more care in the establishment phase (Roman et al., 2014). After this initial phase, we suspect that residents had fully utilised their planting space, according to individual perceptions, or felt that their preferences concerning tree abundance had been met.

Another factor that influenced tree abundance was tree mortality and removal. Monitoring studies on urban tree mortality suggest that trees die as a result of various interactive factors, but little is known of mortality rates for residential trees (Hilbert et al., 2019). A study using a field survey and image interpretation approach estimated that yearly mortality can reach 4% among shade trees (Ko et al., 2015). Other research generally suggests that predictions of residential tree survival tend to be optimistic (Roman et al., 2014). On analysing the rate of tree removal reported in this study, no significant model or significant explanatory variable was found, suggesting that removals happen indiscriminately across variables recorded in the study. The most common reason cited for tree removal was *Inappropriate growing site* (20.3 % of respondents). In contrast, other studies have found aesthetics and functionality of private space to be the main reasons for tree removal on private properties (Kirkpatrick et al., 2013). This discrepancy could be due to several reasons, the most obvious being that aesthetic reasons was not given as one of the pre-listed alternatives. However, none of the answers obtained in the open free text box listed aesthetics. Another reason might be that the residents included aesthetics in the *Inappropriate growing site* option. Even so, since *Inappropriate growing site* was the dominant reason for removing trees on private land in Malmö, good site and species selection can be expected to play a key role in the survival of residential trees (Roman et al., 2015), especially if such site and species selection also takes into account aesthetic reasons. In an analysis of complaints sent to local governments (Delshammar et al., 2015), site selection was identified as the number one issue causing conflicts in Swedish cities, explaining 22 % of total complaints reviewed (Table 3). There was good agreement between this general finding and the actions taken by private tree owners surveyed in the present study. Excluding implementation of additional regulatory measures, efforts to protect and prevent removal of healthy trees in the future should focus on promoting better site and species selection for residential areas today. As natural tree regeneration is rare in residential areas of Malmö, focusing on proper site and species selection would ensure long-term tree survivability and retention of mature trees, enabling them to reach peak production of regulatory ecosystem services. This recommendation, however, does not mean that all vegetation types should follow same set of site-selection criteria in order to reduce the total woody vegetation cover across residential areas.

5. Conclusions

This survey of private tree owners in the city of Malmö, Sweden, showed that positive associations of residential urban trees with benefits did not necessarily result in greater tree and shrub abundance on individual properties. Instead, house age and PPS were identified as being significantly related to shrub and tree abundance, which might indicate that contemporary dense building preferences are problematic when it comes to supporting privately owned trees for ecosystem services. The likelihood of planting a tree was found to decrease with years of residence at a property. The most common reason for removing trees was poor planting site selection, which indicates that providing practical information on appropriate site/species selection could reduce the risk of urban tree removal.

Individuals' attitudes are often assumed to be the core driver of their decision making, so our results may dispel some of the core beliefs about private urban tree retention and stewardship. Swedish authorities are limited in their ability to support local initiatives, so must rely primarily on dissemination of knowledge. Based on our results, knowledge dissemination should focus on more practical tree care in the form of selection of suitable tree species for different sites and performance of maintenance actions that might mitigate later problems. This type of knowledge could yield better results than merely educating urban residents about the various benefits of trees. It would also help residential property owners formulate their preferences with regard to practical care and improve their aptitude for planting, maintaining and retaining valuable urban trees and shrubs.

Author statement on the contributions to the paper

Blaz Klobucar: Conceptualization, methodology, data curation, writing-original draft preparation, vizualization, revising the manuscript, statistical analysis.

Märit Jansson: Conceptualization, writing-reviewing and editing.

Björn Wiström: Conceptualization, methodology, writing-reviewing and editing, statistical analysis, visualization

Johan Östberg: Conceptualization, methodology, visualization, writing-reviewing and editing.

Declaration of Competing Interest

The authors declared no conflict of interest.

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Appendix A. Supplementary data

Supplementary material related to this article can be found, in the online version, at doi:https://doi.org/10.1016/j.ufug.2021.127118.

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Residential urban trees can represent over half of the total number of trees in cities, yet they are rarely part of the urban forest assessments in cities. This thesis studies multi-disciplinary approaches that are required to give an accurate representation of the total urban forest population for the local government, including: governance analysis, field assessments, sampling design, remote sensing and resident surveys.

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