



# Making Trees Visible

Legislation, Policy and LiDAR in Spatial Planning

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— Legislation, Policy and LiDAR in Spatial Planning

*Att synliggöra träd — Lagstiftning, policy och LiDAR i fysisk planering*

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# Abstract

Trees provide irreplaceable ecosystem services, yet they are increasingly threatened by urban development. In response, the legally binding EU Nature Restoration Law, adopted in 2024, mandates no net loss of urban tree canopy cover at the national level by 2030. To comply with these directives and preserve existing trees, a new Swedish standard (SS 990002:2025) requires a physical root protection zone extending four meters from the tree's outermost branches during construction work. Securing this substantial physical space requires establishing tree protection plans and actively moving infrastructure footprints away from trees during the earliest planning stages.

However, today's planning, design, and construction drawings often rely on base maps that represent trees as dimensionless points. This causes an architectural *lock-in effect*, where developments are finalized before a tree's actual physical dimensions are established, leading to inevitable canopy loss. To address this, this thesis explores how landscape architects and urban planners can efficiently detect legally protected trees before this lock-in occurs.

This thesis investigates remote sensing as a solution, combining interviews, literature review and a technical case study in Helsingborg, Sweden. The study evaluates the capacity of high-resolution Airborne Laser Scanning point clouds to act as an early spatial filter. It assesses raster-based **vwf()** and point-cloud-based **li2012()** detection algorithms, alongside a method to estimate diameter at breast height (DBH) from LiDAR-derived crown areas to screen for legally protected trees.

The interview study revealed that despite legal frameworks, trees are systematically deprioritized due to the protracted planning process, conflicting utility interests, and a lack of early 3D spatial representation. The technical application demonstrated that LiDAR is a viable large-scale screening tool. The **vwf()** method achieved an F-score of 0.813 (86.0% recall, 77.1% precision), while the **li2012()** method achieved an F-score of 0.804 (95.3% recall, 69.5% precision), though both methods struggled with over- and under-segmenting complex broadleaved canopies. The tool proved robust at identifying larger trees (DBH >40 cm) but detected no *Trees Worthy of Special Protection* (DBH >100 cm), despite field-validated specimens on site. These results point to the oversegmentation of multi-stemmed individuals and the limitations of crown-area-based allometric proxies for mature broadleaved species. This highlights the need for site- and species-specific models or deep learning approaches capable of handling irregular, multi-peaked canopies.

Automated LiDAR-based detection cannot replace traditional field inventories, but it can function as a strategic early warning system. By translating point clouds into objective spatial constraints at the beginning of a project, planners can proactively secure the mandatory four-meter protection zones required. Ultimately, this facilitates a spatial planning process where mature trees are treated as foundational green infrastructure, prioritized as both ecological and economic assets.

# Preface and Acknowledgements

I've always been interested in trees and greenery. Growing up in Malmö, I grew up in one of Sweden's "grayest" cities. But despite some unfortunate publicity over the years, Malmö plants, researches, and wants to be greener. In the last few years I've visited cities in Europe and North America with a new mindset; Not *'how green is this city?'* but *'how is this city preparing for climate change, is it gearing up or not?'*. Furthermore, that mindset later led me to wonder;

*How can the people who build cities fail to see mature trees as vital assets?*

*Why are we willing to pay millions to plant new trees but reluctant to spend the same amount to save an existing one?*

This spring I discovered that these questions do not have simple answers. During my education I have heard that a planning process takes ten years. I have shrugged and thought 'That's funny', but I haven't grasped the complexity of the policy and politics that steer spatial planning in a city. During my thesis work I have been allowed to take part in meetings to experience the planning process, but I still can't fully grasp it. Understanding how trees gradually disappear in the planning process turned out to be a larger task than I had expected, and a different one than I had imagined when I started.

I came in contact with Hanna Norberg who works as an urban planner at Helsingborgs Stad, a city where I've worked and where I know the engagement is high. She told me that the municipality had recently commissioned its first LiDAR-based canopy coverage map, and that the GIS team was beginning to explore individual tree segmentation. I remember thinking it could not be that hard, forestry has worked with this technology for decades.

I want to thank everyone who has helped me with this thesis. **Hanna Norberg** for introducing me to point cloud data and the range of what it can be used for. **Helsingborgs Stad** and their Detailed Planning Unit for welcoming me into their work and inviting me to talks and workshops throughout the writing period. My supervisor **Christopher Klich**, who has offered guidance, questioning, and good ideas at every meeting. **Everyone who participated in the interview study**: this work would simply not exist without you, and much of the literature review grew out of our conversations. **Kalle Ågren** at Trädkontoret, whose insight shaped the technical study. My friend **Viggo Trobäck**, who reviewed the code and helped me think through methodological alternatives. **My parents**, who have read every draft, however long and unfinished.

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*Saskia Skogh, Alnarp, May 2026*

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# Glossary

- 1 Area-Specific Plan**

A more detailed version of the vision presented in the comprehensive plan for a specific part of town, like the city center (Isaksson & Storbjörk, 2012).
- 2 Canopy Height Model (CHM)**

A digital raster map representing the height of vegetation above the ground surface. It is created by subtracting a Digital Terrain Model (DTM) from a Digital Surface Model (DSM).
- 3 Comprehensive plan**

A long-term vision for the whole municipality and provides guidance for decisions regarding the use of land and water areas and the use, development, and preservation of the built environment. (Isaksson & Storbjörk, 2012), (Persson 2013).
- 4 Environmental Assessment**

The environmental assessment must present the municipality's assessment of the potential environmental impacts of implementing the plan. It is the significant environmental impacts that must be identified, described, and assessed. (Isaksson & Storbjörk, 2012).
- 5 The Swedish Environmental Code**

Framework adopted by Sweden in 1999 that was developed by merging previous national resource legislation with the mandatory environmental standards of the European Union (Isaksson & Storbjörk, 2012).
- 6 Grid-search**

A systematic optimization method that tests all possible combinations of a specified set of parameters to find the most accurate model configuration.
- 7 Lantmäteriet - The Swedish Mapping, Cadastral and Land Registration Authority**

Is the government agency responsible for national geodata and mapping.
- 8 Länsstyrelsen - The County Administrative Board**

Is the regional government agency responsible for ensuring that national policies are implemented regionally, with a specific focus on environmental protection, land use planning, and nature conservation.
- 9 Li2012 () Algorithm**

Method for segmenting individual trees from a LiDAR point cloud. By taking advantage of the relative spacing between trees and using spacing thresholds (dt1, dt2, Zu, R, hmin) the method works top down including nearby points.
- 10 LiDAR, Light Detection and Ranging**

A remote sensing technology that uses laser pulses to measure distances to the Earth's surface, resulting in a highly accurate 3D point cloud.
- 11 Local Development Plan**

A detailed project plan for a specific area in which the land is divided into zones that regulate the placement of residential buildings or roads. This document is legally binding (Isaksson & Storbjörk, 2012).
- 12 MCWS, Marker-Controlled Watershed Segmentation**

An image processing algorithm used to delineate individual objects by.
- 13 The Swedish Planning and Building Act**

A framework that regulates land use and planning in Sweden (Isaksson & Storbjörk, 2012).
- 14 Point Cloud Registration**

The process of aligning and integrating multiple 3D point cloud datasets into a single coordinate system to ensure spatial accuracy.
- 15 Diameter at Breast Height (DBH)**

A measurement used in Forestry, describing the diameter of a tree trunk at a height of 1.3 meters above ground level (Östberg et al., 2015).
- 16 VWF, Variable Window Filter**

An algorithm used to identify treetops in a Canopy Height Model by using a search window that changes size based on the height of the vegetation.
- 17 VWF Intercept**

The constant value in the Variable Window Filter equation that defines the minimum search window size when vegetation height equals zero. A higher intercept prevents the algorithm from over-segmenting small branches or shrubs as individual trees.
- 18 VWF Slope**

The coefficient that determines how the search window grows as the height of the vegetation increases. Allowing the model to adapt to the wider crowns of mature trees.

# 1. Introduction: How Much for A Tree?

## 1.1 Background

In the world of economics and jurisdiction, everything must have a price. A tree that is damaged during the construction process often has a penance. A monetary value that reflects the damage to the trunk or roots. But the question is: can a monetary value capture the complexity of a tree's worth, or is that too narrow a measure?

*“For the woodcutter who was contracted to fell the trees the timber itself is the only thing of value. But what was the value to Malmö's municipal gardener, who expressly claims to want to conserve the city's mature trees? What can the ecologist, who works with green areas in the urban environment, tell us about the value of biological diversity? What is the value of a tree to a child who climbs it? Or for someone who just wants to stand beside it and feel its presence”*

(Gora and Bandolin 2015, back cover)

In their book, Monica Gora and Gunilla Bandolin emphasize that trees should not be seen as an obstacle in the planning process, but as an investment and a prerequisite for a functioning living environment. By putting a price on trees early in the process, a language that economists and decision-makers understand is created (Gora and Bandolin, 2015). In the fiction book *How much for a tree?* Gora and Bandolin tells the narrative of Gottorp Manor outside of Malmö which was a park with giant trees that were felled due to residential development in the area. The municipality could not buy the land since they had no use of the old house that was standing on the grounds. Therefore, even though the area was set as parkland in the local development plan, Gottorp was sold. After the trees were felled by the private buyer the municipality had to build a new park to replace the canopy cover that was lost. The construction of the new park equaled the purchase price of the original land. The new park was a third of the size of Gottorp and the trees planted on the site will probably never be as big as the old ones were. Even though Gora and Bandolin tell a fictional narrative, they are basing it on a true story. And that story tells the frustrating truths of many cases where politics and economics stand in the way of sustainable development.

Spatial planning often leads to the loss of established vegetation, costing us vital ecosystem services like stormwater infiltration, climate regulation, and biodiversity. Even when saving existing vegetation is a goal, standard efforts are often insufficient. While the new Swedish standard SS 990002:2025 mandates a protection zone extending four meters beyond a tree's outermost branches, current base maps used in planning and design often use simplified symbols that fail to show the true crown extent. This spatial inaccuracy frequently leads to a *lock-in effect* during early planning, where allowed placement of buildings and infrastructure are finalized before the tree's actual physical needs are secured.



**Figure 1.** "What is the value of a tree to a child who climbs it?" Kids climbing on a uprooted tree in Cathedral Grove, MacMillan Provincial Park, Vancouver Island. Photo: Skogh (2025)

Today's digital technology is evolving rapidly, with *remote sensing* and *urban digital twins* becoming standard municipal assets. Most municipalities in Sweden now have access to high-resolution airborne laser datasets. While traditionally used to extract measurements of roads and buildings, these tools hold high potential for landscape architecture. By analyzing laser data, we can efficiently estimate canopy cover, identify individual crown spreads, and monitor changes over time. However, urban planning is a field heavily governed by political and economic interests. Simply having access to the technology is not enough; professionals must know exactly what data to ask for and precisely when to ask for it.

Therefore, this thesis argues for the necessity of establishing a standard for tree mapping in the initial phases of spatial planning. Through strategic collaboration with GIS engineers to extract and analyze canopy data early in the process, landscape architects and urban planners can flag potential old-growth trees and motivate crucial field inventories before the architectural lock-in effect occurs.

This raises the question of whether existing spatial data, particularly high-resolution ALS point clouds, can be used earlier in the planning process to make trees visible as spatial constraints before design decisions become too difficult to revise.

## 1.2 Goals and Objectives

The objective of this study is to examine how point cloud data from high-resolution airborne laser scanning (ALS) can support tree inventories for conservation assessments in spatial planning. To meet this objective, the thesis combines three approaches: a literature review, semi-structured interviews, and a technical study. Together, these approaches identify the factors that influence tree preservation in spatial planning and evaluate how remote sensing data can be applied in this context from both academic and applied perspectives.

By applying tree detection and segmentation methods to a point cloud derived from high-resolution ALS data, the technical study seeks to understand the experience of working with specialized software and large datasets without prior experience. In doing so, it tests the feasibility of the interdisciplinary alliance through the analysis of known and unknown landscapes in peri-urban areas.

The overall purpose is to demonstrate why tree conservation must be integrated into spatial planning and to encourage collaborative work toward a more sustainable future.

## 1.3 Research Questions

- *What are the main factors that determine whether trees are preserved or not in spatial planning?*
- *How are trees mentioned and addressed in spatial planning and design processes today, and how does this ultimately affect their continued existence at the end of the construction process?*
- *How can point clouds retrieved from high resolution airborne laser scanning (ALS) be used in decision making regarding existing trees in spatial planning?*

## 1.4 Theoretical Framework

This thesis is situated within the field of urban forestry, an interdisciplinary field including landscape architecture, spatial planning, ecology, and forestry. Rather than approaching tree preservation from any single perspective, the study deliberately occupies the space between them. This approach recognizes that the conditions determining whether a tree survives spatial development depend on actors and decisions across all these fields. This positioning shapes both the scope of the literature engaged with and the way the empirical material is interpreted. By positioning the thesis within urban forestry, a core premise follows: mature trees constitute a form of green infrastructure whose ecological, social, and climatic value cannot be replicated by newly planted trees. The thesis does not seek to defend this premise, but rather to investigate the conditions under which it can be operationalised in spatial planning.

To reflect the interdisciplinary nature of urban forestry, the thesis adopts a Social-Ecological-Technical Systems (SETS) framework (McPhearson et al., 2016). This framework treats urban systems as emerging from the intersection of three interdependent dimensions: social (governance, institutions, professional practice), ecological (vegetation, biodiversity, ecosystem function and services), and technical (digital tools, data, infrastructure). The three sub-studies of this thesis map directly onto these dimensions. The interview study addresses the social dimension, investigating how professionals navigate the institutional conditions under which trees are protected or lost. The literature review addresses the ecological and regulatory dimension, examining the legal frameworks, policies, ecological values, and conservation criteria that determine which trees qualify for protection. Finally, the technical study addresses the technical dimension, testing how ALS-derived point clouds can support decision-making regarding existing vegetation. The central argument of the thesis is that tree preservation fails when these three dimensions are addressed in isolation, and that the proposed workflow, an early-stage screening tool integrated into rezoning applications, offers a way to bring them together. Furthermore, the mitigation hierarchy (Avoid → Minimise → Restore → Compensate; Mellin et al., 2021) informs the thesis by providing the structural logic for the planning process and clarifying why early action carries more weight than late compensation.

The thesis combines three bodies of source material reflecting this interdisciplinary positioning. Swedish and European legislation, policy, and standards provide the regulatory context for tree preservation. These includes the Swedish Environmental Code (SFS 1998:808), the Planning and Building Act (PBL, 2010:900), the Swedish standard SS 990002:2025 (SIS, 2025), the EU Nature Restoration Law (Regulation (EU) 2024/1991), and the European Green Deal (European Commission, 2019). Practical guidance is drawn from Swedish municipal practice and Trädkontoret's handbook for tree protection during construction (Bruhn et al., 2026). The technical perspective is informed by the long-standing tradition of remote sensing research in forestry, which has developed many of the methods now being adapted to urban contexts. Interviews with researchers at the University of British Columbia (UBC) in Vancouver, a research environment with leading expertise in forest remote sensing, provide a complementary external perspective on the technical methods tested.

# 1.5 Materials and Methods

*Three approaches were used to answer the research questions: a literature review, a thematically analysed semi-structured interview study, and a technical case study (See Fig. 2). The thesis examines the use of LiDAR data in municipalities and private companies as well as preservation of trees in context to planning and design.*

## 1.5.1 Literature Review

The literature review consisted mainly of scientific articles, scholarly books, reports and dissertations. Scientific articles were searched for using the search engines SLU Primo, Google Scholar, Science Direct and Research Gate in English. The search terms used were ‘LiDAR’, ‘remote sensing’, ‘point cloud’, ‘ecosystem’, ‘forest’, ‘vegetation’, ‘tree’, ‘segmentation’, ‘urban’, ‘peri-urban’, ‘landscape architecture’, ‘landscape’, ‘planning’.

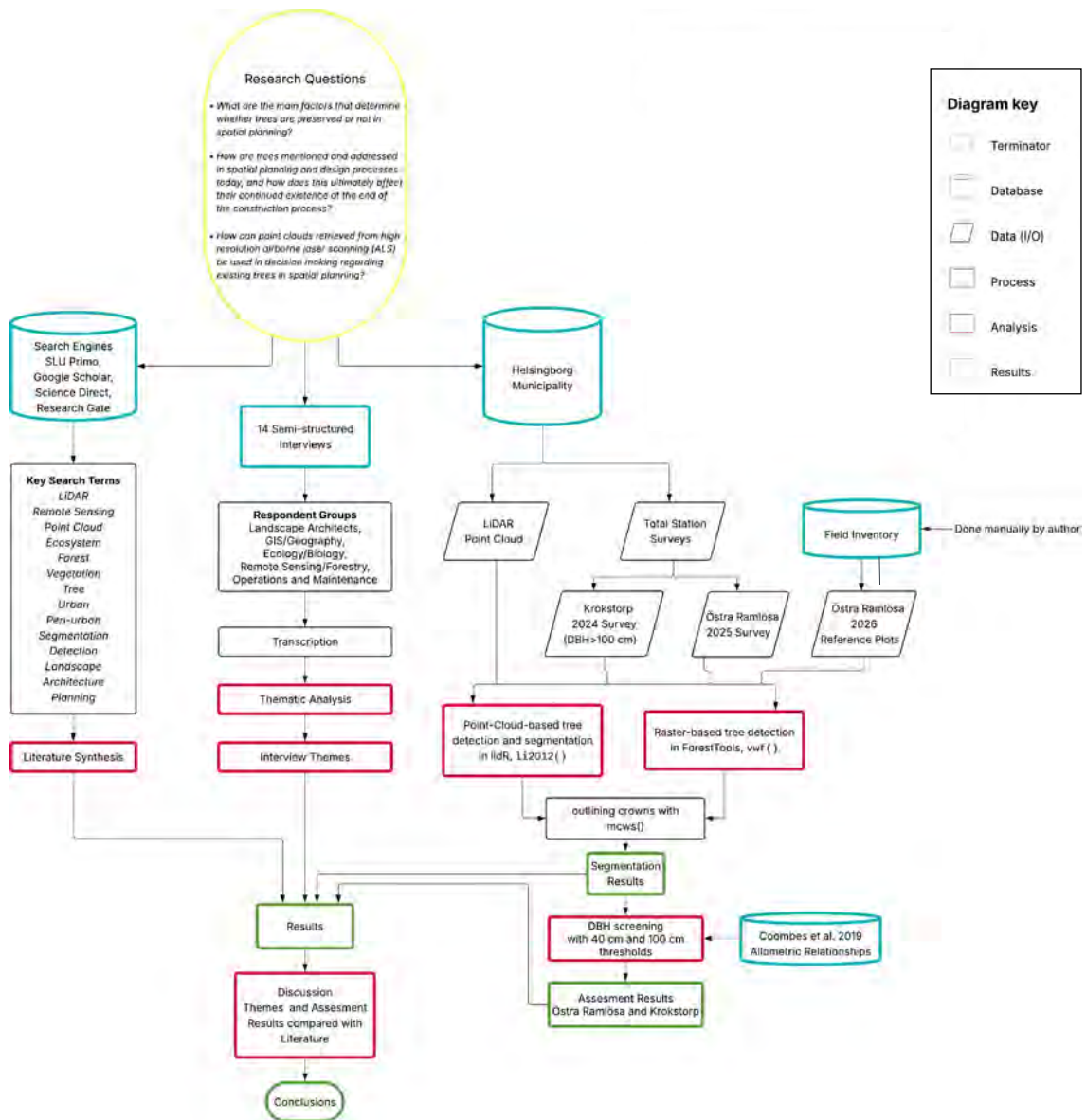
## 1.5.2 Interview study

The interview study consisted of 14 interviews lasting approximately 30 to 60 minutes, five of which were conducted on site and nine via online meetings. All respondents were given the opportunity to review the interview section and have consented to the publication of their names, personal information, and quotes. Respondents were selected to obtain as broad a picture as possible of everyone involved in or knowledgeable about tree protection in the planning- and construction process as well as the use of remote sensing in connection with tree inventory (See Table 1).

In total, seven of the fourteen interviewees (50%) are employed by municipal authorities, while the remaining seven (50%) work in the private sector or academia. The interviews were conducted with respondents based in Sweden and Canada.

The interviewees were asked a few set questions (see Appendix A), and then each interview was adapted with spontaneous follow-up questions to create a relaxed conversation, known as a semi-structured interview (Lantz, 1993). The interviews ended with an open question for an optional statement that each interviewee felt was relevant to the topic. During the interview, questions were asked and keywords and quotes were noted. The interviews were recorded and transcribed. The compilation was analyzed and general themes were highlighted. The themes were then presented in the results section and further analyzed by comparing them with the literature in the discussion section.

# Flowchart Explaining the Methodology of The Entire Study



**Figure 2:** The figure illustrates the methodology used to examine the study's research questions. Illustration: Skogh (2026)

# Information About the Interview Respondents

**Table 1:** The interview respondents were selected to ensure the broadest possible range of expertise regarding tree preservation in spatial planning. Source: Skogh (2026)

Name	Education	Job Title	Workplace at the time of the interview	Work experience (years)
Annika Kruuse	Master's degree and PhD in ecology - LU	Ecologist	City of Helsingborg <i>Comprehensive planning unit</i>	26
Hanna Norberg	Landscape Architecture Programme -SLU* & Manchester	Urban planner	City of Helsingborg <i>Detailed planning unit</i>	4
Jesper Krantz	Certified arborist - European Arboricultural Council (ECA)	Planning Manager Trees	City of Gothenburg <i>Operations and Maintenance Unit</i>	23
Johan Larsson	Bachelor's degree in horticultural engineering with a focus on design and master's thesis in biology - SLU	Urban Forest Strategist	City of Lund <i>Strategy Unit</i>	3
Kalle Ågren	Landscape Architecture Programme - SLU	Landscape architect	Trädkontoret	3
Linnéa Dahlén	Bachelor's degree in physical geography and master's degree in geomatics - LU**	Cartographer	City of Helsingborg <i>Detailed planning unit</i>	8
Martin Brattström	Landscape Architecture Programme - SLU	Landscape architect LAR/MSA	Edge	4
Nicholas Coops	Master's degree in cartography and PhD in remote sensing - Melbourne	Professor in remote sensing	UBC <i>Dep. of Forest Resources Management</i>	30
Nils Ekström	Landscape Architecture Programme - SLU	Landscape architect LAR/MSA	Liljewall	28
Ola Svensson	Studied archaeology and holds a master's degree in geographic information systems - LU	Technical surveyor	City of Lund <i>Digitalisation and development unit</i>	14
Rebecka Olsson	Landscape Architecture Programme - SLU	Landscape architect LAR/MSA	Sweco	11
Ryan Davidsson	Technician	Research Engineer, Biosystems and Technology	SLU	12
Sara Hultqvist	Bachelor's degree in urban planning and urban studies + 2 years of vocational training in GIS - MAU****	Geodata coordinator	City of Lund <i>Digitalization and development unit</i>	1
Yuhao Lu	Bachelor of Science in Forest Resource Management and PhD specialising in remote sensing in forestry - UBC***	Assistant Professor of Landscape Architecture	University of Manitoba <i>Dep. of Landscape Architecture</i>	3

\*SLU, Swedish University of Agricultural Science

\*\*LU, Lunds University

\*\*\*UBC, University of British Columbia

\*\*\*\*MAU, Malmö University

## Spatial Extent: Östra Ramlösa and Lussebäcken



**Figure 3:** Aerial view of the urban area of Helsingborg and its surrounding countryside. The white rectangle marks the Östra Ramlösa area and the blue line illustrates the stream Lussebäcken.  
Source: Google Earth Pro, © 2026 Maxar Technologies; Illustration: Skogh (2026)



## Trees in Östra Ramlösa

**Figure 4. (left)**

There are a number of valuable trees in Östra Ramlösa. The photo shows a field and scattered large broadleaf trees that provide valuable habitats.

Photo: Helsingborg 2020

**Figure 5. (bottom)**

The photo shows an areal image of Östra Ramlösa and the many tree-lined avenues that divide the fields.

Photo: Helsingborg 2019



### 1.5.3 Technical Study

The interview study highlighted the need for an early understanding of existing vegetation, particularly large trees, in areas subject to new local development plans. Simultaneously, the literature review identified promising tools for individual tree detection using point cloud data. Therefore, the technical case study was conducted to investigate how well-suited these tools are for Swedish peri-urban conditions. In addition, the site application explored how accessible the detection and segmentation methods are and how much prior knowledge is required to use them effectively and accurately in an urban planning context.

The technical case study was based on airborne laser scanning (ALS) data collected by Hexagon on behalf of Helsingborg municipality in 2025. The point cloud has a density of approximately 106.56 points per square meter. The study was conducted through a process involving remote sensing analysis, field validation, and algorithmic optimization. The objective was to test different methodologies for tree detection and segmentation to evaluate the possibility of generating results that align with the structural representativeness of the vegetation in the study site Östra Ramlösa.

Östra Ramlösa is located in the eastern suburbs of Helsingborg, Sweden (See Fig. 3). The area covers approximately 230 hectares, and represents a small but significant fragment of the approximately 430,000 hectares of agricultural land in Scania currently at risk of urban encroachment. While the area currently consists of agricultural land, a new comprehensive plan was formally adopted by the municipality in 2024. This plan identifies the site for future development as a new residential community and a regional hospital complex (See Appendix B). The vegetation in the area primarily consists of mixed deciduous broad-leaved trees and shrubs, scattered along the sides of the agricultural fields (See Fig. 4-5). One of the main goals of this plan is to develop Östra Ramlösa around existing landscape structures such as the stream Lussebäcken and the large oaks that grow along it. The objective and nature of this plan makes it a suitable site for this study. The algorithmic analysis was conducted using two individual tree detection methods implemented in R: a raster-based approach using a canopy height model, and a point cloud-based approach operating directly on the 3D data. Both methods are described in section 2.8.

## Field Surveys: Östra Ramlösa & Krokstorp



**Figure 6:** Aerial overview of Östra Ramlösa and surrounding areas. White squares indicate the two reference plots visited by the author on 5 March 2026. Cyan rectangles indicate field surveys conducted by Helsingborg stad. The Östra Ramlösa field survey was conducted by Helsingborgs stad on 6 February 2025; the Krokstorp field survey was conducted by Helsingborgs stad on 29 October 2024. The present study examines the Z-shaped extent of the Östra Ramlösa survey area only. Source: Google Earth Pro, © 2026 Maxar Technologies (accessed 1 April 2026)

### 1.5.3.1 Field Inventory

Two reference plots were selected within the study area to represent the dominant vegetation structures present in Östra Ramlösa: Plot 1, containing seven large trees standing in close proximity with understory vegetation, and Plot 2, containing four large trees in a more open configuration (see Fig. 6). The plots were visited on the 5th of March 2026 and physical inspections were conducted at each plot to establish a ground truth tree count which then served as the starting base for evaluating the accuracy of the LiDAR-based tree detection and segmentation. The inventory included species: Alder (*Alnus glutinosa*), Ash (*Fraxinus excelsior*), Birch (*Betula pendula*), Oak (*Quercus robur*) and Willow (*Salix cvs.*).

In addition to the reference plots, two separate field surveys conducted by the City of Helsingborg were used. These inventories were carried out by an urban planner and land surveyor through visual inspection to determine species and value, a total station for trunk location, and a tape measure for DBH. The first survey was conducted on the 6th of February 2025 as part of the local development plan of Östra Ramlösa and documented the trunk positions of over a hundred trees. This specific survey included both large free-standing trees and smaller clustered trees along watercourse Lussebäcken. To narrow the scope of this study, only the portion of the survey that included the larger trees was used, while clusters of closely spaced smaller trees were excluded (See Fig. 6). This distinction led to the survey containing 43 individually identified trees including species: Alder (*Alnus glutinosa*), Ash (*Fraxinus excelsior*), Aspen (*Populus Tremula*), Birch (*Betula pendula*), Cherry (*Prunus cvs.*) and Oak (*Quercus robur*). The survey including the 43 larger trees served as the primary spatial reference for the accuracy assessment of the LiDAR-based tree detection.

The second survey was conducted on the 29th of October 2024, 5 kilometers from Östra Ramlösa as a part of a local development plan regarding an area called Krokstorp in Påarp, Helsingborg (See Fig. 6). This survey included several trees with very high conservation value according to the Swedish Environmental Protection Agency's national action strategy, *Trees Worthy of Special Protection* (Naturvårdsverket, 2012b). The purpose of testing the segmentation method in the Krokstorp area at the end of the study was to determine, without specifically training the algorithm to identify trees particularly worthy of protection, whether it was possible to obtain results in an area where such trees were certainly present.

### 1.5.3.2 Raster Based Tree Detection and Segmentation in ForestTools

The following analysis was performed on the ALS data collected by Hexagon on behalf of Helsingborg municipality in 2025 (see section 1.5.3). Tree detection and segmentation from raster data was performed using the variable window filter algorithm `vwf()`<sup>1</sup> (Popescu & Wynne, 2004) (see Fig. 7 and Appendix C) implemented in the ForestTools library in R (Plowright, 2018). The algorithm applies a moving local maximum filter over a Canopy Height Model (CHM), where the search window radius scales linearly with canopy height ( $x$ ) according to a user-defined window function (see section 2.8.1.1):

$$f(x) = slope^2 \times x + intercept^3$$

All point clouds were height-normalised using the algorithm `normalize_height()` (Roussel, 2026) in the lidR library in R, then filtered to retain returns between 0 and 50m above ground. A CHM was then generated from the normalised point cloud using the algorithm `pitfree()` (Khosravipour et al., 2014) in the lidR library at 0.5m resolution with a subcircle parameter of 0.2m to reduce pitting artefacts.

The `vwf()` detection method was first applied to the two reference plots (Östra Ramlösa, visited 26-03-05) using default thresholds to determine how well the default settings identified the vegetation structures:

Default: `vwf({0.05 * x + 0.6})` and `minHeight = 2m`

Following the treetop detection, crown boundaries were delineated using the *marker-controlled watershed segmentation algorithm* `mcws()` (Plowright, 2018), which is also implemented in the ForestTools library. The `mcws()` algorithm utilizes the treetops identified by `vwf()` as markers to segment the CHM into individual tree crowns (see section 2.8.1.2). Segmenting the crowns was a necessary step not only to visually evaluate instances of under- and over-segmentation but also to enable the subsequent extraction of crown area metrics used for estimating conservation value.

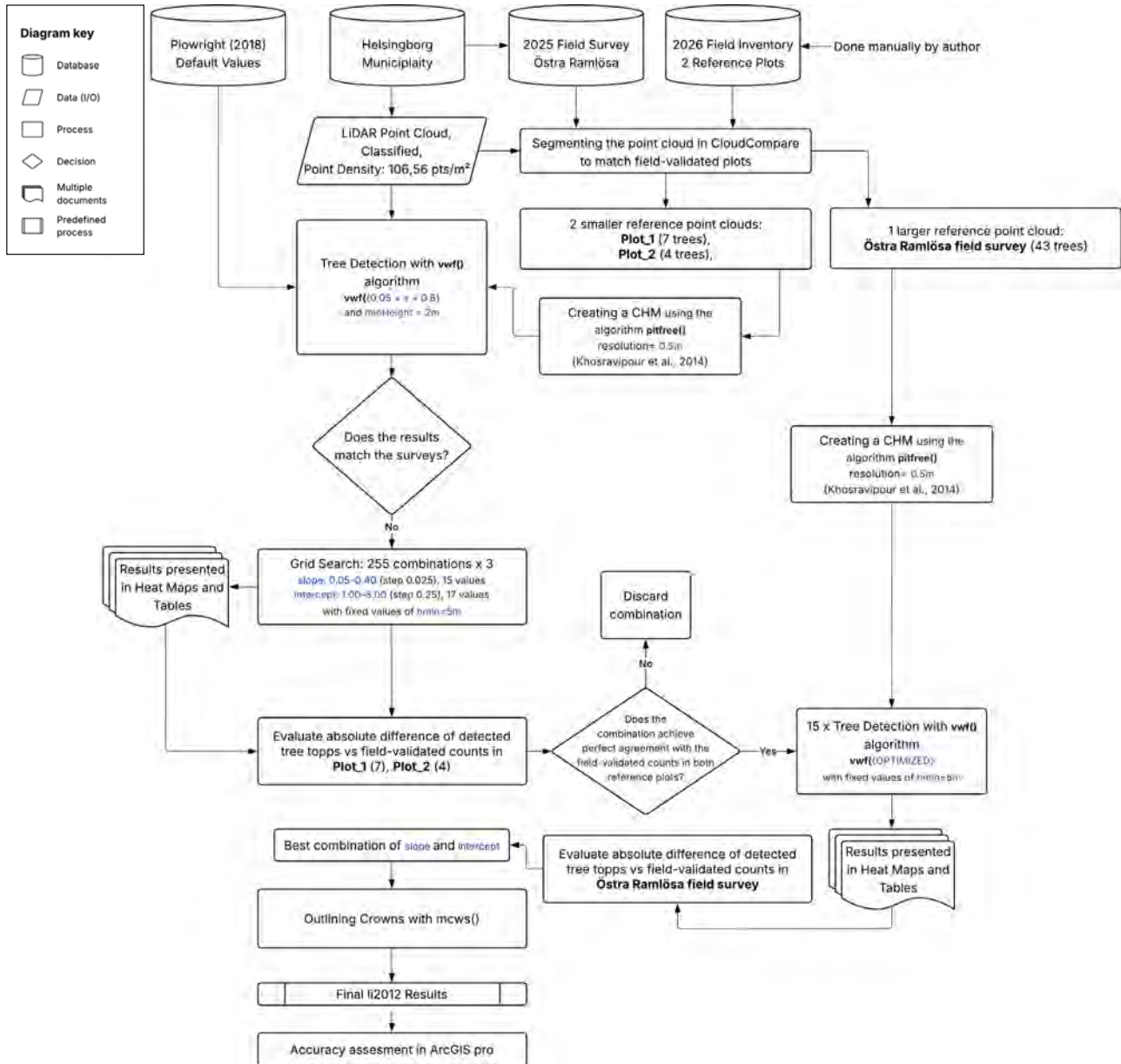
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<sup>1</sup> `vwf()`, An algorithm used to identify treetops in a Canopy Height Model by using a search window that changes size based on the height of the vegetation.

<sup>2</sup> `vwf()` *Slope*, The coefficient that determines how the search window grows as the height of the vegetation increases. Allowing the model to adapt to the wider crowns of mature trees.

<sup>3</sup> `vwf()` *Intercept*, The constant value in the Variable Window Filter equation that defines the minimum search window size when vegetation height equals zero. A higher intercept prevents the algorithm from over-segmenting small branches or shrubs as individual trees.

# Flowchart Explaining Individual Tree Detection and Segmentation in Forest Tools



**Figure 7:** The figure illustrates the methodology used to extract individual tree metrics from high resolution ALS point clouds within the R library ForestTools. Illustration: Skogh

To determine optimal window function parameters, a custom *grid search*<sup>4</sup> script was developed in R (see Appendix D) to systematically evaluate slope and intercept combinations across the two reference plots. The search used a full factorial design:

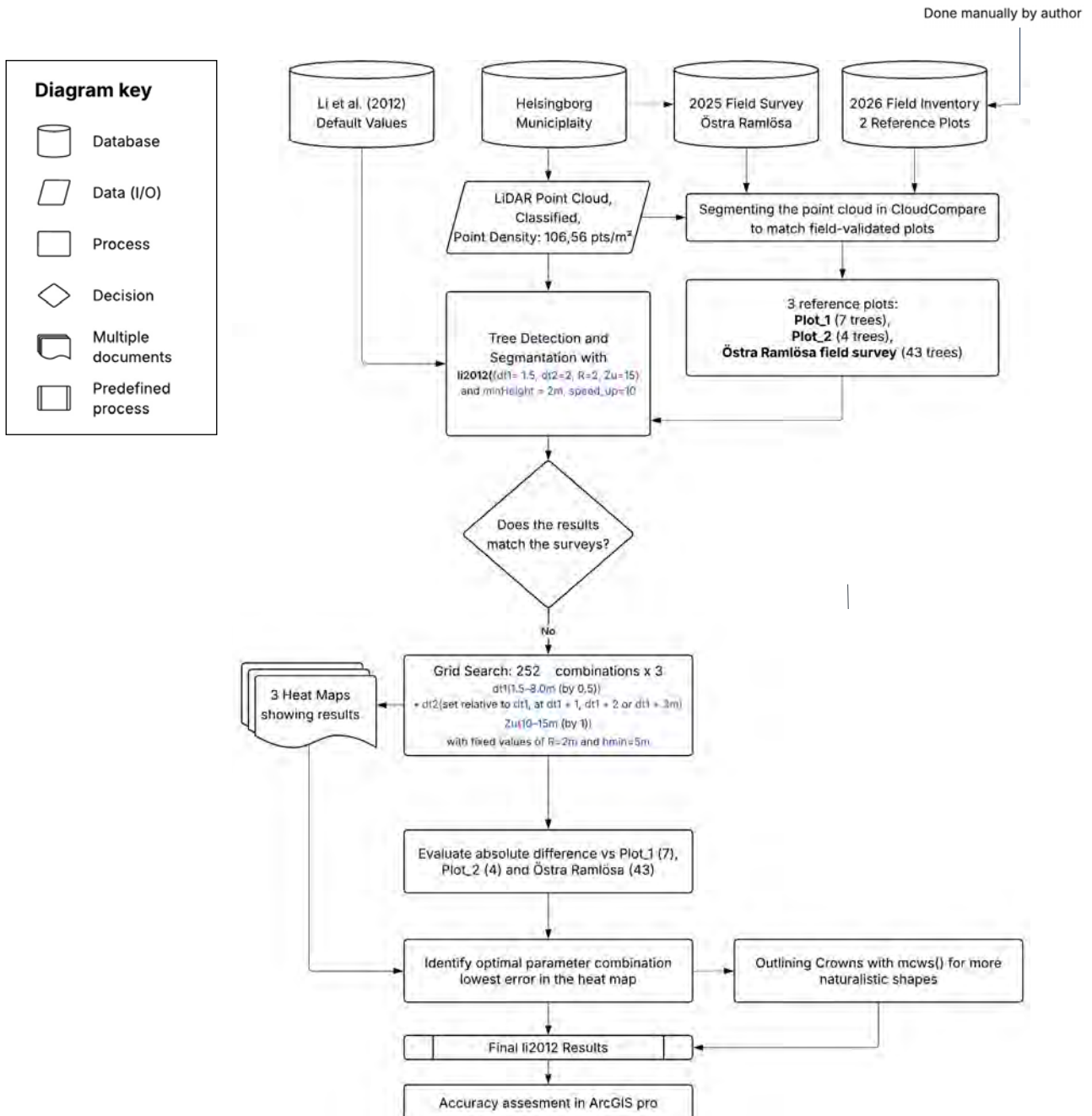
- `slope: 0.05-0.40` (step 0.025), 15 values
- `intercept: 1.00-5.00` (step 0.25), 17 values

This gave 255 unique parameter combinations. A minimum detection height (`hmin`) of 5m was applied throughout to exclude ground returns and low-growing vegetation. Scan angle was not varied, as the point clouds had been pre-clipped to site boundaries. Performance was evaluated as the absolute difference between the detected count and the field-validated tree count for each site, with a combined error summed across both sites. All parameter combinations achieving perfect agreement with the field-validated counts on both reference plots were subsequently applied to the Östra Ramlösa 2025 field survey, executed by Helsingborgs Stad. The 2025 field survey served as a larger validation area with a field-validated count of 43 trees, to determine which combination worked best at a broader spatial scale, which formed the final ForestTools result.

---

<sup>4</sup> *Grid Search*, A systematic optimization method that tests all possible combinations of a specified set of parameters to find the most accurate model configuration.

# Flowchart Explaining Individual Tree Detection and Segmentation in lidR



**Figure 8:** The figure illustrates the methodology used to extract individual tree metrics from high resolution ALS point clouds within the R library lidR. Illustration: Skogh

### 1.5.3.3 Point Cloud Based Tree Detection and Segmentation in lidR

The following analysis was performed on the ALS data collected by Hexagon on behalf of Helsingborg municipality in 2025 (see section 1.5.3). CHM-based detection is sensitive to pixel resolution, susceptible to pitting artefacts, and may merge or split crowns in dense or mixed vegetation. To address these limitations, a secondary segmentation was performed using the algorithm `li2012()` (see Fig. 8 and Appendix E) (Li et al., 2012), implemented in the lidR library in R (Roussel, 2023). The algorithm `li2012()` operates directly on the 3D point cloud without CHM dependency (see section 2.8.1.3) (Li et al., 2012). The `li2012()` detection method was first applied to the two reference plots (Östra Ramlösa, visited 26-03-05) using default thresholds to determine how well the default settings identified the vegetation structures:

```
Default: li2012(dt1 = 1.5, dt2 = 2, R = 2, Zu = 15, hmin = 2, speed_up = 10)
```

To identify optimal parameters for the `Li2012()` detection method, a grid search script was developed in R (see Appendix F) and applied to the two reference plots. The search tested 252 combinations on each plot of three algorithm parameters:

- `dt1`(1.5–8.0m (by 0.5))
- `dt2`(set relative to `dt1`, at `dt1 + 1`, `dt1 + 2` or `dt1 + 3m`)
- `Zu`(10–15m (by 1))

with fixed values of `R=2m` and `hmin=5m`.

Performance was evaluated with the absolute difference between the detected count and the field-validated tree count for each site, 7 trees for Plot\_1 and 4 trees for Plot\_2. Subsequently, an identical grid search was performed on the 2025 field survey, using the same parameter ranges for `dt1`, `dt2`, and `Zu`, with `R = 2m` fixed, but with `hmin` fixed at `5m` to reflect the taller canopy at that site. To also test whether `R` affected the tree detection results, three separate runs were performed with the optimal parameter values identified by the grid search held constant, and the only variable was the `R` value. The three runs used (`R = 4`, `6`, and `8`), respectively. As all four configurations consistently detected the same number of trees, `R` was found to have no effect on the output within this range, and the default value of `R=2` was retained for the final result.

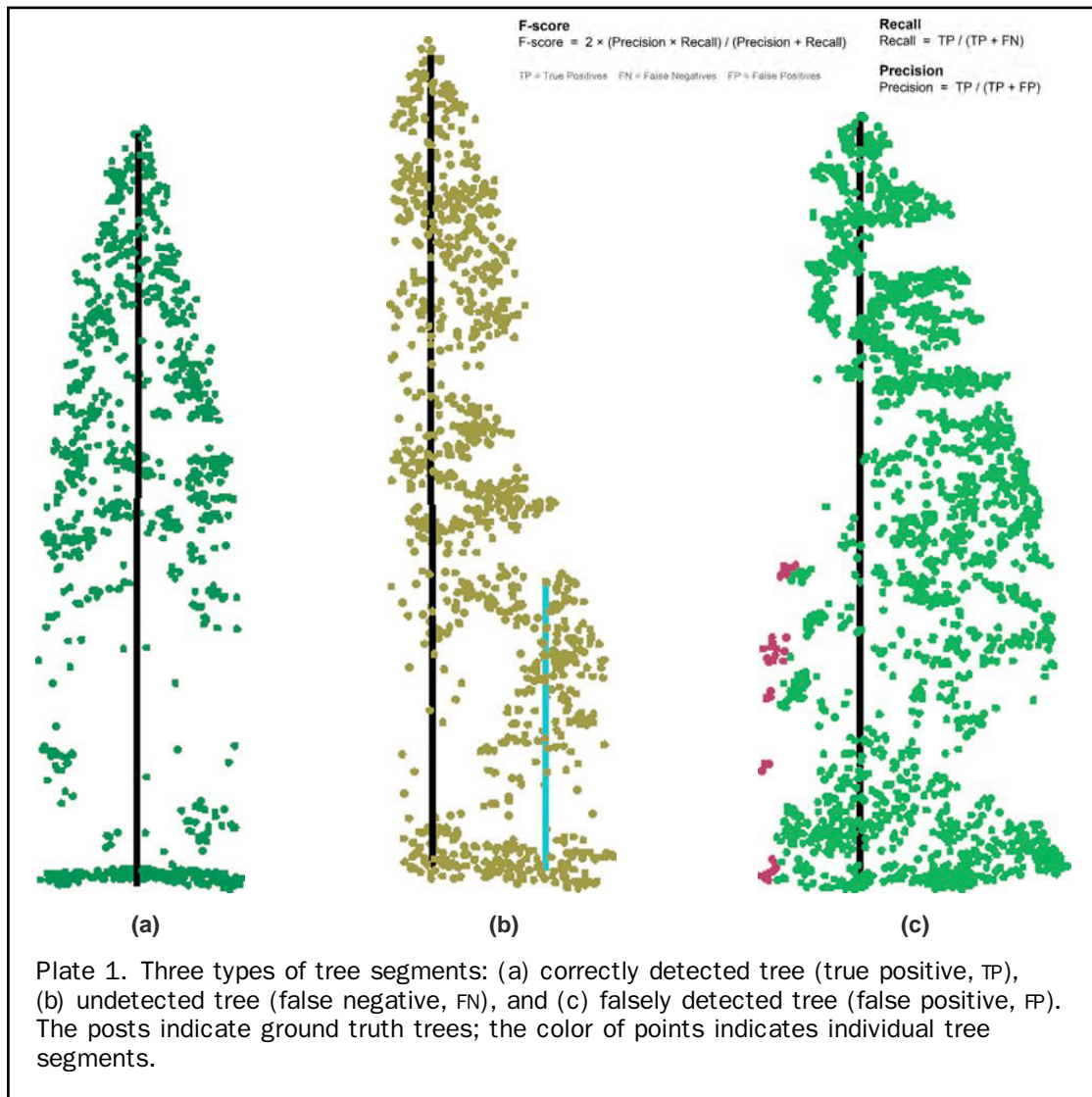
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<sup>5</sup> The algorithm `li2012()` identifies tree tops and groups nearby points into individual crowns using adaptive distance thresholds based on tree height (`h`). The allowed spacing is determined by the height parameter `Zu`. If the tree height is lower than `Zu` (`h < Zu`), the stricter threshold `dt1` is applied. If the height is greater than `Zu`, the more generous threshold `dt2` is applied.

### 1.5.3.4 Accuracy Assessment

Spatial accuracy of both detection methods (`vwf()` and `li2012()`), was evaluated using a buffer-based matching approach in ArcGIS Pro. In which 5 m buffer zones were created around each of the 43 field-validated tree positions. Buffer zones containing a tree top detected by the algorithm were designated as true positives (TP). Detected tree tops that did not match a specific buffer zone, or were located within a buffer zone that had already been assigned another tree top, were designated as false positives (FP). Buffer zones that did not contain any tree tops at all were designated as false negatives (FN). The method's recall, precision, and F-score were thereby calculated based on the number of TPs, FPs, and FNs (see Fig. 9).

## True Positives, False Negatives and False Positives



**Figure 9:** Evaluation metrics for tree detection. Recall (r) indicates the tree detection rate, while precision (p) indicates the correctness of the detected trees. The F-score (F) represents the overall accuracy, accounting for both commission and omission errors. All values range from 0 to 1, where a value of 1 indicates perfect segmentation. Illustration & Text: Li et al. (2012) p. 80

### 1.5.3.5 Extracting tree DBH from the output data

To evaluate the potential of LiDAR data for screening legally protected trees, the crown sizes of the segmented trees from both the `vwf()` and `1i2012()` methods were examined. DBH was estimated indirectly from the LiDAR-derived crown area. Rather than applying the allometric relationships established by Coombes et al. (2019) through a strict circular diameter assumption, the actual delineated crown area was used directly in ArcGIS Pro. This approach accounts for irregularly shaped crowns while retaining the original allometric thresholds: a DBH of 40 cm, associated with hollow structures and veteran characteristics (see Fig. 10), corresponds to a crown area of 78.54 m<sup>2</sup>, and a DBH of 100 cm (the threshold for mandatory legal protection in Sweden) corresponds to a crown area of 490.87 m<sup>2</sup> (Naturvårdsverket, 2012b).

Based on these calculations, the segmented trees were categorized into three priority tiers for screening:

- Standard (< 78.54 m<sup>2</sup>)
- High Value (78.54–490.87 m<sup>2</sup>)
- Protected (> 490.87 m<sup>2</sup>)

The screening tool was first applied to the Östra Ramlösa area and then to the Krokstorp area, which was segmented using the same methods and optimized threshold values as Östra Ramlösa. The aim was to test the method in both an area without trees having a trunk diameter exceeding 100 cm (Östra Ramlösa) and an area with trees having a trunk diameter exceeding 100 cm (Krokstorp) in order to assess the method's accuracy.



**Figure 10:** A linedated barbet feeds its chick inside a hollow tree. Trees with complex structures such as this provide valuable habitats for various animals, fungi, and lichens. Photo: chokniti/Adobe Stock

## 1.5.4 Delimitations

The scope of this study is delimited in six main aspects. Geographically, the empirical work centres on southern Sweden, with peri-urban Helsingborg as the primary site for the technical study. However, the Canadian interviews, EU legislation, and international literature extend this geographic frame, providing broader international relevance.

In terms of vegetation, the focus is strictly on mature and veteran trees, rather than street trees, commercial forestry plantations, or planting design more broadly.

Technically, the study uses airborne laser scanning (ALS) data and open-source tools in the programming language R. While mobile and terrestrial laser scanning are discussed for comparison, they are not tested, and commercial software or proprietary machine learning pipelines fall outside the scope.

Methodologically, the thesis relies on existing allometric models from literature and municipal field inventories as ground truth, rather than developing new models or conducting independent ecological field surveys.

Conceptually, the economic valuation of trees, as well as questions of private property law and individual landowner rights, are excluded, except when they arise as topics of professional discussion.

Finally, the thesis focuses primarily on spatial planning, specifically local development plans. While comprehensive planning, design, and maintenance are discussed as relevant topics, they are not the primary subjects of the research questions, nor are they described in detail in the literature review.

## 2. Literature Review

### Securing Urban Well-Being: Integrating Tree Preservation into Spatial Planning

#### 2.1. The Value of Trees and the Regulatory Mandate

*To understand why tree preservation must be integrated into spatial planning, it is essential to first recognize their multifaceted value and the new, binding legal frameworks demanding their protection.*

##### 2.1.1 The Value of Ecosystem Services

Biodiversity refers to the variety of life on Earth and the natural patterns it forms (Convention on Biological Diversity, 2009). One aspect of biodiversity is the variety of ecosystems that occur in forests, wetlands, and agricultural landscapes (ibid.). In each ecosystem, living creatures form relationships, interacting with one another and with the air, water, and soil around them. Direct and indirect benefits from ecosystems are known as ecosystem services (see Fig. 11) (Forest Europe, 2014).

Trees and forests provide great value to society by contributing to human well-being, biological diversity, and environmental stability (Forest Europe, 2014; Deak Sjöman, Sjöman & Johansson, 2015; Boverket, 2022). Trees deliver crucial services such as regulating the global carbon cycle, maintaining water balance, controlling erosion, and preventing natural hazards (ibid.). However, a major challenge is that many of these benefits are non-market goods, provided for free. Because their true economic value is often difficult to assess, there is a growing need for proper valuation and financing mechanisms to compensate forest owners and developers to ensure the continued provision of these vital services (Forest Europe, 2014).



**Figure 11:** Man resting in the shade provided by a tree in Hamburg, Germany.

Trees offer a wide range of ecosystem services, and one of the most vital ones is the lowering of local temperatures.

By both casting shade and increasing humidity, trees make city environments more livable in hot climates. Photo: Skogh (2026)

## 2.1.2 The European Green Deal and Legal Requirements

Urgent calls for climate actions by EU citizens have led to the president of the European Commission launching the *Green Deal* in 2019 (European Commission, 2019). The document emphasizes the need for a new EU Forest Strategy that focuses on effective afforestation, forest preservation, and restoration in Europe to increase CO<sub>2</sub> absorption and reduce the incidence of forest fires (ibid.). A core pillar of the Green Deal is the *EU Biodiversity Strategy for 2030*, which explicitly commits to strictly protect all remaining primary and old-growth forests within the EU (European Commission, 2020). The document also emphasizes the need to improve the overall health, quantity, and resilience of European forests (ibid.).

In 2024, the EU environmental ministers in council adopted the *EU Nature Restoration Law*, representing the final component of the Green Deal to be made legally binding (Regulation (EU) 2024/1991). The EU Nature Restoration Law is the first European-wide law to set legally binding targets to restore biodiversity and degraded ecosystems. Driving the preservation effort is the EU Nature Restoration Regulation's Article 8, which requires no net loss of urban tree canopy cover at the national level by 2030 (Regulation (EU) 2024/1991):

*"Member States shall ensure that there is no net loss in the total national area of urban green space or of urban tree canopy cover in urban ecosystem areas by 2030"*  
(Regulation (EU) 2024/1991).

To meet the requirement in Article 8.1 regarding no net loss, the total area of urban green spaces and the tree canopy cover must remain at the same level in urban ecosystem areas at the national level in 2030 compared to 2024 (Boverket, 2026). Exceptions may be made for urban ecosystems that have more than 45 percent green space and over 10 percent tree canopy cover. These exceptions do not apply to 21 municipalities in Sweden which gives those municipalities a strong incentive to meet the requirements.

### 2.1.3 Swedish legislation for the protection of specific trees

In Sweden, *Trees Worthy of Special Protection* is a national action strategy developed by the Swedish Environmental Protection Agency (Naturvårdsverket, 2012), that serves as a guideline for county administrative boards and municipalities when assessing trees protection values. The strategy's criteria correspond to many other countries' understanding of which trees require protective measures and are primarily focused on stem diameter at breast height, DBH (see Fig. 12).



**Figure 12:** Environmental analyst measuring the circumference of an old oak. When the environmental assessment analysts visit the trees, they also record other features important for biodiversity, such as whether there are cavities, and if so, where. Photo: Anna Lundmark, SLU

The strategy defines three categories of trees that are classified as worthy of special protection:

- **Giant trees** with a DBH exceeding 100 cm
- **Very old trees** (over 200 years for slow-growing species, or over 140 years for other species)
- **Coarse hollow trees** with a DBH of at least 40 cm and a visible cavity (Naturvårdsverket, 2012b).

The reason behind these criteria is that large, old, and structurally complex trees provide irreplaceable habitats for bats, birds, insects, fungi and other organisms (Naturvårdsverket, 2012b). The older and larger the tree, the greater the number of species it can support.

It is important to note that classification as a Tree Worthy of Special Protection does not in itself confer statutory protection under Swedish law. The strategy is a national guideline rather than a self-standing legal instrument, and individual trees are protected only through other mechanisms in the Swedish Environmental Code (Miljöbalken, SFS 1998:808). These mechanisms include:

- **Formal area protection** (SFS 1998:808, Ch. 7), (e.g., National parks, nature reserves, biotope protection areas (see Fig. 13) and Natura 2000 sites designated under Ch. 7, Sec. 28 (see Fig. 14).
- **General consultation duty** (SFS 1998:808, Ch. 12, Sec. 6), frequently invoked for individual veteran trees outside formal protected areas.

In addition, the Species Protection Ordinance, which serves to implement the strict species protection rules of the Habitats and Birds Directives into Swedish law, protects species that depend on hollow trees, thereby indirectly protecting their host trees. The Swedish Planning and Building Act also allows municipalities to protect individual trees with high biological- or ecological value through Local Development Plans (LDPs).

## Biotope Protected Areas in Sweden



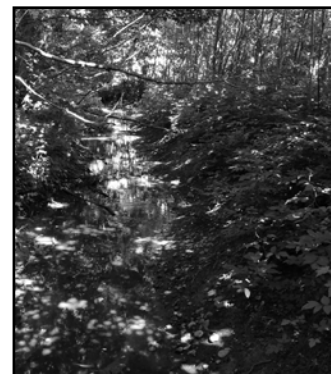
*Allé*

Mature deciduous trees planted in a single or double row consisting of at least five individuals along a road or in an open landscape. Photo: Hamburg (Skogh 2026)



*Åkerholme*

An islet of natural or cultivated land surrounded by farmland or cultivated pasture. Photo: Östra Ramlösa (Helsingborgs Stad 2025)



*Småvatten och Våtmark i jordbruksmark*

Small bodies of water or wetlands on agricultural land. Photo: Östra Ramlösa (Helsingborgs Stad 2025)



*Stenmur i jordbruksmark*

A stone wall which serves or has served as a fence, a boundary marking for agricultural fields, or some other purpose. Photo: Östra Ramlösa (Helsingborgs Stad 2025)



*Pilevall*

Pollarded willows planted in a row on, or close to, farmland. Photo: Unknown (Mats/Adobe Stock 2026)



*Källa*

A spring surrounded by wetlands in an agricultural context. Photo: (Piotr Wawrzyniuk/Adobe Stock 2026)



*Odlingsröse i jordbruksmark*

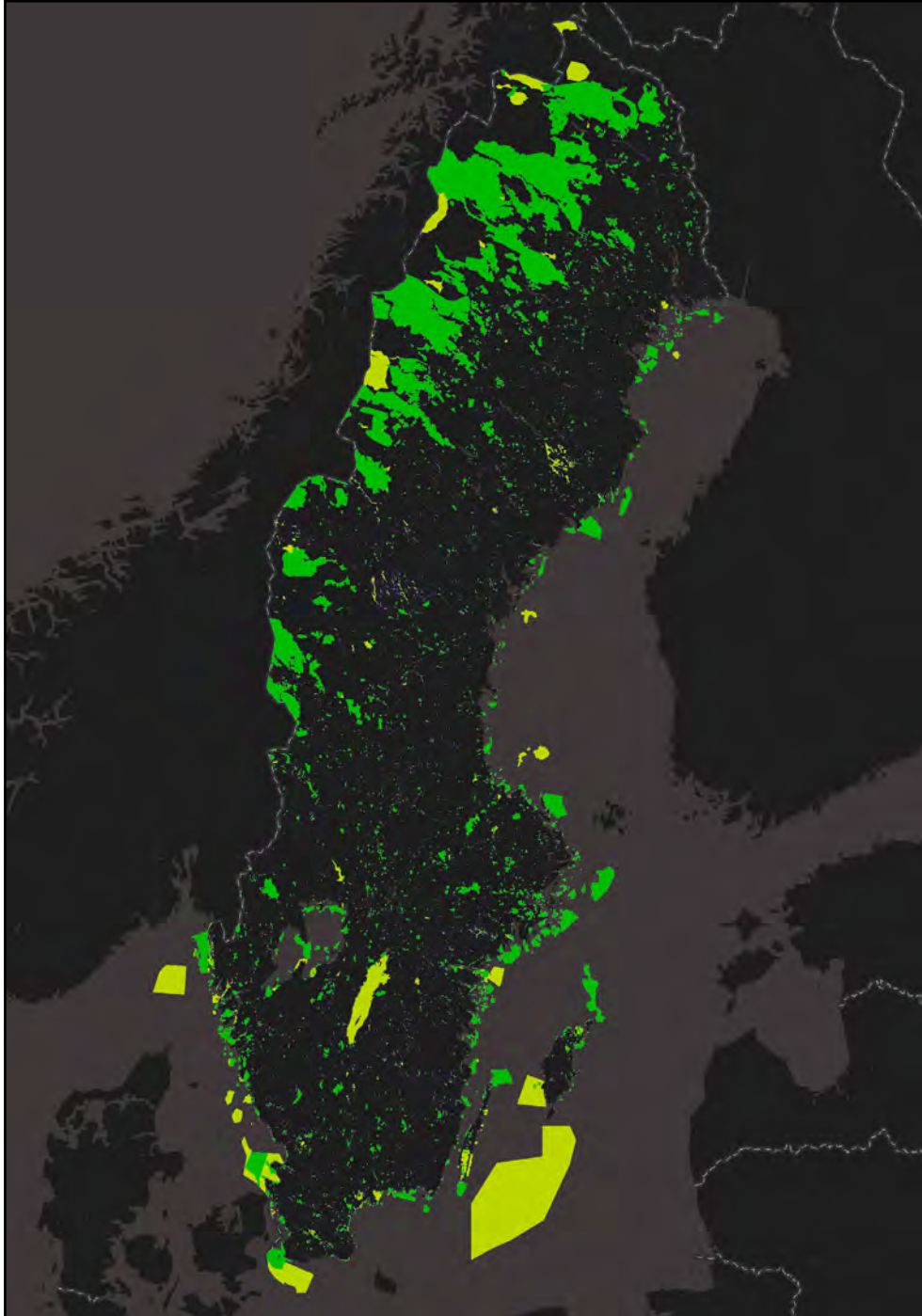
A pile of stones originating from agricultural operations, located on or adjacent to farmland. Photo: Östra Ramlösa (Helsingborgs Stad 2025)

### Figure 14:

These biotopes have been protected because they serve as important habitats, refuges, and dispersal corridors for plant and animal species, but their numbers have declined sharply as a result of rationalized land use (Naturvårdsverket 2012). Since the biotopes are generally protected without prior consultation with affected property owners, a key principle has been that they should be easy to define, demarcate, and recognize for property owners and other stakeholders (ibid.).

## Protected Nature in Sweden

- Natura 2000 Sites
- Nature Reserves and National Parks



**Figure 15:** Protected natural areas in Sweden, including Natura 2000 sites, nature reserves, and national parks. These are the primary areas protected under the Swedish Environmental and the EU Birds and Habitats Directives. Source: Naturvårdsverket; Lantmäteriet; Geodatasamverkan

## 2.2. The Challenge of Tree Valuation

In many projects, the trees on the site are valued before construction starts to ensure that a suitable penalty can be applied in case of damage. In Sweden, many consultants and planners are using *Alnarpsmodellen* when assessing a tree's monetary value. *Alnarpsmodellen* was developed in Alnarp, Sweden at the Swedish University of Agricultural Science (Östberg, Sjögren & Kristofferson, 2015). The model aims to enable the economic valuation of trees that are not planted for production purposes and is based on market value and prices from nurseries. Östberg et al. (2015) state that it is therefore not a tree-valuation model but rather a model for calculating the cost of repairing or restoring something that has been damaged. They further note that many other calculation models also include what is known as soft values, such as aesthetics, architecture, flourishing, fragrance and bark patterns. The reason behind not including these values in the model is to reduce difficult-to-define assessments and increase the reliability. Basing the model on the cost of the tree, planting cost and maintenance, strengthens the model's credibility, as the valuation is less dependent on subjective assessments.

Another tool commonly used is the US Forest Service's *i-Tree Eco application*. Van Stan et al. (2025) state that i-Tree had over 500,000 users in approximately 150 nations by 2020. Furthermore, over 1000 research articles either used i-Tree or contributed to its development (ibid.). The i-Tree eco application uses DBH for both carbon storage and sequestration estimators (Nowak et al., 2017; i-Tree Tools, 2018). Van Stan et al. (2025) talk about the tool in their journal article *A cautionary tale about urban trees: could ecosystem services monetary estimates become economic sleight of hand?*

*“Before you stands a tool of immense power, a device capable of translating the wonders of nature into the universal language of money.”* (Van Stan et al., 2025)

In the text they argue that assigning a price for a tree only makes that tree a subject of comparison. If the tree has a price, that price can be compared with the various economic gain depicted in developers' plans to construct new parts of the city (Van Stan et al., 2025). It undermines the perception of a tree as an irreplaceable habitat for numerous species. Van Stan et al. (2025) and Östberg, Sjögren & Kristofferson (2015) presents two different perspectives on tree valuation and serves as a topic of discussion within the industry.



Figure 13: Sketch of a business agreement. Illustration: Skogh/Adobe Stock

## 2.3. Standardizing Tree Protection in the Planning Process

*To navigate the complexities of environmental laws, tree valuation, and urban growth, systematic integration into the municipal planning framework is essential.*

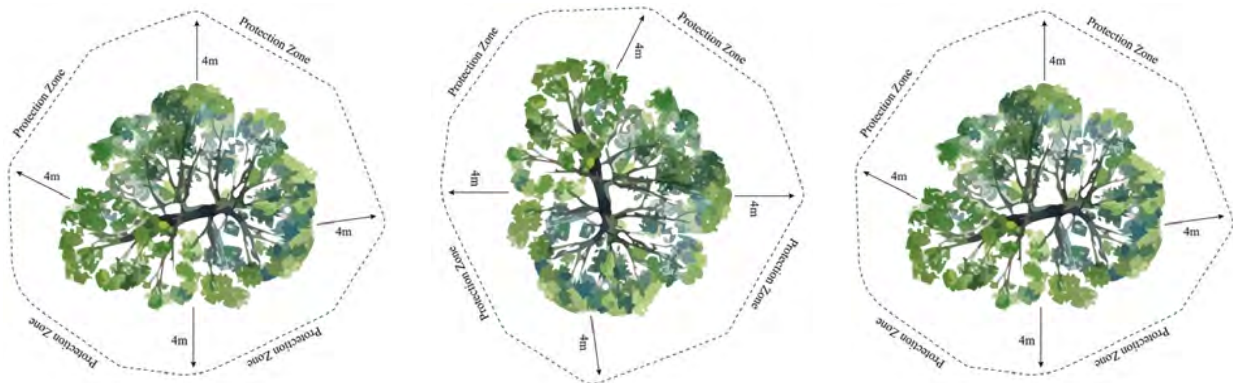
### 2.3.1 The Planning Process & The Swedish Context

In Sweden, spatial planning is primarily a municipal concern. This is due to the planning monopoly, a principle established in the Planning and Building Act (Isaksson & Storbjörk, 2012; Persson, 2013). The municipality has the exclusive right to decide if, where, and when a formal planning process should begin. While they must follow national laws, no other authority, not the state, nor the region, can force a municipality to develop or protect land. This gives the local authority a very strong position. However, it also places the entire responsibility for balancing economic growth against the preservation of ecosystems and trees solely on the municipal organization (ibid.).

Despite this autonomy, the Swedish parliament (2025) has noted that coordination and efficiency in spatial planning can be improved:

*"The parliament considers that the current system for state claims on land and water can be improved in terms of efficiency, predictability, and transparency. The parliament therefore intends to conduct a review of existing systems and regulations with the aim of establishing a more coherent system for national spatial planning, based on a comprehensive socio-economic analysis. The review will aim to improve the conditions for weighing different interests against each other, increase national equality, increase legal certainty, and improve coordination between public actors." (Sveriges Riksdag, 2025)*

This critique highlights that the current framework lacks transparency, making it difficult to effectively weigh conflicting interests in the planning process. Trees are directly affected by these challenges. Since most development areas in Sweden are vegetated, decisions about tree preservation versus removal often involve competing interests such as development pressures and economic gains (Isaksson & Storbjörk, 2012; Persson, 2013).



**Figure 16:** Sketch of the Swedish Standard SS 990002:2025 demanding a 4 meter protection zone from a trees' outermost branches during construction. Illustration: Skogh/Adobe Stock

## 2.3.2 Standardizing Tree Protection and Valuation

In 2025, the Swedish Institute for Standards released a new standard for the protection of trees during construction work (see Fig. 16) (SIS, 2025). Prior to 2025, the Swedish standards for tree care focused primarily on pruning practices. In 2020, the Swedish Institute for Standards published two standards, SS 990001-1:2020 and SS 990001-2:2020, establishing requirements for the commissioning and execution of tree pruning (SIS, 2020). While these represented an important step toward standardising tree care in Sweden, no equivalent framework existed for the protection of trees during construction and planning until the release of SS 990002:2025 (SIS, 2025).

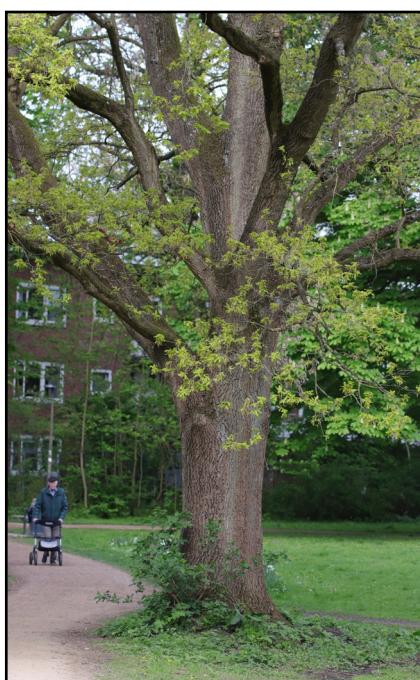
A tree's conservation value is an inventory parameter that lacks a standardized national definition. Consequently, the new standard SS 990002:2025 does not provide specific criteria for this assessment. To fill this gap, the consulting firm Trädkontoret developed a handbook, *The Tree Office's Handbook For Tree Protection During Construction - A practical guide to tree protection*, for evaluating conservation values (Bruhn et al., 2026). Their methodology is based on the British standard BS 5837:2012. It categorizes trees based on social, biological, and cultural values, aligning with the Swedish inter-agency document *Fria eller fälla 2.0* (Riksantikvarieämbetet et al., 2023). *Fria eller fälla 2.0* was developed by the Swedish National Heritage Board in collaboration with several agencies, serving as a joint guide to facilitate work with trees in public spaces. It provides a general overview of various public tree environments, the value of trees, and the reasons why trees sometimes need to be removed or otherwise managed (ibid.).

In Trädkontorets handbook, the same tree may have a high value in one category but a low value in another (See Table 2 and Fig. 17 - 18). The highest value determines the overall conservation value. If the tree is likely to require disproportionate conservation efforts in relation to its expected lifespan, function, or risk assessment, it is classified as “U” in all categories, which means the tree is not suitable for conservation. The handbook also includes a flowchart (see Fig. 19) that illustrates how decisions made early in the tree protection process have implications for subsequent steps. With this flowchart, the Tree Office aims to encourage that issues related to tree protection be addressed as early as the planning stage (Bruhn et al., 2026).

# The Tree Office's Handbook: Conservation Evaluation

**Table 2:** The table is showing information gathered from p. 37 - 39 in the Tree Offices' Handbook: *The Tree Office's Handbook For Tree Protection During Construction - A practical guide to tree protection*. This is a translated and simplified version of the handbook's classification of conservation value. The original includes two additional categories between very high and low value, described as high value and moderately high value, to provide further nuance.

Value type	Very High	← Example	Low	← Example
<b>Social value</b>	Trees that are strongly linked to local identity, gatherings, social recreation, or significant contributions to ecosystem services that benefit many people.	Trees used as gathering points for events or school activities, with documented tradition or regional origin.	Low or insignificant social value – often young trees or trees that are not seen/experienced by more than a few people.	Newly planted trees without an established function or connection to human activity.
<b>Biological value</b>	The tree is classified as worthy of protection by the Swedish Environmental Protection Agency. The tree is over 1 meter in DBH) or is a hollow tree over 40 cm in diameter or is over 200 years old (spruce, pine, oak, beech) or 140 years old (other tree species).	Very old oak tree with cavities and a rich occurrence of wood-dwelling insects; large spruce tree with a diameter of 1.1 m that provides a habitat for mosses and fungi; hollow trees in a park environment with nesting owls.	Biological value is low or none at all, usually young trees. The tree has no damage of biological significance, nor any cavities or sap flows.	Newly planted hornbeam, rowan without biologically interesting structures, young tree without damage or dead wood.
<b>Cultural value</b>	Formally protected trees, trees that, through maintenance or historical connection to the environment, are essential to the cultural and historical value of the environment.	Avenues, trees in cemeteries, cloned trees with documented backgrounds, pollarded or topiary trees in culturally and historically valuable environments.	Low or no cultural value – no historical connection.	Common trees in newly developed areas without historical relevance.



**Figure 17. (Left)**

A tree with low conservation value according to Trädkontorets handbook. The reason the tree has a low conservation value is due to that it is newly planted and too young to have developed any of the values that matches the handbook's criteria.

Photo: Skogh (2026)

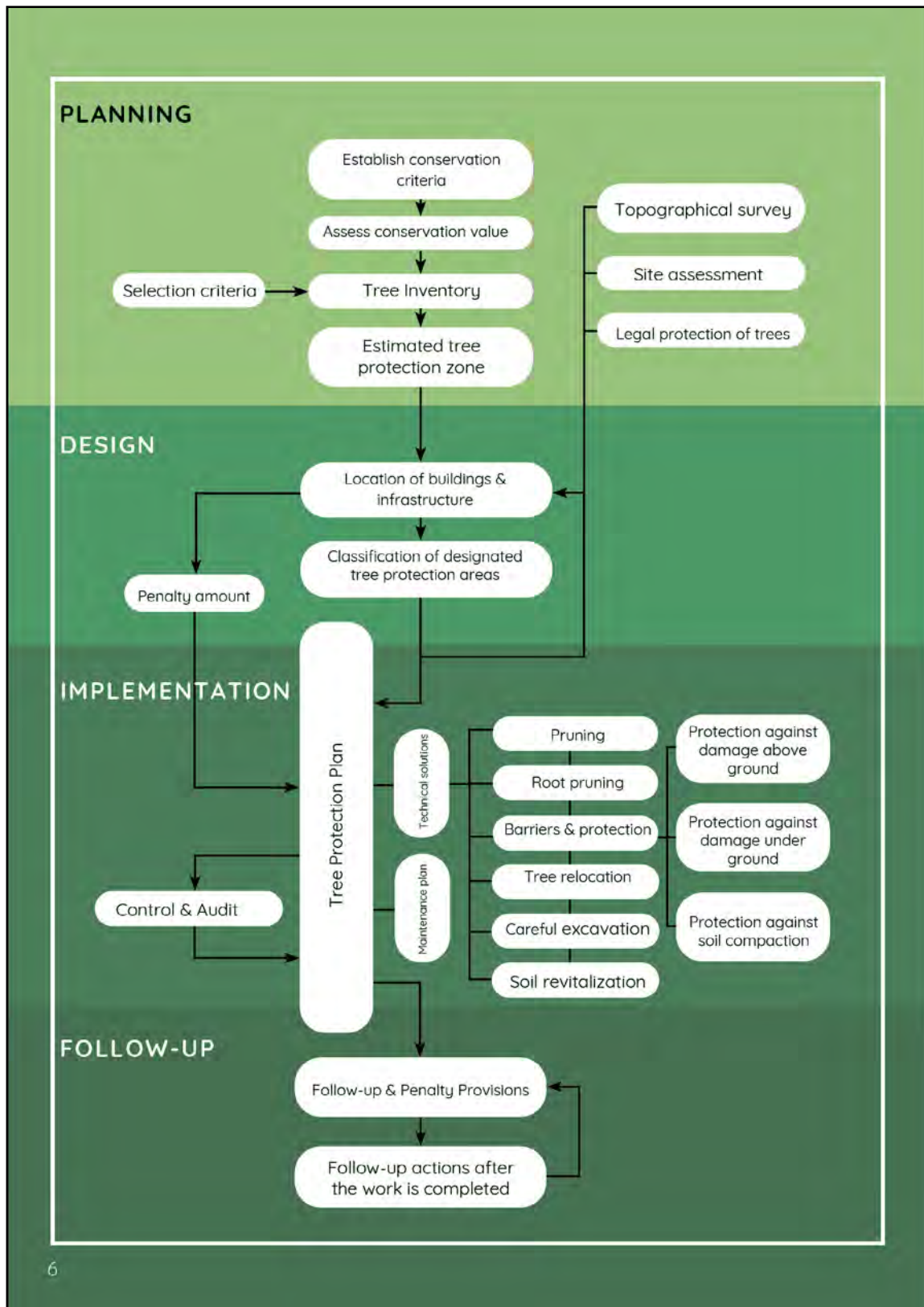
**Figure 18. (Right)**

A tree with very high conservation value according to Trädkontorets handbook.

The reason the tree has a very high value is because it has historical ties (planted in 1970's in Eichtalpark, Hamburg) and biological significans (old maple tree with sap flow) as well as social values (being a shade giving tree in a large park)

Photo: Skogh (2026)

# The Tree Office's Handbook: Trees in Spatial Planning



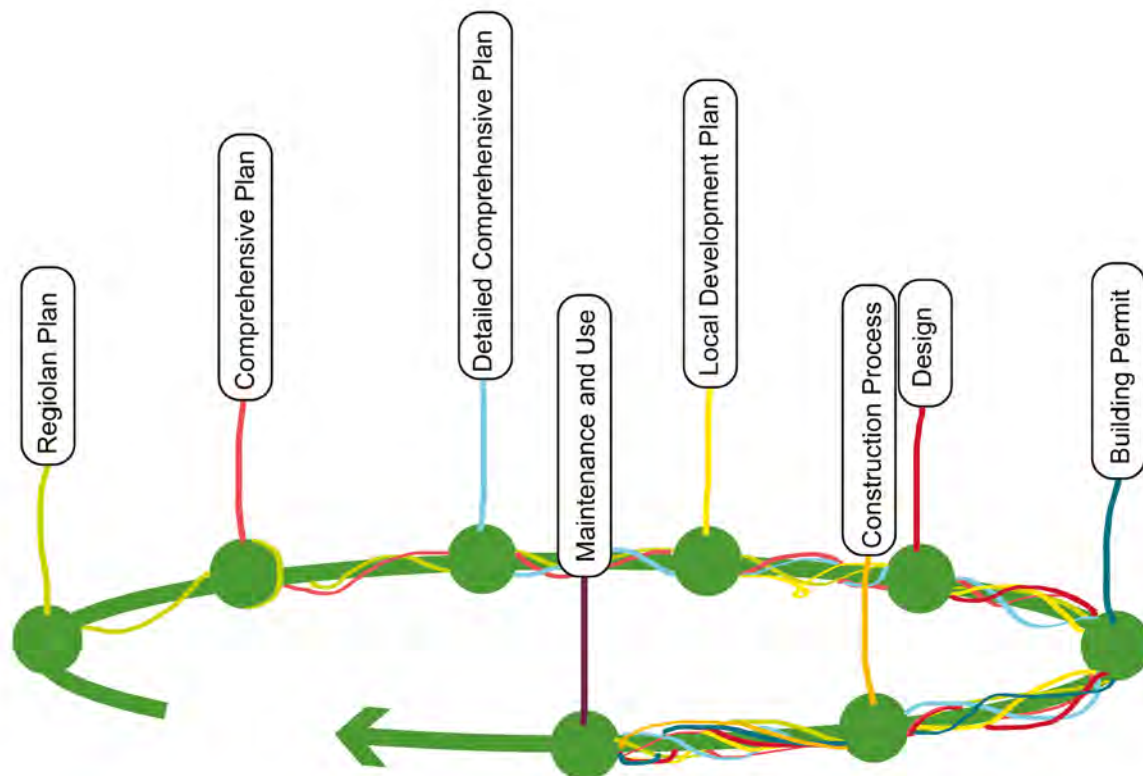
**Figure 19:** The picture is showing page 6 of the Tree Office's handbook, describing the protection of trees throughout the planning,- design, and construction phases. (Translated with DeepL.com) (Bruhn et. al 2026: 8).

## 2.4. How Trees are Considered in Spatial Planning

Since Article 8 of the EU Nature Restoration Law does not specify what qualifies as adequate compensation at the project level, it leaves considerable responsibility for decision-making to municipalities. To manage this throughout the planning process, the concept *The damage mitigation hierarchy* (*Skadelindringshierarkin*) serves as a four-step framework for decisions on exploitation, where the primary aim is to try to avoid negative environmental impact (Mellin et al., 2021). The framework aims that compensation applied through the creation of new value is only a last resort if possible, all net loss should be avoided. The four steps are:

1. **Avoid** – assessment of possible alternatives that avoid environmental impact.
  2. **Minimize** – adjustments within the selected area to reduce environmental impact.
  3. **Restore** – restoration of environmental damage caused within the development area.
  4. **Compensate** – creation or protection of environmental values in another location.
- (Mellin et al., 2021)

The damage mitigation hierarchy is not legally binding under the Swedish Planning and Building Act and is applied voluntarily by municipalities (Mellin et al., 2021). In the Swedish planning process under The Swedish Planning and Building Act, decisions are made in stages with increasing levels of detail as construction approaches (see Fig. 20) (PBL, 2010:900). The following sections explain how trees are considered at each step of this process, guided by the mitigation hierarchy.



**Figure 20:** A simplified illustration of the Swedish planning process under the Swedish Planning and Building Act, where decisions are made in stages with increasing levels of detail as construction approaches. Illustration: Skogh (2026)

## 2.4.1 Step 1: Comprehensive Planning

### (Hierarchy Step: Avoid)

*The overarching goal at this stage is the assessment of possible alternative locations to avoid environmental impact entirely.*

The *Comprehensive Plan*, while not legally binding, serves as a crucial document outlining the municipality's long-term intentions for land and water use (Boverket, 2023). According to the *Swedish Planning and Building Act*, each municipality must have an up-to-date comprehensive plan covering the entire municipality (PBL, 2010:900). Many municipalities choose to extract specific issues, such as green structure, into a separate document. Ecologically sensitive areas, parks, and recreational areas are therefore described in a so-called *Green Structure Plan*, which the comprehensive plan then refers to when considering future land use (Boverket 2024; Naturvårdsverket, 2026).

#### 2.4.1.1 The Planning Framework

When drafting the plan, the municipality identifies areas of high natural or cultural value, national interests, and risk areas, such as those prone to flooding. This stage establishes the framework for where development is appropriate and which environments must be preserved (PBL Chapter 3, Sections 2–5). This stage involves a multidisciplinary team, including strategic urban planners, policy strategists, climate strategists, stormwater engineers and municipal ecologists. Simultaneously, the county administrative board monitors state interests to ensure national goals are met (PBL Chapter 3, Section 10).

#### 2.4.1.2 The Review Process

The municipality must allow the draft to be reviewed two times by state, regional and municipal agencies as well as to the general public and organizations. First during a consultation and after revision again as a review for at least two months. Following this, all comments must be compiled into a statement, and the plan must be adjusted accordingly. If significant changes are made after the review, the proposal must be submitted for review again (PBL Chapter 3, Sections 12–18).

#### 2.4.1.3 Rezoning Application

Before a local development plan is initiated, a developer, citizen, company, the municipality or multiple stakeholders submits a rezoning application. Planners and politicians who are members of the municipal building committee make an initial formal assessment of whether the site is suitable for development. If the site is considered too sensitive or unsuitable, the municipality may issue a rejection of the planning proposal (PBL Chapter 5, Section 2). However, research suggests that this 'suitability' is often framed by a powerful perception that development projects are of key importance for the city's long-term development. Isaksson and Storbjörk (2012) highlight how assumptions about economic development can become so dominant that they become difficult to challenge, effectively locking the process into a sort of *path dependence*.

## 2.4.2 Step 2: Local Development Plan

### (Hierarchy Step: Avoid, Minimize, Restore, Compensate)

*Detailed planning incorporates all steps of the damage mitigation hierarchy. Avoidance is achieved by designating land with existing trees as natural areas in public spaces. The environmental impact is minimized through planning regulations and tree protection zones. Restoration is achieved by planning new natural areas and restoring land. Compensation is provided through new tree plantings and compensatory measures outside the planning area.*

If the municipality accepts the planning proposal, a *Local Development Plan* (LDP) is drawn for the specific area. In this process the municipality needs to investigate whether the plan is likely to have a significant environmental impact by conducting an Environmental Assessment (EA) (PBL Ch. 5, Sec. 11). This investigation should be conducted in accordance with *The Swedish Environmental Code* Chapter 6, Sections 5–7 (SFS 1998:808, Ch. 6, Sec. 5–7).

#### 2.4.2.1 Evaluation Environmental Impact

When evaluating whether the removal of existing trees constitutes a significant environmental impact, the municipality considers both the individual value of each tree and the broader role the vegetation plays in the local green infrastructure. In Sweden, trees located in protected areas such as Natura 2000 sites are subject to protection under the Swedish Environmental Code (SFS 1998:808, Ch. 7). Additionally, trees that meet the criteria of Trees Worthy of Special Protection (Naturvårdsverket, 2012b) may be granted protection under the LDP. However, this requires that they be identified during the EA.

If a project involves the removal of, or construction near, such trees, it is generally considered a significant environmental impact. However, Isaksson and Storbjörk (2012) found that the EA process often starts too late, after key decisions have already been made. This reduces it to a formal exercise rather than a tool for preservation (Isaksson & Storbjörk, 2012).

#### 2.4.2.2 Green Infrastructure and the 3-30-300 Principle

Another driver for tree preservation is the connectivity of green infrastructure. If the felling of trees severs these connections, it leads to habitat fragmentation. Maintaining these spatial continuities is essential for the long-term survival of protected species (Naturvårdsverket, 2012a).

Furthermore, many Swedish municipalities have adopted the 3-30-300 principle in urban planning (Boverket, 2023). This principle stipulates that every citizen should see at least 3 trees from their home, live in a neighborhood with 30% canopy cover, and be within 300 meters of a high-quality green space (ibid.). If an existing vegetated area serves as a key node within the urban fabric under the 3-30-300 framework, it constitutes a strong argument for preservation.

### 2.4.2.3 Establishing Protection Areas

The Tree Office's handbook recommends that the planning process consist of two steps (1) Inventory of current situation and (2) Application of conservation value and estimated tree protection area for each tree located within the project area (Bruhn et al., 2026). Based on the EA, the valuation model (see Table 2), and other steering documents, each tree is given a conservation value between 1 and 4, where 1 represents the trees that are most worthy of preservation.

An estimated tree protection area is drawn around each tree in accordance with SS 990002:2025. The standard states that each tree must have protection extending 4 meters from the outermost branch (SIS, 2025; Bruhn et al., 2026).

### 2.4.2.4 Review Challenges

The review period for a local development plan is, just as with the comprehensive plan, done in two steps. For a local development plan the second review period is usually limited to six to eight weeks which puts a significant pressure on the county administrative board to identify environmental risks. If the initial data provided by the municipality lacks precision, there is a high risk that valuable nature will not be flagged in time. In some cases developers hold a legal right to build, but is later stopped by the species protection ordinance during the construction phase. These delays result in high costs as well as damage to the valuable species. This lack of predictability is the type of systemic issues currently criticized by the Swedish parliament (2025).

### 2.4.2.5 The Balancing Principle

The balancing principle is similar to the damage mitigation hierarchy but originated, and is legally binding, in Germany (Mellin et al., 2021). It is frequently used in municipal planning in Sweden, although not legally binding (Ridell, 2019). The principle does not specify what qualifies as adequate compensation, which makes application arbitrary (ibid.). Compensation in reality is often reduced to a numerical exercise, trees removed are replaced by an equivalent number of new trees, without accounting for the ecological, social, and cultural values that mature trees represent (Ridell, 2019). Strengthening the legal frameworks around compensatory measures remains an important area for future development. If a municipality adopts this principle, it is implemented during the detailed planning process. At that point, a budget is set for compensation, and measures are proposed. This is then followed up during the design phase, when the measures are developed, and during the construction phase, when the measures are implemented.

## 2.4.3 Step 3: The Design Process

### (Hierarchy Step: Minimize, Restore, Compensate)

*During the design phase, the impact is minimized through grading, groundwork, and the placement of walkways and ancillary buildings. Restoration is achieved by recreating ecosystems and designing suitable habitats for the trees. Compensation is provided through the implementation of mitigation measures, as potentially described in the detailed plan, and, in some cases, the relocation of trees.*

#### 2.4.3.1. Root Protection and The Lock-In Effect

In the design process, vegetation, primarily trees, must be balanced against infrastructures competing for the same limited space. These systems carry strict technical requirements that often conflict with the needs of the tree (Bruhn et al., 2026; SIS, 2025). When an LDP requires trees to be preserved, a new assessment follows. Certified arborists are typically hired to perform risk analyses (International Society of Arboriculture, n.d.) and define the root protection zone, the underground area that must remain undisturbed (SIS, 2025). According to Trädkontoret's handbook, the zone formulated in SS 990002:2025 is only an estimate; an established protection area is determined on-site by a tree expert, who maps actual root spread where needed (Bruhn et al., 2026). Because exploitable land is set in the LDP, there is little room to adjust. This lock-in forces the designer to fit living trees into a pre-set web of infrastructure (Persson, 2013; Isaksson & Storbjörk, 2012). When a building sits too close, the options narrow to three difficult choices: prune the roots heavily, build over them, or fell the tree.

#### 2.4.3.2 Establishing a Tree Protection Plan

The handbook states that the established tree protection area should be identified early in the design phase to serve as the basis for the layout. Once determined, a tree protection plan should be formulated (Bruhn et al., 2026). It describes which trees are to be preserved, their conservation values, and how work should be adapted to avoid damage (ibid.). A tree protection plan is not mandatory but a recommendation, however its usage is in accordance with the *Damage Mitigation Hierarchy* (Mellin et al., 2021) and the new SIS standard SS 990002:2025 (SIS, 2025).

#### 2.4.3.3 Management Plans and Penalties

In addition to the protection plan, there should also be a management plan for affected trees, detailing staking, fertilizing, and watering (Bruhn et al., 2026). The handbook considers this to be the time when the penalty amount and method of damage settlement are determined. By establishing the penalty clause at this stage, the penalty amounts are part of the agreement even before the construction has begun (ibid.).

#### 2.4.3.4 Operational Review

Finally, maintenance experts from the city evaluate the project focusing on future cost and practical difficulty of caring for the tree. If the tree is left in a space that is too tight or lacks enough soil, it may be deemed a risk or too expensive to maintain. At this late stage, the tree can be removed simply because the design is not practical.

## **2.4.4 Step 4: The Construction Process**

### **(Hierarchy Steps: Minimize, Restore, Compensate)**

*During the construction phase, damage is minimized by fencing off the root zone, protecting tree trunks, keeping the roots moist throughout the construction period, and limiting excavation. Restoration is achieved by re-establishing plant beds. Compensation is provided both when it was already decided during the detailed planning phase and in the event that damage occurs during the construction phase.*

#### **2.4.4.1 Restore - Restoration of ecological values**

According to the handbook, compensation may be payable when unforeseen damage occurs or when damage has been permitted by a tree expert (Bruhn et al., 2026). Restoration efforts may include particularly favorable growing media, fertilization, additional irrigation, or mulching. For more extensive damage, tilling large areas with an air lance or replacing the entire plant bed using a vacuum excavator may be necessary (ibid.).

#### **2.4.4.2 Compensate - Creation or protection of values in another location**

When damage cannot be avoided, minimized, or restored on site, the final step involves creating or protecting ecological values elsewhere. This most commonly takes the form of new planting. However, compensation through new planting is widely acknowledged as an insufficient substitute for mature trees (Gilhen-Baker et al., 2022; Hilbert et al., 2019). As Trädkontoret's handbook states, big trees deliver ecosystem services at a scale that newly planted trees cannot replace (Bruhn et al., 2026).

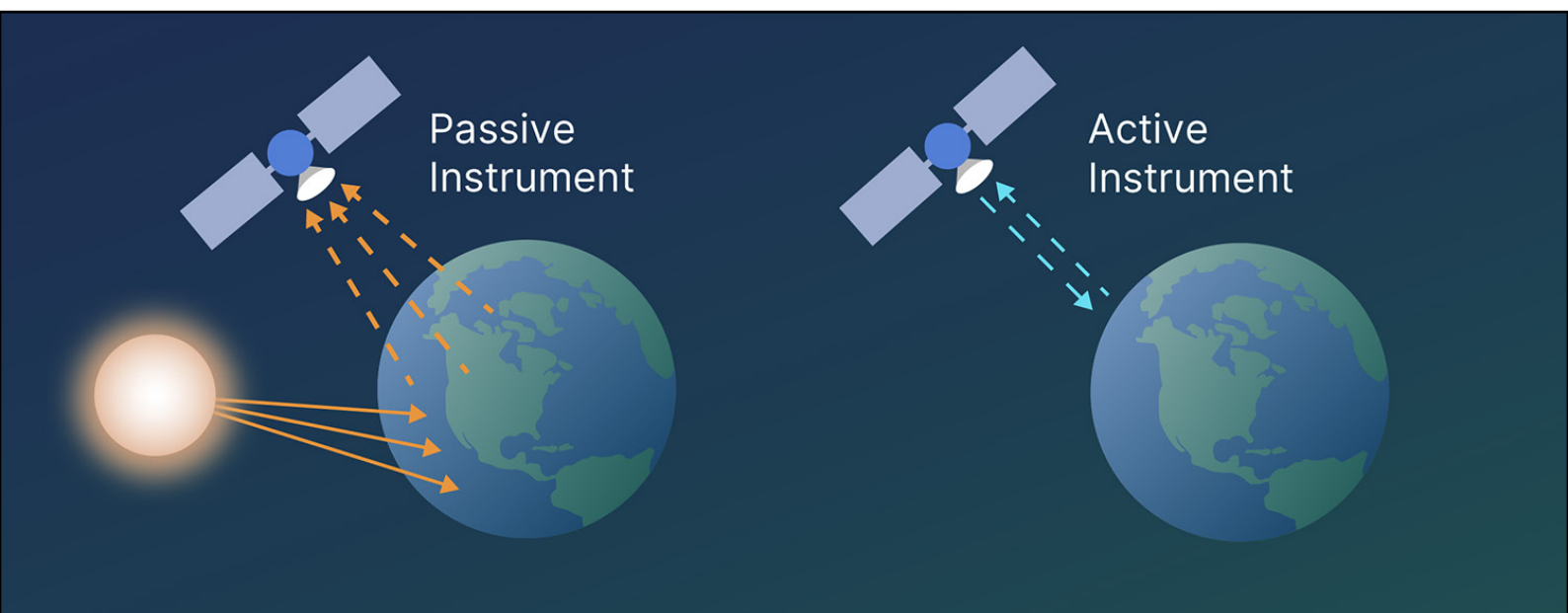
## 2.5. Remote Sensing as a Planning Tool: Principles and Methods

*While the previous sections detailed the legal frameworks and the planning hierarchy, this section addresses the technical feasibility of proactive preservation. To understand how point clouds can support decision-making regarding existing trees, it is necessary to explore the underlying principles of remote sensing and how raw spatial data is translated into the planning metrics required to challenge development interests.*

### 2.5.1. Defining Remote Sensing: Passive vs. Active

Remote sensing is the process of gathering information about an object or area from a distance (Hay, 2000), typically using sensors mounted on satellites, aircraft, or drones. These technologies are categorized into passive and active systems depending on their energy source (see Fig. 21) (NOAA, 2023). Passive sensors record existing energy, usually reflected sunlight, such as standard digital cameras or high-resolution satellite imagery (e.g., Google Earth). Active sensors, however, use an internal light source, a laser, to collect information (NOAA, 2023). These sensors emit a signal and measure the reflection that returns, allowing them to analyze shapes and heights regardless of solar light.

A primary example of active remote sensing is LiDAR (Light Detection and Ranging). LiDAR sensors project laser pulses onto a surface and measure the time it takes for the reflection to return (Lefsky et al., 2002). By multiplying the elapsed time by the speed of light and dividing by two, the exact distance between the sensor and the target is calculated, mapping the environment with high precision (ibid.).

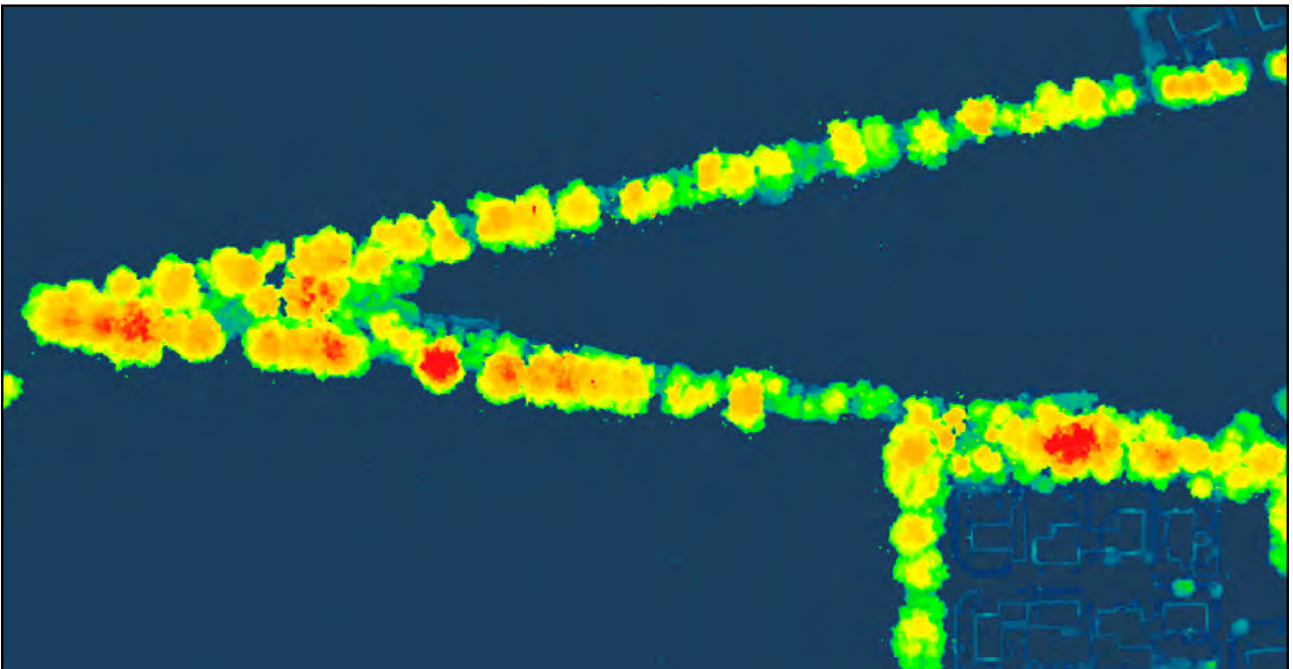


**Figure 21:** Schematic diagram of passive(left) versus active(right) remote sensing systems (NASA Earthdata n.d.)

## 2.5.2. Canopy Height Model (CHM)

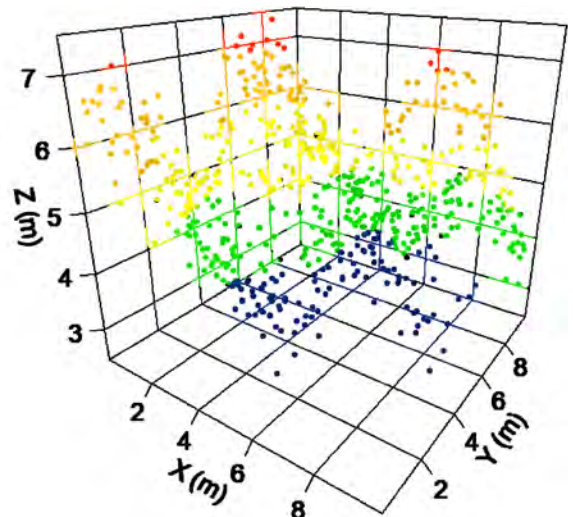
The continuous measurement of the vertical distance between an airborne sensor and the Earth's surface results in an outline of both the ground and the covering vegetation (Lefsky et al., 2002). In highly vegetated areas, most return signals bounce off plant canopies, while some penetrate to the ground, resulting in a highly accurate mapping of canopy height (See Fig. 22) (ibid.).

To create a Canopy Height Model (CHM), the 3D point cloud must first be rasterized into a grid of square cells (See Fig. 23). Each cell is assigned a Z-value representing height, resulting in a 2D image that is computationally lighter than a point cloud while preserving essential vertical information. A key factor is cell size. While a point cloud with a density of 20 points per square meter can support a  $5 \times 5$  cm resolution, tree leaves are typically larger than this. Therefore, a resolution of  $10 \times 10$  cm or  $25 \times 25$  cm is often preferred to maintain accuracy while significantly improving processing speed and reducing RAM usage.



**Figure. 22 (top)**  
Canopy Height Model (CHM) of the Krokstorp area.  
Coordinate system: SWEREF99 TM, Resolution: 0.5 m.  
Source: Hexagon; Helsingborgs Stad; Skogh (2026)

**Figure. 23 (right)**  
A schematic illustration of a point cloud derived from a Canopy Height Model. The  $10 \times 10$  m plot features a maximum vegetation height of 8 m. Illustration: Skogh/Claude by Anthropoc (2026)



## **2.6. Data Acquisition Methods**

*Selecting the appropriate data acquisition method is crucial, as the method dictates the scale, cost, and resolution of the resulting tree inventory.*

### **2.6.1. Airborne Laser Scanning (ALS)**

Airborne Laser Scanning involves mounting a LiDAR scanner on an aircraft (see Fig. 24) (Holopainen et al., 2013). ALS produces georeferenced point clouds suitable for calculating digital terrain, surface, and canopy models. While it requires high point density to segment individual trees and is affected by dense canopy closure, ALS remains the most practical and widely studied option for regional-scale monitoring.

### **2.6.2. Mobile Laser Scanning (MLS)**

Mobile Laser Scanning mounts a LiDAR scanner on a moving ground vehicle or person (see Fig. 25) (Holopainen et al., 2013). MLS easily achieves high pulse rates for shorter distances but is highly affected by understory shrubs, which can lower segmentation accuracy for overstory trees.

### **2.6.3. Terrestrial Laser Scanning (TLS)**

Terrestrial Laser Scanning mounts the scanner on a stationary tripod (see Fig. 26) (Holopainen et al., 2013). TLS dominates contemporary literature for under-storey mapping due to its extreme precision (Murtiyoso et al., 2022). However, the resulting ultra-high-resolution point clouds are computationally demanding, requiring substantial investments in processing devices and user training. Furthermore, TLS is technically challenging, requiring manual relocation to ensure correct scan overlap (ibid.).

## Data Acquisition Methods



**Figure 24.**

AI-generated representation of an airborne LiDAR system in flight. The image was generated by Gemini PRO according to the user's instructions.

Photo: Skogh/ Gemini PRO



**Figure 25.**

At the Ljungberg Laboratory, students will develop a wearable laser scanning device that collects 3D points from tree trunks as they walk through the forest.

Note that mobile laserscanners also can be mounted on moving vehicles like cars.

Photo: Linnea Kyrö Stenlund, Umeå Universitet, SLU.



**Figure 26.**

Multiple Trimble TX8 laser scanners collecting data from a dense stand that will be merged into one dataset.

Photo: Ljungbergslaboratoriet (2017)

## 2.7. Understanding Point Clouds

### 2.7.1. Point Density and Resolution

Point clouds are highly detailed 3D maps capturing the shape of objects like trees or buildings (Wang & Tian, 2025). The LiDAR sensor's resolution, its point density, directly dictates how accurately terrain and vegetation are represented (see Fig. 27 -29). Low point density leaves blank spaces. To create a solid surface, algorithms must fill in these gaps, often leading to interpolation bias where the computer "guesses" the shape between points (Aguilar et al., 2010). If density is too low, fine details are lost, making objects appear smoother or smaller than they are in reality (Dash et al., 2019). This leads to a systematic underestimation of vegetation size, from individual branches to entire understory layers, which critically impacts accurate landscape planning and climate strategies (ibid.).

However, point clouds with a density of 5–20 points per m<sup>2</sup> have demonstrated good results in tree detection in conifer forests (Li et al., 2012). As Holopainen et al. (2013, p. 547) state:

*"By increasing the number of laser pulses per m<sup>2</sup>, individual trees can be recognized... it is possible to derive the stem diameter, age, development class, basal area and stem volume for each individual tree."*

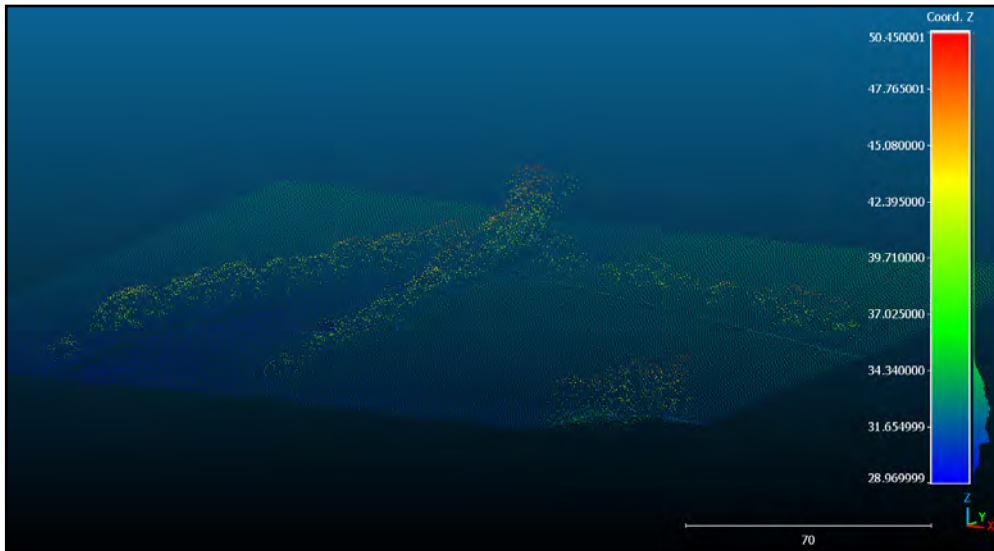
In Sweden, the open-source data from Lantmäteriet has a resolution ranging between 0–1 point per m<sup>2</sup> (Lantmäteriet, 2024). This density is useful for terrain modeling but limited for detailed vegetation analysis (see Fig. 27). In their study *A benchmark of lidar-based single tree detection methods using heterogeneous forest data from the alpine space*, Eysn et al., (2015) demonstrate how single trees can be obtained from airborne laser scanning data. However, in their conclusion section, they state that future studies should investigate the effect of different point densities on the detection results, but that such datasets are rarely available (Eysn et al., 2015).

### 2.7.2. First and Last Returns

Each laser pulse can produce multiple returns as it travels through a canopy. The first return typically hits the canopy top, while the last return is used to model the ground (Esri, 2024). However, in a dense canopy, a pulse may be fully absorbed and never reach the ground. Conversely, a low pulse rate may miss branches entirely, hitting the ground and creating gaps in the CHM that cause an underestimation of biomass (Esri, 2024; Fischer et al., 2024).

Urban landscapes add immense complexity. The mix of dense stands, solitary trees, buildings, and paved surfaces tends to cause an overestimation of low canopies and an underestimation of high canopies, known as the OLUH effect (Dong et al., 2025). Distinguishing real canopy gaps from those caused by buildings requires sophisticated, context-aware models.

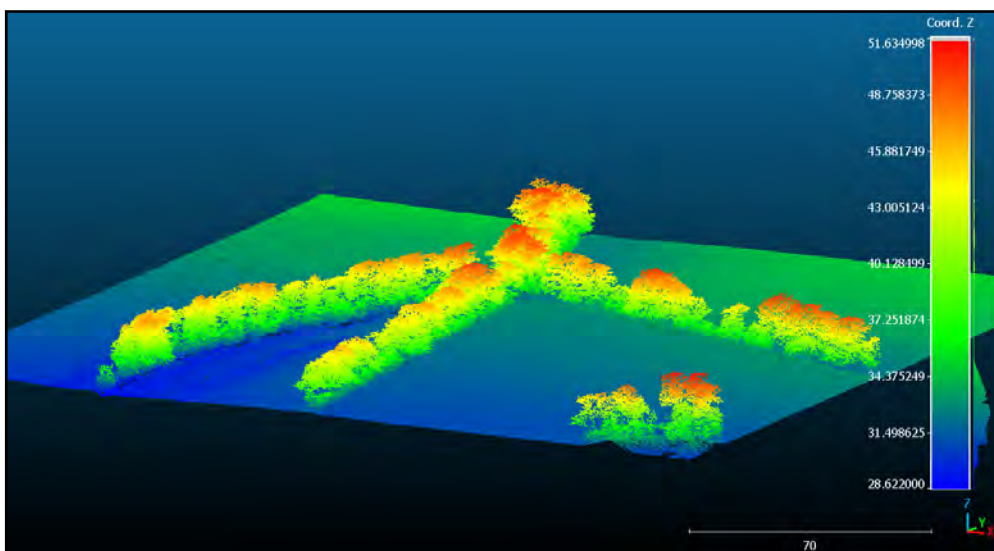
## Data Resolution: Number of Points per Square Meter



**Figure 27.**  
Point cloud consisting of 38,801 points within a 250 x 250 m area.

The data shows the Välluv area in Östra Ramlösa with an average point density of approximately 0.62 pts/m<sup>2</sup>

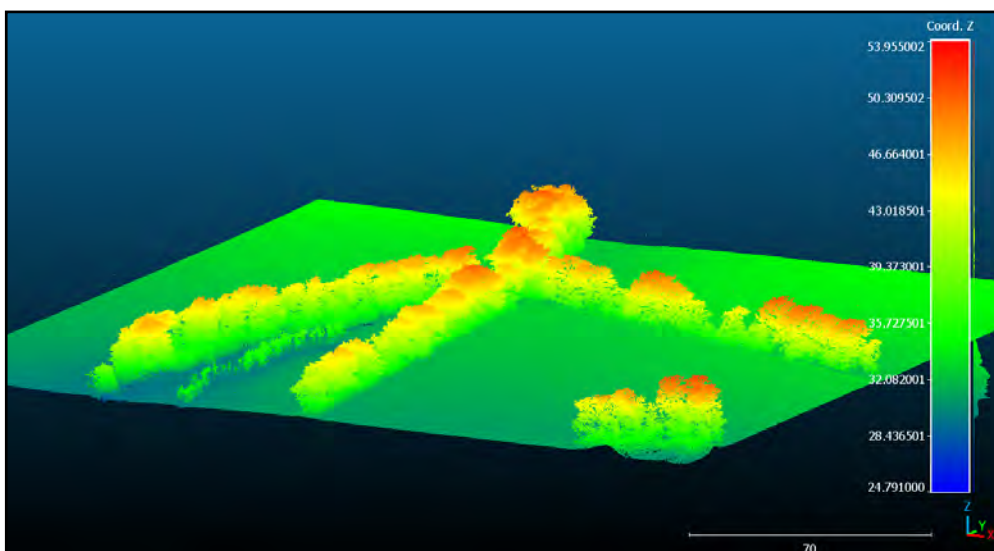
Source: Lantmäteriet (2026) Illustration: Skogh (2026)



**Figure 28.**  
Point cloud consisting of 2,045,936 points within a 250 x 250 m area.

The data shows the Välluv area in Östra Ramlösa with an average point density of approximately 32,7 pts/m<sup>2</sup>

Source: Hexagon (2022); Helsingborgs stad (2022) Illustration: Skogh (2026)



**Figure 29.**  
Point cloud consisting of 6,660,000 points within a 250 x 250 m area.

The data shows the Välluv area in Östra Ramlösa with an average point density of approximately 106,56 pts/m<sup>2</sup>

Source: Hexagon (2025); Helsingborgs stad (2025) Illustration: Skogh (2026)

## 2.8. Automated Individual Tree Detection (ITD)

*LiDAR has been used in forest science for a long time and has shown to be very useful in both fire modeling and forest management since the late 1990s (Li et al., 2012; Popescu and Wynne, 2004). Recently there has been an increase in studies using LiDAR for spatial planning and urban forest management (Fekete and Cserep 2021; Lu and Pankratz 2024; Alencar et al., 2026; Huo et al., 2026).*

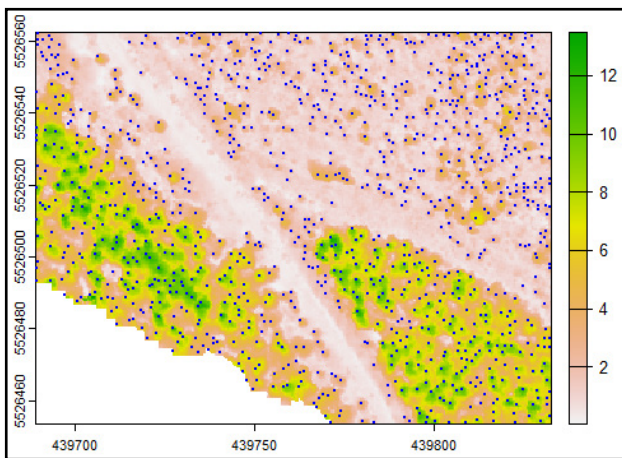
Segmenting individual trees from a point cloud is done in two steps;

1. *Individual Tree Detection*
2. *Individual Tree Segmentation*

Individual tree detection is the process of spatially locating trees and recording their heights, in other words, tree top detection (see Fig. 30) (Plowright, 2026). Individual tree segmentation is the process of individually delineating tree crowns around the detected tree tops, in other words, determining which points in the point cloud correspond to which treetops (see Fig. 31) (ibid.).

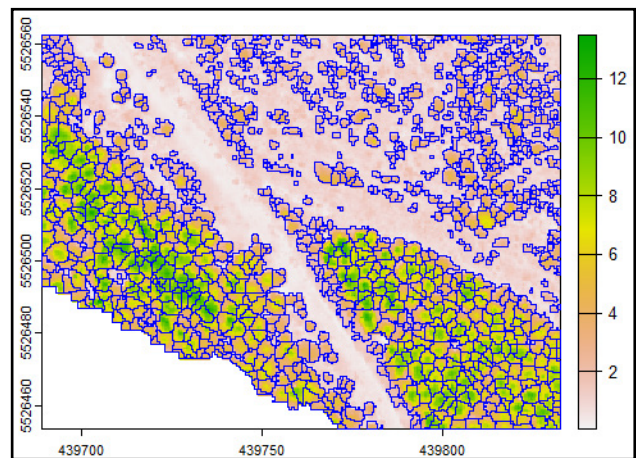
Most studies use coding-based tools to detect and segment individual trees from point clouds. Essentially, there are two different ways to perform segmentation. Either by using an algorithm- or a data-driven method. Algorithmic functions are traditional and follow fixed mathematical rules; most automated tools based on algorithmic methods are well-established and have long been used in forestry science. Data-driven methods are newer and in some contexts also include AI-based methods.

Individual Tree Top Detection



**Figure 30:** Results of a tree top detection using library ForestTools in software R. Source: Plowright (2023)

Individual Tree Top Segmentation



**Figure 31:** Results of a tree top segmentation using library ForestTools in software R. Source: Plowright (2023)

## 2.8.1 Algorithmic-driven methods in R

R is a free, open-source programming language for statistical computing and data manipulation (R Core Team, 2026). It utilizes libraries containing ready-to-use tools. The `lidR` library in R is an open-source package for manipulating ALS data, emphasizing forestry research (Roussel, 2023).

*“lidR is an R package for manipulating and visualizing airborne laser scanning (ALS) data with an emphasis on research & development for forestry and ecology applications. The package is entirely open source and is integrated within the geospatial R ecosystem.”*  
(Roussel, 2026)

Another library in R is `ForestTools`;

*“ForestTools are tools for analyzing remote sensing forest data, including functions for detecting treetops from canopy models, outlining tree crowns, and calculating textural metrics.”*  
(Plowright, 2026)

There are tools for segmenting forest point clouds in both `lidR` and `ForestTools`. While the `lidR` library has many different segmentation tools grouped under a function called `segment_trees`, `ForestTools` mainly has one way of segmenting trees in a point cloud (Plowright, 2026; Roussel, 2026). The method used in `ForestTools` is a raster-based method and `lidR` has both raster-based methods and point-cloud-based methods.

### 2.8.1.1 Raster Based Tree Top Detection

All raster-based methods require the creation of a canopy height model from the point cloud. Some methods use the CHM only for tree detection and then the point cloud for segmentation, while others use the raster model for both steps. Performing tree detection on a CHM is faster because there is less data to process, but it is also more complex because the output depends on how the CHM has been built (Roussel, 2026). The spatial resolution (i.e. pixel size), the algorithm used, and any additional post-processing steps will influence tree detection results (ibid.).

Raster based methods detect trees using the conceptual algorithm known as a *Local Maximum Filter* `lmf()`. This means that the tool first creates a list of coordinates that correspond to tree tops and then attempts to fill in the trees around those points. If the filter misses a top, the entire tree is omitted.

In coding environments like R, this principle is implemented in various ways. For instance, in the `lidR` library, the function `lmf()` (Roussel, 2026) can be used with either a fixed or a variable window size. When using a fixed window size, the algorithm can be explained as holding a magnifying glass over a raster map. Each time looking through the magnifying glass, marking the highest point visible, and in this way, moving across the entire map. The locally highest points that have been marked become the resulting treetops. As a general rule, when using a fixed window size, a large window is suitable for large, widely spaced trees, while a small window size is preferable for small, closely spaced trees (see Fig. 32) (Roussel, 2026).

If using a magnifying glass with a diameter of 5 meters, it is impossible to find a tree with a crown radius greater than 5 meters, because it won't fit inside the magnifying glass. Then trees with a crown radius larger than 5 meters will be divided into two or even more parts. This can lead the viewer to believe that the area is filled with lots of small trees when in reality they are large. Similarly, there are risks associated with using a window size that is too large. If the window size is 10 meters in diameter, the algorithm will

# Applying a Local Maximum Filter to a CHM

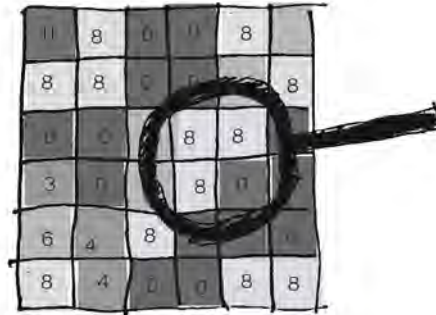


## 1. Choosing Window Size

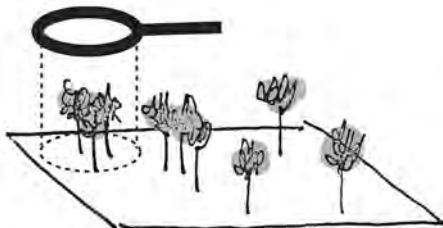
The local maximum filter is like looking through a magnifying glass. The size of the magnifying glass is where you will search for your local maximas (tree tops).

## 2. Finding Tree Tops

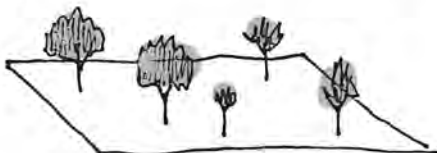
The search window detects the local maxima (in this case 11 meters) within the local search field and defines it as a tree top.



Landscape:



Results:



## 3. Interpret The Results

If the window is too large It skips over smaller peaks (shorter trees) near a taller one, merging them into one crown like shown in the image(undersegmentation).

If the window is too small It might count multiple branches of the same tree as separate individual trees (over-segmentation).

**Figure 32.** Simplified process of tree top detection using a Local Maximum Filter, illustrating how search window size influences result accuracy. Illustration: Skogh

only capture the highest point within the 10 x 10-meter area and ignore everything else. This can result in groups of small trees appearing as very large trees, or in small, sparsely distributed trees disappearing entirely from the dataset.

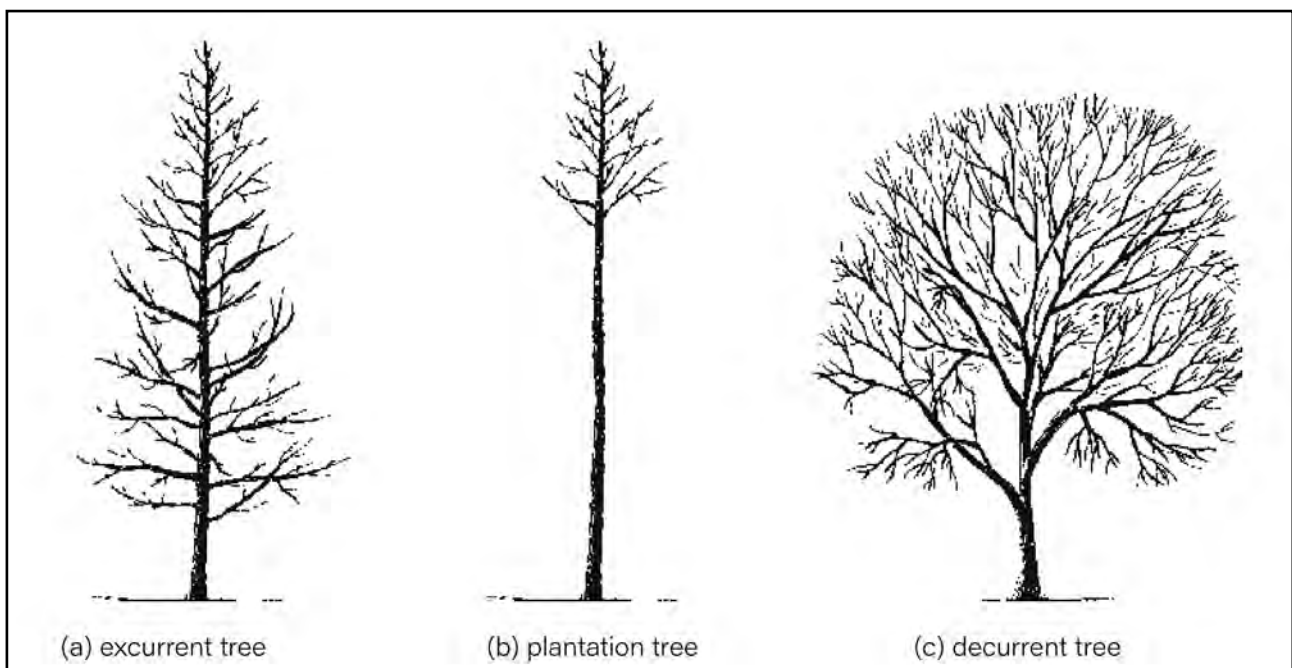
To avoid this, a variable window size,  $\mathbf{vwf()}$ , that adjusts the size of the search window based on the height of the tree can be used (Roussel, 2026).

*“In lidR a user can design a function that computes a windows size as a function of point (or pixel) height. When designing a function to define the window size based on point heights we need to determine what the minimum and maximum window size should be related to the minimum and maximum tree heights. In general, the minimum window size should not be smaller than 3 meters.”*  
(Roussel, 2026)

Depending on how the function is written, the method can be adapted for different forest types. Generally, the function can be thought of as a funnel; the taller the tree, the larger the search window becomes. However, this can create problems in mixed forests where deciduous and coniferous trees stand close together. Since a 20-meter-tall pine has a much smaller crown than a 20-meter-tall beech, it becomes difficult to adapt the algorithm to such conditions (see Fig. 33). Additionally, knowledge of the species present in the stand is required before the algorithm is designed.

In forestry, the client commissioning the analysis often knows which trees the landowner is growing in the area, and the analysis is used to calculate the timber volume of those trees. Applying these algorithms to a landscape to estimate how many and how large the trees are thus becomes difficult because the method relies, to some extent, on a certain degree of prior knowledge. However, there are algorithms that are already designed to be adaptable for complex forest stands, like the variable filter algorithm developed by Popescu and Wynne (2004) used in ForestTools (Plowright, 2026).

### Crown Size Depending on Habitus and Spacing



**Figure 33.** Different tree habits including (a) excurrent habit with a single leader (b) excurrent habit in dense plantation stand (c) Decurrent habit with spreading growth and no single leader (James 2010).

### 2.8.1.2 Raster Based Tree Top Segmentation

Following the `vwf()` tree top detection, ForestTools uses the algorithm *marker-controlled watershed segmentation* `mcws()` (Beucher & Meyer, 1993) to segment the created CHM into individual tree crowns (Plowright, 2026). The algorithm `mcws()` inverts the CHM and treats it like a terrain model. By assuming that the tree tops (formally the highest points of the model) are now the lowest points, these would be the terrain models drainage basins in case of a flood or rainfall. By letting the algorithm “flood” the inverted CHM it finds where the crowns meet and is able to outline the individual canopy shapes. This method is an efficient technique, both for the results produced and for the user control retained throughout the process and can also be applied to point cloud based tree detection results for more natural crown shape result.

Beucher and Meyer makes an important point in their discussion of their study on the `mcws()` method;

*“Image segmentation cannot be performed accurately and adequately if we do not construct the object we want to detect. Image segmentation is not the primary step in image understanding; it is its consequence.”*  
(Beucher & Meyer, 1993, p. 480)

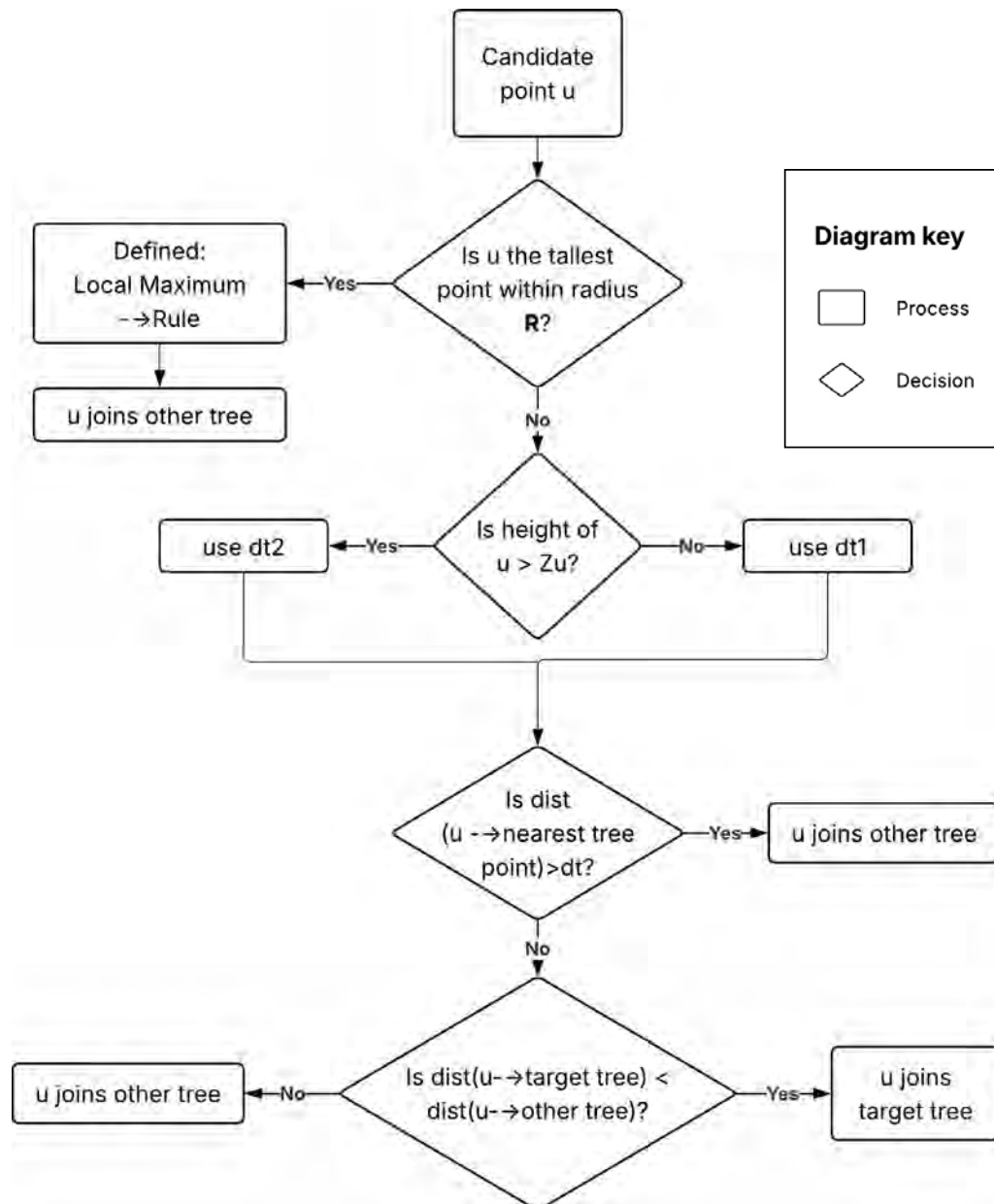
Thus, if the segmentation is incorrect, it is not because the `mcws()` failed to recognize the image. But because the initial interpretations of the image (the tree-top detection) provided the segmentation algorithm with insufficient information to construct a correctly segmented model. Consequently, this argues against using detection and segmentation algorithms as the sole tools for tree inventory in an unknown landscape. Comparisons with aerial photographs or other image data are necessary to gain an initial understanding of the types of trees one wishes to segment using this method.

### 2.8.1.3 Point Cloud Based Tree Top Detection and Segmentation

In the `lidR` package, the local maximum filter is point-cloud based, meaning that the filter is applied directly on the point cloud instead of on a CHM (Roussel 2026). It works exactly the same way, but skips the step of creating a CHM. In addition to `lmf()`, the `lidR` package also includes other point-cloud-based detection methods, one of them is `Li2012()`.

Instead of deciding a search window size and looking for a local maximum inside that window, `Li2012()` starts by finding the global maximum of the whole dataset (Li et al. 2012). This highest point represents the highest tree in the research plot. By starting at the highest point, the algorithm works its way down and uses the algorithm *k-mean clustering()* to determine which points should be assigned to the tree top. After `Li2012()` has segmented the first tree, the points that were assigned to the segmented tree will be removed from the pointcloud. `Li2012()` will be asked the question “*Is the point cloud empty?*” and if it is not, the algorithm will start over by identifying the new global maximum until the whole point cloud has been divided into individual trees (see Fig. 34) (ibid.).

# Individual Tree Detection and Segmentation with The li2012() Algorithm



**Figure 34:** Simplified schematic diagram of the logic of tree detection and segmentation with the li2012() algorithm in lidR library. Illustration: Skogh

The algorithm **li2012()** is just like the local maximum filter method tuned by thresholds (Li et al., 2012). In the study by Li et al. (2012), thresholds were decided by trial-and-error (Li et al., 2012). In their case, they assumed that a tree that is taller than 15 meters has a tree spacing at the upper level greater than 1 meter and that the crown diameter of that same tree is also greater than 1 meter (ibid.). Users of li2012() should tune the parameters based on the tree spacing in the study area.

*“In our algorithm, the uncertainty in tree segmentations mainly derives from the spacing threshold. In sparse forests where the tree spacing is large, we can use a relatively large threshold to isolate trees. [...]*

*We show that adaptive threshold approaches are sufficient in conifer forests in this study. In other forests, such as those dominated by deciduous trees with larger and more complex crowns and elongated branches, more object-oriented and shape-related rules should be incorporated to improve the accuracy.”*  
(Li et al., 2012)

In study areas like Östra Ramlösa, where large trees are commonly free-standing and small trees are usually grouped, both an adaptive threshold and shape-related rules would improve accuracy.

## 2.8.2. Machine learning- Methods

Advances in AI and automated analysis have led to one of the biggest changes in computer programming’s 80-year history (Thompson, 2026). A term that is often used is *AI-powered engineering* which refers to engineers who use AI agents to write, test, and monitor code. Clive Thompson interviews more than 70 software developers in his article *Coding after coders: The end of computer programming as we know it*, published in the New York Times on March 12, 2026. In the article Steve Yegge, a veteran coder who has worked at many companies, including Amazon and Google, gives the following statement;

*“It’s like we’ve been walking our whole lives, but now we have been given a ride, and it’s fast as [expletive].”*  
(Yegge cited in Thompson, 2026)

The new availability of code-savvy AI agents, such as Anthropic’s Claude Code or Google’s Gemini, has led to rapid advancements in deep learning tools (Thompson, 2026). Machine learning involves allowing a computer to identify patterns and correlations in data on its own, without the need to control every step of the analysis (Google Cloud, 2026). Deep learning is a more advanced form of machine learning in which the computer is trained to think and learn like a human brain using deep neural networks (ibid.). These advancements have resulted in open source deep learning models like the tree detection tool in the deep learning package in arcgis (Esri, 2026) and multiple tools for tree detection in Raster Vision (Azavea, 2024). Even though Raster Vision and ArcGIS Pro are non-specialist software packages that enables users to quickly and repeatably configure experiments that execute a machine learning pipeline (Azavea, 2024; Esri, 2026), they still require a basic understanding of the analytical method, and, as Beucher and Meyer (1993) point out, an understanding of what we want the results to be.

The advantage with most deep learning models is that they usually work both with aerial and drone imagery as well as point cloud or other height data (Zhang et al., 2025; Esri, 2026). Since remote sensing imagery is less costly than high-resolution point cloud data, it has a wider range of applications and offers high potential for individual tree detection due to its easy availability which also increases opportunities to monitor temporal change (Zhang, 2025). A common way to use deep learning when detecting trees is to show the model images capturing trees and then train it to find trees by itself in different imagery. Subsequently, the model can test the accuracy of the detected trees in the aerial image against a point cloud to test if there are enough elevated points to justify the detected tree

## 2.9. Technical and Institutional Constraints of using Point Clouds in Spatial Planning

*While LiDAR is a transformative tool, integrating it into spatial planning poses significant challenges that require an informed interdisciplinary alliance to overcome.*

### 2.9.1. The Landscape Planning Context

Digital tools like GIS, spatial analysis, and computer-aided design have become central to planning and landscape architecture. LiDAR has become a valuable data source within this shift (Urech et al., 2020). Although, using point cloud data in spatial planning poses challenges beyond data resolution and acquisition. One of the major concerns is that hardware and software requirements are high and file sizes are often too large for standard office equipment (Holopainen et al., 2013; Wang & Tian, 2025). Determining the minimum point resolution needed for accurate tree detection is an ongoing challenge. If set too high, the files become unworkable, if set too low, important detail is lost (Holopainen et al., 2013). However, studies show that institutional resource constraints are not a primary barrier, instead providing a solid methodological scaffolding allows designers to achieve high-precision, site-specific results and effectively transfer these complex digital skills to others, regardless of their starting point or available budget (Urech, Ahn & Lee, 2026).

Landscape architecture has a long tradition of drawing tree crowns as perfectly symmetrical circles (see Fig. 35). However, as noted by Kaartinen et al. (2012), representing crowns as simple circles can lead to significant overestimation or underestimation of canopy area. Datasets with lower point densities may only capture the dense center of a tree, leading to a small circle that underestimates the crown, while higher point densities capture outer branches that, when fitted to a circular model, exaggerate the tree's footprint (Kaartinen, 2012). Making changes in how data is presented and visualized in large institutions like municipalities requires interdisciplinary cooperation and a clear understanding of why precision in visualization is ecologically and practically necessary.



**Figure 35:** Landscape architect in Malmö drawing neighbourhoods Kroksbäck and Lindängen in the 1960s. Photo: Imager/Malmö Stadsarkiv

This shift towards data-driven planning has laid the foundation for the concept of *Urban Digital Twins*. Megha Hooli (2025) describes digital twins as a transformative technology that is currently revolutionizing the field. Similarly, Lei et al. (2023) describe Digital Twins (DTs) as virtual ecosystems of the built environment that facilitate improved management and decision-making in the physical world. In the context of landscape architecture, a DT is used to translate complex ecological data into visual, actionable insights for non-specialist decision-makers (Durden, 2025). However, a significant constraint in current DT implementations is the tendency to visualize vegetation using simplified, symmetrical symbols (Schrotter & Hürzeler, 2020). For a Digital Twin to be able to analyse microclimates, such as shadow patterns, wind mitigation, or urban heat island effects, the structural parameters derived from remote sensing must be represented with higher biological accuracy. Integrating species-specific allometric models would make the Digital Twin a more reliable tool for long-term ecological strategy (Schrotter & Hürzeler, 2020; Urech et al., 2020; Lei et al., 2023).

Finally, most research on remote sensing for tree detection focuses on dense or uniform forest stands. While studies on urban street trees exist, since urban forestry is a relatively young practice, therefore research tracking how urban vegetation changes over time is not yet accessible (Shafaat et al., 2025).

## 2.9.2. Noise and Processing Bias

Raw LiDAR data always contains noise, stray points from moving objects, sensor errors, or atmospheric interference. This noise must be removed before the data can be used. However, this cleaning process often creates a systematic bias. Sithole & Vosselman (2004) and Yan et al. (2018) note that algorithms often classify low or scattered vegetation as noise. This leads to errors, where the filtering algorithm accidentally deletes low-lying shrubs or thin branches because they look like errors (Sithole & Vosselman, 2004; Yan et al., 2018). The cleaning process usually favors smooth shapes. Trees are not smooth or regular. This means canopy edges get softened and crowns appear smaller and less dense than they really are (Sithole & Vosselman, 2004; Yan et al., 2018). For urban planners, this creates a risk. Valuable trees might be underestimated or completely erased from the digital model before a field survey even begins. Being able to review references and sources, in this case the dataset, is crucial in order to evaluate it critically and effectively. This becomes a constraint because knowledge of various data collection methods and filtering techniques cannot be assumed to be possessed by everyone working in municipalities or other interdisciplinary settings involved in urban planning. The final output, a clean vegetation layer, gives no indication that anything has been removed. A planner without remote sensing expertise has no obvious reason to question it.

### 2.9.3. The Availability of Open Data

Many LiDAR datasets are described as open or free. But free does not mean accessible, especially for non-specialists (Bara, 2025). Working with raw geodata requires specialist software, technical knowledge, and powerful hardware. Even community-sourced data like OpenStreetMap requires tools such as PostGIS, a specialist spatial database, useful for planning (Bara, 2025).

*“Datasets marketed as “publicly accessible” typically require minimum investments of \$1,000+ for serious analysis, with complex processing pipelines demanding \$10,000–100,000+ in infrastructure costs. More fundamentally, these barriers create a two-tier system where theoretical openness masks practical exclusivity, contradicting the democratization promises of the open data movement.”* (Bara, 2025)

This creates a situation where only specialists can manage the raw data, while smaller agencies that lack in-house expertise are hindered by high consultant costs and complex data models (Bara, 2025). There are also legal complications. Crowdsourced datasets sometimes contain personal metadata, which creates GDPR compliance issues for planners working in European jurisdictions (Bara, 2025).

## 2.10. From Point Clouds to Planning Metrics

Remote sensing technologies offer opportunities for tree inventory in municipal spatial planning. These technologies can provide detailed information about urban vegetation early in the planning process. This early information helps municipalities make informed decisions about when to engage the municipalities' mapping and surveying unit or external consultants or for detailed, costly, tree inventories.

Compared to point clouds created from photogrammetry, LiDAR point clouds provide a non-solid, structural representation of vegetation. The laser penetration of canopy allows for the extraction of complex metrics such as crown volume, vertical structure, and, in some cases, stem diameter (Holopainen et al., 2013).

Diameter at breast height (DBH) is a key measurement for tree assessment and is directly linked to the formal protection of trees in Swedish planning (Naturvårdsverket, 2012b). However, DBH is complex and sometimes impossible to extract directly from point cloud data. Therefore, an allometric relationship must be assumed. By measuring the crown extent, which is clearly visible from above, we can predict the DBH.

### 2.10.1. Tree Allometry in Urban Contexts

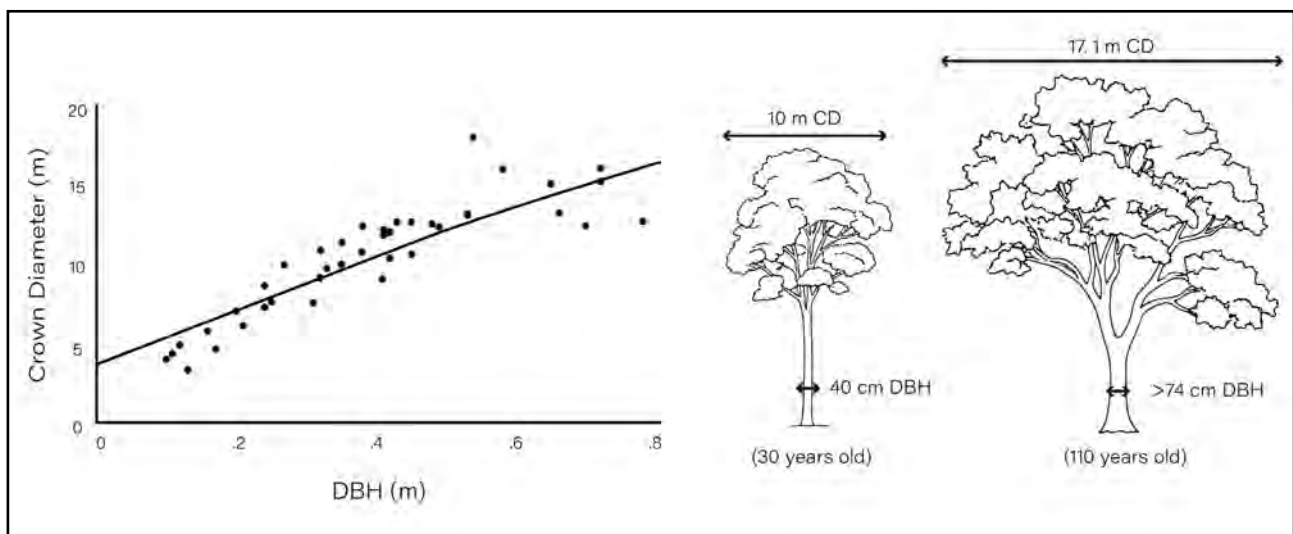
In forestry, tree allometry has been studied for a long time (Söderberg, 1986; Henry et al., 2013). However, not all equations are adapted to free-growing trees or very large individual trees. For urban and peri-urban contexts, where trees grow under different constraints than forest trees, specialized allometric relationships are needed (McPherson and Van Doorn, 2016; Pretzsch et al., 2015). Coombes et al. (2019) researched regression equations for crown diameter based on DBH measurements for four different species. The study was conducted on free standing urban trees in two UK cities; Norwich and Peterborough. Results included allometry predictions for *Acer platanoides*, *Quercus robur*, *Betula pendula*, and *Acer pseudoplatanus* (Coombes et al., 2019). The study found that the relationship between the trunk and the crown was very similar for all four species studied. Additionally, factors such as asphalt covering the roots, soil type, or whether the tree had been pruned previously did also not significantly alter the relationship between the trunk and the crown (ibid.). What does, however, affect the relationship between the trunk and the crown is the tree's age (see Table 3). When trees are young and narrow (up to 50 cm in DBH), the ratio between the trunk and the crown varies considerably. Small trees often invest a lot of energy into spreading their crowns quickly. The more the trees grow, the more stable the ratio becomes. When trees become large, the ratio of trunk to crown tends to be 1:25 (see Fig. 36) (ibid.).

However, more extensive datasets (Pretzsch et al., 2015) indicate that this relationship is better described by a logarithmic function, particularly for older, solitary trees (see Fig. 37). Furthermore, Pretzsch et al. (2015) emphasize that logarithmic models are superior because they account for the increased variability in crown size during a tree's expansion phase (20–60 cm DBH). This variability makes fixed-ratio thresholds less reliable for younger trees.

## Allometry: Free Standing Urban Oaks: Coombes et al. (2019)

**Table 3.** Individual allometry predictions for a given age of free-standing oaks in urban context.  
Source: Coombes et al. 2019; Illustration: Skogh (2026)

	Age (Yrs.)	DBH (m)	Crown Diameter (m)
<b>y</b>	15	0.25	7.3
<b>o</b>	20	0.29	8.1
<b>u</b>	30	0.37	9.7
<b>n</b>	40	0.44	11.1
<b>g</b>	50	0.50	12.4
<b>o</b>	60	0.56	13.5
<b>l</b>	70	0.61	14.5
<b>d</b>	80	0.65	15.4
<b>e</b>	90	0.69	16.1
<b>r</b>	100	0.72	16.7



**Figure 36.** Crown diameter versus DBH for *Quercus robur* in urban context (left) and a simplified illustration of what a tree with the given dimensions might look like (right). Source: Coombes et al. 2019; Illustration: Skogh (2026)

## 2.10.2. Defining Crown Area Thresholds for Preservation

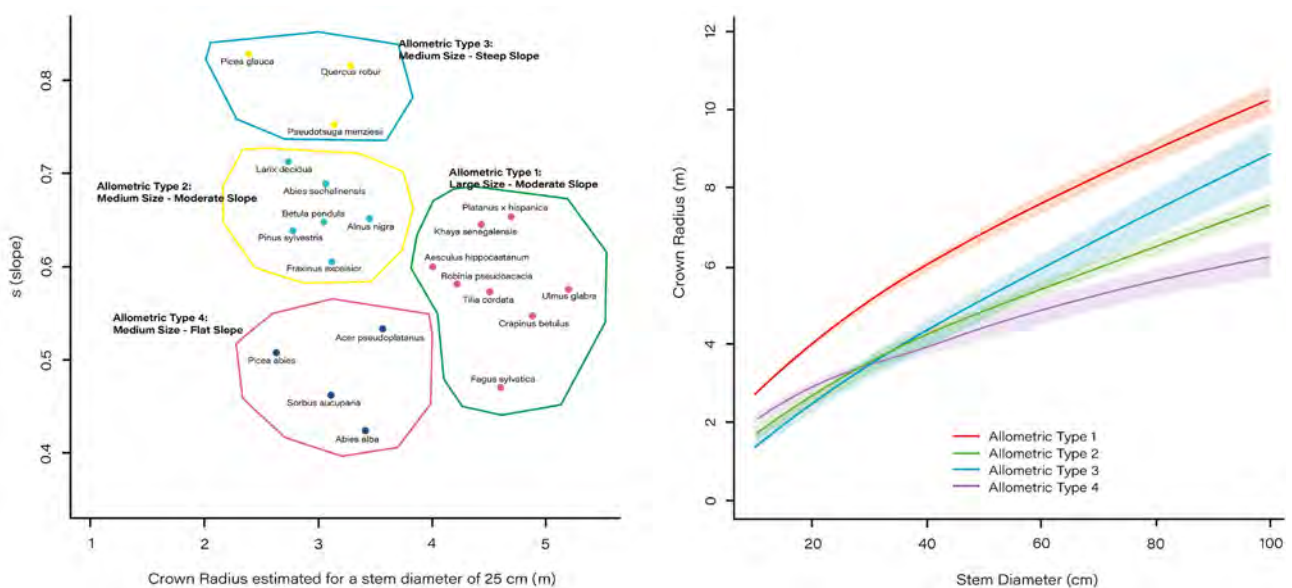
Deriving a DBH measurement from crown polygons extracted from LiDAR data will always be an estimate. The most important thing is to avoid the risk of overlooking large trees that have a legal protection like Särskilt skyddsvärda träd. Therefore, a simpler model, such as the one proposed by Coombes et al. (2019), may suffice for municipalities' needs in the early planning stages.

To account for the irregular shapes of urban trees (Kaartinen, 2012), a crown area threshold is more robust than a simple diameter measurement. Assuming that a tree with the crown diameter  $D$  has a crown radius  $r = D/2$ , the predicted area of a tree in that size range can be calculated as:  $A = \pi r^2$ . According to Coombes et al. (2019) a free-standing oak in urban conditions would have a crown diameter of 10 meters when having a DBH of 40 centimeters and a crown diameter of 25 meters when having a DBH of 100 centimeters (Coombes et al., 2019). These two thresholds would result in crown areas of 78.54 m<sup>2</sup> and 490.87 m<sup>2</sup>, respectively.

To ensure all potentially valuable vegetation is captured, applying the precautionary principle, the most conservative allometric relationship from the dataset should be used for initial screening. Moving forward, the logarithmic functions mentioned by Pretzsch et al. (2015), should be further studied since they, among other things, examine alder (*Alnus glutinosa*) which is very common in Swedish agricultural landscapes. Alders are also closely linked to habitats worthy of protection, as they often grow along watercourses. They also have a slender, upright growth habit, which means that large alders can be missed if a formula trained on broader trees such as oak and maple is used.

Finally, LiDAR data often underestimates vegetation size, especially in datasets with lower point density or high flight altitudes. Therefore, even trees falling slightly below this area threshold should arguably be flagged for further significance in the planning process.

### Allometry: Habit Types: Pretzsch et al. (2015)



**Figure 37.** A logarithmic function describing the relationship between crown size and DBH. This approach accommodates the increased crown size variability seen during a tree's expansion phase (20–60 cm DBH). Source: Pretzsch et al. (2015).

## 3. Interview Study

### Views from Academia and Industry on Tree Preservation in Spatial Planning

#### 3.1. Why Trees Matter in Spatial Planning

Across all interviews, interviewees described trees as providing a wide range of values, ecological, social, cultural, and climatic, that are difficult to quantify but widely acknowledged. Johan Larsson, an urban forest manager, talked about how to weigh these 'soft' values against the hard costs and timelines of urban development (Larsson, pers. comm., 23 February 2026). Because trees carry so many kinds of value simultaneously, they are both hard to assess and the consequences of their loss tend to be underestimated until it is too late. Rebecka Olsson, landscape architect, mentioned that the growing interest in the conservation of species in need of protection, such as bats, has increased awareness of the value of habitat trees (Olsson, pers. comm., 24 March 2026). A common understanding in all the interviews was a strong interest in protecting trees worthy of preservation, and that this is done to some extent in most large-scale projects.

Kalle Ågren, a consultant specialising in tree protection, said that economic valuation of trees is a powerful tool when weighing trees against other interests such as housing construction, new power lines, and other projects that offer significant economic gains (Ågren, pers. comm., 16 February 2026). In those projects he uses *Alnarpsmodellen* when assessing a tree's value (see Östberg et al., 2015). He says that the combined cost of buying a tree of the same size as the one to be felled, establishment and maintenance, amounts to a lot of money (Ågren, pers. comm., 16 February 2026).

Several interviewees referenced the growing regulatory and policy context that formalises this recognition. Both Annika Kruuse (pers. comm., 19 February 2026), an ecologist, and Ola Svensson (pers. comm., 25 February 2026), technical surveyor, noted that Article 8 of the EU Nature Restoration Regulation identifies urban vegetation as a priority. The regulation states that member states shall ensure that there is no net loss in the total national area of urban green space or of urban tree canopy cover in urban ecosystem areas by 2030 (Regulation (EU) 2024/1991). Note that this is not a direct ban on construction, but rather a requirement for net zero loss of tree cover. In practice, however, this means that new construction that takes up green space must be compensated for elsewhere, which can be very difficult in densely populated cities, making tree preservation in planning a relevant topic of discussion. At the municipal level, green structure programmes, species protection assessments, and documents like the balancing principle<sup>6</sup>, were frequently cited as the key frameworks within which tree-related decisions are made.

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<sup>6</sup> *The Balancing Principle* - A policy document used in spatial planning. In short, the policy means that if a natural value is destroyed or impaired by a construction project, it must be compensated for by creating or restoring an equivalent or higher natural value elsewhere.

A recurring theme was the mismatch between these formally recognised values and what actually happens on the ground. All interviewees agreed that when trees and economics are in conflict the trees consistently lose, if they are not protected under any specific regulation like the Swedish framework for trees worthy of special protection, biotope protection and nature reserves (Naturvårdsverket, 2012a). This gap between ambition and practice set the stage for many of the methodological and organisational challenges outlined in subsequent sections.

## 3.2. The Planning Process: Where do Trees Get Lost?

Multiple interviewees identified the statutory protection of designated trees and the timing of ecological and landscape input as the most important factor in whether trees are ultimately preserved. Many agree that larger plans tend to involve ecological assessments early, while smaller projects often proceed without them until very late in the process.

Once a Local Development Plan has been formally adopted it carries legal weight, making revisions costly and time-consuming (Norberg, pers. comm., 12 February 2026). As a result, there is an institutional reluctance to designate vegetation for protection unless it meets a high threshold of ecological or cultural significance. Protecting a specific tree in a local development plan that later proves to occupy a strategically important location, for utility infrastructure, for example, constrains the planning and construction process and reduces the flexibility available to developers and planners.

Hanna Norberg, an urban planner working with local development plans, made a connecting observation: she noted that a local development plan can take everything from one to 10 plus years to develop (Norberg, pers. comm., 12 February 2026). Thus, the same person rarely follows an urban development project through all phases, meaning that knowledge about specific trees and their significance could potentially be lost in handover. Rebecka Olsson, landscape architect, agreed (pers. comm., 24 March 2026):

*“In some cases, the trees on the site may have become worthy of protection since the plan was drawn up.”*  
- Rebecka Olsson

Johan Larsson noted that, especially when external parties apply for detailed planning permission, how big a part the trees get to play in the planning process is sometimes person-dependent (Larsson, pers. comm., 23 February 2026).

*“It works as long as people are on top of things, but the problem is that it is not part of the routines. That's what I strive for in my work, that trees should be included throughout the process, but there are so many levels. They have to be incorporated into routines, templates, and documents, so it's an enormous amount of work.”* - Johan Larsson

The institutional division of responsibility was another critical factor. Jesper Krantz, planning manager for trees, highlighted that his department, the urban environment administration, acts in an advisory capacity but holds no formal mandate over the development administration, the body that ultimately controls development decisions (Krantz pers. comm., 17 February 2026). Recommendations from the urban environment administration to preserve trees are frequently overruled in favour of cost and efficiency. Krantz pointed out that utility infrastructure is routinely placed in green spaces because this is cheaper than routing it through already paved areas. Once cables are laid, the owners can have the right to mandate a 10-metre tree-free zone around them - depending on the type of cable. This means that even green spaces without current trees can become permanently unavailable for future planting, creating

conflicts between urban canopy expansion and underground infrastructure that persist for decades (Krantz, pers. comm., 17 February 2026).

Nils Ekström, landscape architect, observed that awareness of tree protection has grown over the last decade, partly driven by the introduction of financial penalties, but that the fundamental challenge remains a gap early in the planning process where vegetation simply does not register as a constraint (Ekström, pers. comm., 13 February 2026).

Some of the interviewees identified a more technical version of the same problem: the legally required base map for municipalities, registers trees only as points, capturing no information about crown extent or root zone. Since planners often begin designing around this base map, trees effectively occupy no space in the early design model. By the time more detailed information is available, buildings and infrastructure have already been positioned.

Martin Brattström, who works as a consulting landscape architect in design and planning says he often comes in late in the process, after the zoning map has been established (Brattström, pers. comm., 27 February 2026).

*“Our wish is to be involved earlier in the process, to be able to influence the details. We want to monitor design issues more actively. Does the building have to be located there? Can we move it so that we can save this vegetation, etc.?” - Martin Brattström*

The idea that green expertise should be brought in earlier in the planning process was a recurring topic in the interviews, and the opportunities for doing so seem to vary greatly from project to project.

### 3.3. Inventorying Trees: from Field-Mapping to Remote Sensing

Inventorying trees, establishing what there is, where it is, how large it is, and what condition it is in - is the foundation of any protection or planning effort. Interviewees described a spectrum of methods, ranging from traditional fieldwork to large-scale remote sensing, and most emphasised that the two approaches are complementary rather than substitutable.

Field-based methods described across the interviews included visual assessment, measurement of trunk diameter and crown extent, root mapping and arborist assessments. Several interviewees described the limitations of field-based approaches at scale. Johan Larsson (pers. comm., 23 February 2026) outlined how airborne LiDAR and aerial photography enabled the municipality to create an individual-tree-level inventory for the entire urban area, something that would be impossible through field surveys alone. Sara Hultqvist, Geodata coordinator, described how remote sensing using LiDAR provides a 'bulk inventory' covering thousands of trees including those on private land, used as a directional estimate rather than an exact count (Hultqvist, pers. comm., 26 February 2026). Nicholas Coops, professor in remote sensing, says that tree segmentation done with standard routines like the lidR package in R will get you an 80 - 90% accurate assessment of the size of trees in an area (Coops, pers. comm., 26 February 2026).

*“There are problems with getting small trees under large trees. But if we want the big trees, the over story trees, the ones that give the biggest amount of shade, the ones that contribute the most to the ecosystem services, the ones that most people like, then we know that LiDAR can get that”*

- Nicholas Coops

The combination of remote and field inventory was presented by multiple interviewees as best practice.

*“If it's a research project then you actually have to go to the field and see: if the model identified five trees - is it really five trees in the real world, and the same for the height” - Yuhao Lu*

Yuhao Lu, assistant professor in landscape architecture, noted that airborne data always requires field validation to confirm what the remote data suggests (Lu, pers. comm., 25 February 2026).

## 3.4. LiDAR Data: Current Use and Potential

The remote sensing technology discussed most during the interviews was LiDAR. Out of the 14 interviews, nine people had actively used some form of LiDAR or Point Cloud data in their work. The usage and type of data varied between everything from terrain modelling to individual tree crown segmentation.

Those working in technical roles (such as the cartographer, surveyor and geo data coordinator) used point clouds directly for analysis. The urban planners and the urban forest manager used LiDAR data that had been processed by the previously mentioned professional groups. They used the data when drawing maps and visualisations as arguments in their work.

### 3.4.1. The Data Resolution

Kalle Ågren (pers. comm., 16 February 2026), consultant, uses the Swedish National Land Survey's (Lantmäteriets) open source nationwide LiDAR dataset, with a resolution of 1–2 pts per square meter, because of its wide coverage across the country. Using this data allows him to deliver analyses and decision-making support regardless of the client's resources or local data availability (Ågren, pers. comm., 16 February 2026). Johan Larsson believes that such low-resolution data is difficult to work with if you do not have the knowledge or ability to process it yourself (Larsson, pers. comm., 23 February 2026).

*“Crown cover measurements have been taken nationally in all cities, but they rarely have the quality or resolution that would allow them to be used at the level that would be desirable in a municipality. If you look at Husqvarna's analyses, they often interpret farmland as vegetation areas, which makes them very rough and very difficult to use in practice.” - Johan Larsson*

Lu works with publicly available open source data with a point density comparable to the Swedish National Land Survey's laser dataset. In his opinion, this is sufficient for a city-wide tree crown mapping (Lu, pers. comm., 25 February 2026). He cautioned that the output is not 100 % reliable, but good enough as an indication on where the city has big valuable trees.

Svensson (pers. comm., 25 February 2026), Hultqvist (pers. comm., 26 February 2026), and Dahlén (pers. comm., 19 February 2026), all working at municipalities, use high-resolution LiDAR data purchased commercially by their respective cities. Both Helsingborg and Lund worked with data bought from the industry-leading airborne mapping company Hexagon, at a point density of approximately 22–25 points per square metre, delivered pre-classified into high, medium, and low vegetation categories.

Norberg pointed out that in Helsingborg's most recent acquisition from 2022, urban areas were purchased at this density, while the country side was covered by cheaper, less classified data (Norberg, pers. comm., 12 February 2026). Data acquisition is typically organised through regional agreements. Hultqvist noted that municipalities often collaborate, with scanning occurring approximately every two to four years (Hultqvist, pers. comm., 26 February 2026).

### 3.4.2. The Timing of Data Collection

Several interviewees highlighted that a scan conducted leaf-off reveals ground conditions and understory vegetation, while leaf-on data is better suited for visual tree analysis. Since the National Land Survey's dataset is collected primarily during the leaf-off season, it is less reliable for crown mapping purposes, a trade-off that must be accounted for when choosing a data source.

### 3.4.3. Flexible Generation of Point Clouds using Drones

Coops noted that there is a big potential both in airborne LiDAR and drones from an urban planners point of view. He described data collecting with drones as an ongoing trend that is currently revolutionizing the industry (Coops, pers. comm., 26 February 2026).

*“It's the ability to launch and collect data when you want, instead of relying on a satellite program or a provincial state program, that makes drones so extraordinarily powerful. So that's a massive change that we're currently undergoing, the ability of foresters, landscape planners, city planners to collect their own data, and that's a revolution.”* - Nicholas Coops

Ryan Davidson, research engineer, talked about the different types of drones he had used for field data collection (Davidson, pers. comm., 20 March 2026). He specifically compared traditional photogrammetry with the latest advancements in LiDAR technology, such as the DJI Matrice 350 RTK equipped with a Zenmuse L2 sensor. Davidson emphasized that this integrated LiDAR system represents a significant leap in efficiency; because the laser scanner requires less side-overlap (20%) compared to a photo-based sensor, the drone can cover an area three times faster (ibid.). Furthermore, the L2 sensor's ability to capture 20-megapixel RGB data simultaneously allows for the creation of colorized 3D point clouds without the edge-distortion often found in photogrammetry (Davidson, pers. comm., 20 March 2026). The resulting datasets are significantly denser and heavier than airborne data, but the high resolution - with a pixel size of 2.7 cm - offers a level of detail that is unmatched (ibid.).

### 3.4.4. Processing and Segmentation

The process of converting raw LiDAR point clouds into usable information about individual trees was described by several interviewees. All interviewees that processed raw LiDAR scans described a workflow carried out in R. A number of consistent themes emerged: the challenge of processing large datasets, the bias and limitations of automated segmentation, and the need for parameter tuning.

Lu processed the Winnipeg city-wide scan tile-by-tile, which took approximately two weeks on a single computer, with per-tile runtimes of one to two hours, longer for forested or complex tiles (Lu, pers. comm., 25 February 2026). Hultqvist found that standard segmentation parameters embedded in the R libraries she used were too coarse for Swedish urban environments and required significant manual tuning through testing on smaller sub-areas (Hultqvist, pers. comm., 26 February 2026). Results were affected by segmentation kernel size and angle, and the method struggled to distinguish multiple small trees from a single multi-stemmed crown, a common problem in dense canopies (Hultqvist, pers. comm., 26 February 2026).

Ola Svensson, at city of Lund, used FME, a data integration platform from Safe Software, alongside ArcGIS Pro and R, for automated, repeatable LiDAR-based workflows (Svensson, pers. comm., 25 February 2026). Ågren (pers. comm., 16 February 2026) worked with machine learning via the Python framework Raster Vision to segment tree crowns from aerial photography, finding that integrating height rasters from LiDAR improved precision. He noted that he had not yet worked with unclassified point clouds to the same extent (Ågren, pers. comm., 16 February 2026).

## 3.5. Using the Results - Planning Support, 3D Visualisations and Analysis

Interviewees described a range of applications for the outputs of LiDAR-based analysis in landscape architecture. The use ranged from operational tree management to 3D environmental simulations used in detailed planning and design.

Dahlén (pers. comm., 19 February 2026) described her role as a cartographer supporting planners in creating 3D environments for detailed plan assessments. She described extracting tree height and green volume from LiDAR to generate complete 3D vegetation models, which planners used for shadow analysis, visibility assessment, and sightline evaluation. She noted that the point cloud gave more of a volume rather than a distinction between crown and trunk (Dahlén, pers. comm., 19 February 2026).

Hanna Norberg, urban planner, used a tree canopy layer, created by Helsingborg municipality from LiDAR data processed with machine learning, when visualising crown extent as an initial base when planning and transferred outputs to CAD for design work (Norberg, pers. comm., 12 February 2026). She also worked in ArcGIS Pro to view pointcloud to extract sections and used Photoshop or Illustrator for final presentations. She noted that while the municipality's basemap represents trees as points and crowns could be added as round icons, the organic shapes used in the new tree layer created a stronger emotional connection to the trees (Norberg, pers. comm., 12 February 2026).

Ågren (pers. comm., 16 February 2026) mentioned how LiDAR could tie into the 3-30-300 framework, which specifies that every urban resident should be able to see at least 3 trees from their window. A LiDAR-derived crown map could directly support this by offering 3D views from buildings, assessing how many trees are visible from residents' windows.

Coops described droneborne LiDAR scans at UBC to analyze movement patterns in public parks.

*“The study used drones just to see how people use parks. So the drones sit there and collect imagery during the day monitoring where people are walking, what parts are being used the least, what groups of trees are being avoided, it comes to questions like How accessible is the park? How usable is the park? Is it meeting the needs of the local community?” - Nicholas Coops*

Coops also mentioned collaborations with municipalities where the city had an issue with invasive species (Coops, pers. comm., 26 February 2026). With LiDAR and hyperspectral imagery they demonstrated to the municipality how the technologies could be used to identify where those species are growing.

## 3.6. Challenges

### 3.6.1 Technical and Computational Challenges

The sheer size of LiDAR datasets was the most cited technical challenge. Ågren, Svensson, Hultqvist and Lu (pers. comm., 16, 25, 26 February 2026) all described data volumes that strain consumer hardware and require either tiled processing or dedicated infrastructure.

*“They are difficult to work with on a consumer level computer. But that is regarding the city scale, if you have a site that's 2 hectares then it is not a problem.” - Yuhao Lu*

Svensson argued that dedicated GPU hardware is required for efficient processing. Because a computer with a dedicated GPU adds approximately 15,000 SEK per user, municipalities cannot afford to provide such machines to non-specialists (Svensson, pers. comm., 25 February 2026). Norberg observed that LiDAR processing was slow on her current workstation. Another challenge was that the program procured by the municipality to construct local development plans was outdated and not compatible to display point clouds in 3D. Transition to a program with that compatibility had been delayed for years. This makes the use of point clouds an extra step in the workflow (Norberg, pers. comm., 12 February 2026).

### 3.6.2. Organisational Challenges

#### 3.6.2.1. Inconsistent Mapping

The interviewees who worked in municipalities talked about having multiple separate GIS maps that include trees, maintained by different departments with different collection methods, attribute structures, and quality levels. This was leading to overlaps, inconsistencies, and significant errors (Krantz, pers. comm., 17 February 2026), (Dahlén, pers. comm., 19 February 2026).

*“We have three different GIS layers with trees that are used in three different departments/units. This means that there are large areas where no one has entered any trees and other areas where trees have been entered from three different sources.” - Linnea Dahlén*

#### 3.6.2.2. Interdisciplinary competence and education

One challenge that was brought up during the interviews was to work in urban forestry and bring planning, design and forestry, that historically has been separate fields, together in terms of competence and collaboration. Ågren (pers. comm., 16 February 2026), consultant, highlighted that while consultants often have expertise, municipalities need in-house competence, a landscape architect or landscape engineer, to identify conflicts between green and grey infrastructure and to manage consultant relationships effectively.

This gap is also reflected at the educational level. According to professor Nicholas Coops, one of the challenges is finding students with an interest in both remote sensing and urban planning or development.

Remote sensing has traditionally been closely tied to forestry, and has not yet been meaningfully integrated into landscape architecture education, meaning that the practitioners best positioned to bridge the two fields are rare (Coops, pers. comm., 26 February 2026).

*“As a researcher in remote sensing and a professor in a university the challenge is finding students that have an interest in urban planning and in remote sensing, there are not many. Because urban planners don't learn about remote sensing and they've got this reticence about using it. And then remote sensing people in forestry don't particularly care about urban areas.”* - Nicholas Coops

As interest in urban forestry grows, practitioners without coding background are increasingly turning to tools like R, often relying heavily on AI assistants to do so. Assistant professor Yuhao Lu also recognizes that due to landscape architecture students not having any training in coding, their use of AI tools can be harmful for the basic understanding of coding (Lu, pers. comm., 25 February 2026).

*“I think that one of the drawbacks of using AI as your copilot is that you can get stuff done pretty fast in coding but the process of comprehension might take longer time.”* - Yuhao Lu

He mentioned that the process of debugging might be difficult since they are not writing the code themselves (Lu, pers. comm., 25 February 2026). A recurring theme in the interviews was that not everyone has the expertise to work with point clouds. This stemmed both from a sense that the tools currently in use for tree crown mapping work well for their intended purposes, and from the fact that there is limited time to learn new software alongside regular work duties.

### 3.6.2.3. Institutional challenges

Nearly every interviewee described structural tension between development interests and tree preservation, with several noting that protection plans are frequently disregarded in practice and that penalty clauses are often set too low to act as an effective deterrent. Krantz described a situation in which a widening of a cycling path caused tree damage assessed at 8 million SEK, but compensation paid was only 1.5 million SEK due to inadequate pre-construction inventory and documentation (Krantz, pers. comm., 17 February 2026). Additionally, the penalty of 1.5 million SEK reached the penalty limit specified in the contract between the municipality and the contractor, which prevented the traffic reconciliation unit from issuing the additional penalties they had intended. This illustrates both the real financial value at stake in tree protection and the practical consequences of inadequate documentation and contract design (Krantz, pers. comm., 17 February 2026).

## 3.7. Summary of Themes

This interview study examined how professionals work with tree protection in urban development, and how LiDAR and point cloud data are currently used for tree crown mapping. The interviews reveal a field in transition, where the value of urban trees is broadly acknowledged, digital tools are improving, and a growing number of practitioners are actively working to strengthen trees' role in planning. LiDAR emerged as the most widely used remote sensing technology, with applications ranging from city-wide crown mapping to 3D visualisation in detailed planning. While workflows are becoming more accessible, barriers remain. Including computational demands, inconsistent data quality, and a shortage of practitioners bridging remote sensing and urban planning. The interviewees themselves represent an emerging group navigating exactly this gap.

Despite the challenges described, the interviews conveyed a sense that the field is moving rapidly. A shared aspiration emerged: to move from reactive, underdocumented tree protection toward routinely available spatial data integrated into standard planning workflows. LiDAR-based crown segmentation is one important component of this transition. Powerful, but most effective when embedded in organisational, legal, and political frameworks that genuinely prioritise urban trees.

# 4. Technical Study

## Testing Two Methods of

## Automated Individual Tree Detection

*The following section presents the results obtained from the technical site application. The aim was to test various methods for tree detection and segmentation based on the findings from the literature and interview studies.*

### 4.1. Raster Based Tree Detection and Segmentation using ForestTools

Initial testing of the variable window filter-, `vwf()`, and marker-controlled watershed segmentation-, `mcws()`, algorithms, with default thresholds at the two reference plots indicated that the default parameters were not well calibrated for the vegetation in Östra Ramlösa (see Fig. 38). The vegetation types that the algorithm had the most difficulty interpreting were closely spaced deciduous trees. These were not necessarily small trees; even large trees were under- or over-segmented when their crowns were intertwined.

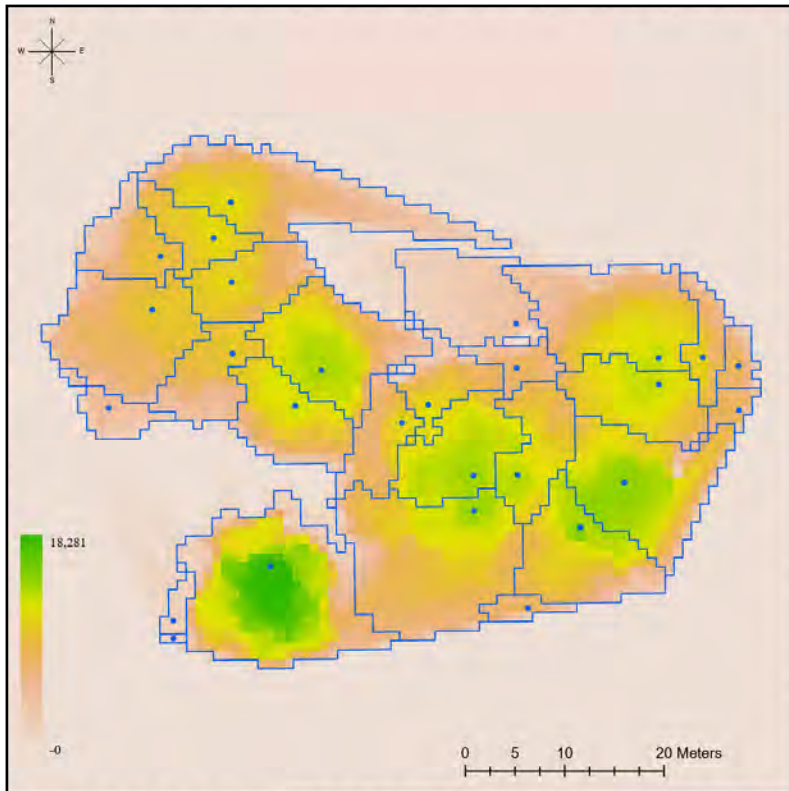
The results of the *grid search*<sup>7</sup>, testing 255 combinations of algorithm parameters `slope` and `intercept`, at the two reference plots are presented in Fig. 39 and Fig. 40. The lowest error was achieved by 15 different `slope`- and `intercept`-combinations, which produced exact count matches on both plots (see Table 4). Performance was strongly determined by an inverse linear relationship between the `slope` and `intercept` parameters. As visualized by the yellow diagonal band in the Site\_1 heat map, there is a direct trade-off between the two values: a higher intercept (a larger minimum search window) requires a proportionally lower `slope` (a slower increase in window size relative to tree height) to yield an accurate tree count. Additionally, the heat maps reveal that Site\_1 had a significantly narrower tolerance for parameter variation than Site\_2, indicating that the denser, more complex vegetation structure of Site\_1 acted as the primary limiting factor in the overall optimization process. Thus, the optimized baseline formed the final `vwf()` result of: `vwf({0.05 * x + 3.0})` and `minHeight = 5m`

Both the default (`slope=0.05x`, `intercept=0.6m`, `minHeight=2`) and the fifteen optimized parameter set combinations (see Table 4.) were applied to the Östra Ramlösa survey area, which contained a ground-truthed count of 43 trees. Among the fifteen optimized combinations, the best result was achieved by the parameter set utilizing a `slope` of `0.05x` and an intercept of `3.00m`, which detected 48 trees (see Fig. 41). While this specific combination yielded the lowest error, overestimating the actual count by only 5 trees, a general trend of over-segmentation was observed across the board.

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<sup>7</sup> *Grid Search*. A systematic optimization method that tests all possible combinations of a specified set of parameters to find the most accurate model configuration.

## Default Values of `wvf()` Algorithm

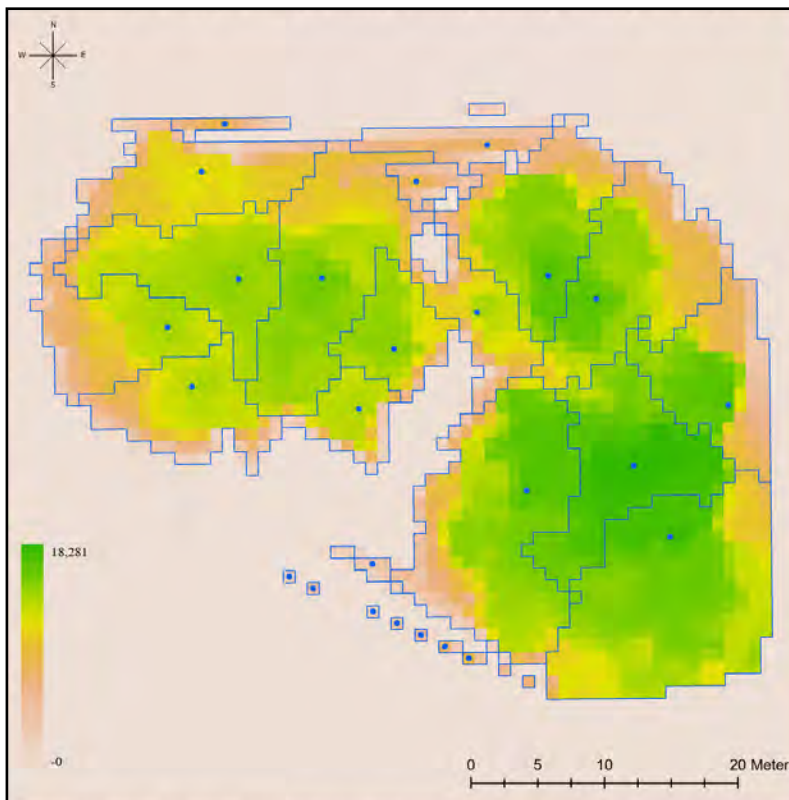


- Detected Tree Crown
- Detected Tree Top

### Plot\_1

Field Validated Tree Count: 7

`wvf()` Detected Tree Count: 27



### Plot\_2

Field Validated Tree Count: 4

`wvf()` Detected Tree Count: 25

**Figure 38.** Applying the default thresholds of the `wvf()` algorithm to the reference plots resulted in oversegmentation. In Plot\_1, 27 trees were detected compared to a ground truth of 7; in Plot\_2, 25 trees were detected compared to a ground truth of 4.

## Grid Search: Site\_1: vwf()

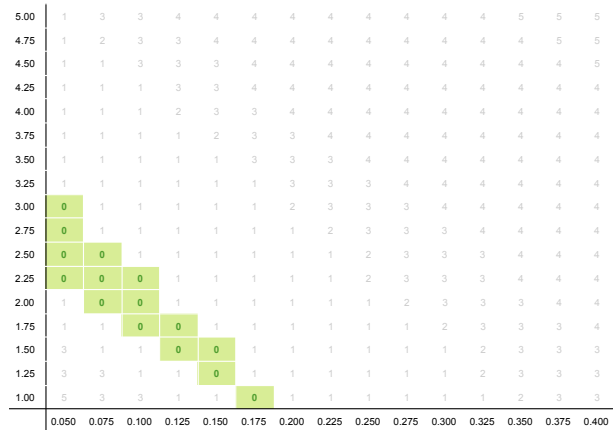


Figure 39. Grid search results for the vwf() algorithm at Plot\_1 (ground truth = 7 trees, minHeight = 5 m). Each cell shows the absolute detection error for a given window function slope × intercept combination.

## Grid Search: Site\_2: vwf()

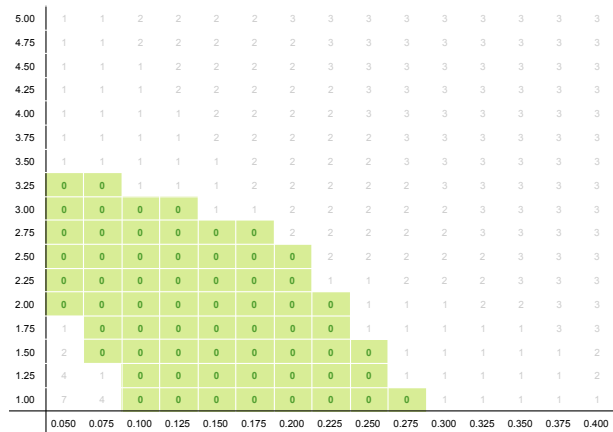


Figure 40. Grid search results for the vwf() algorithm at Plot\_2 (ground truth = 4 trees, minHeight = 5 m). Each cell shows the absolute detection error for a given window function slope × intercept combination.

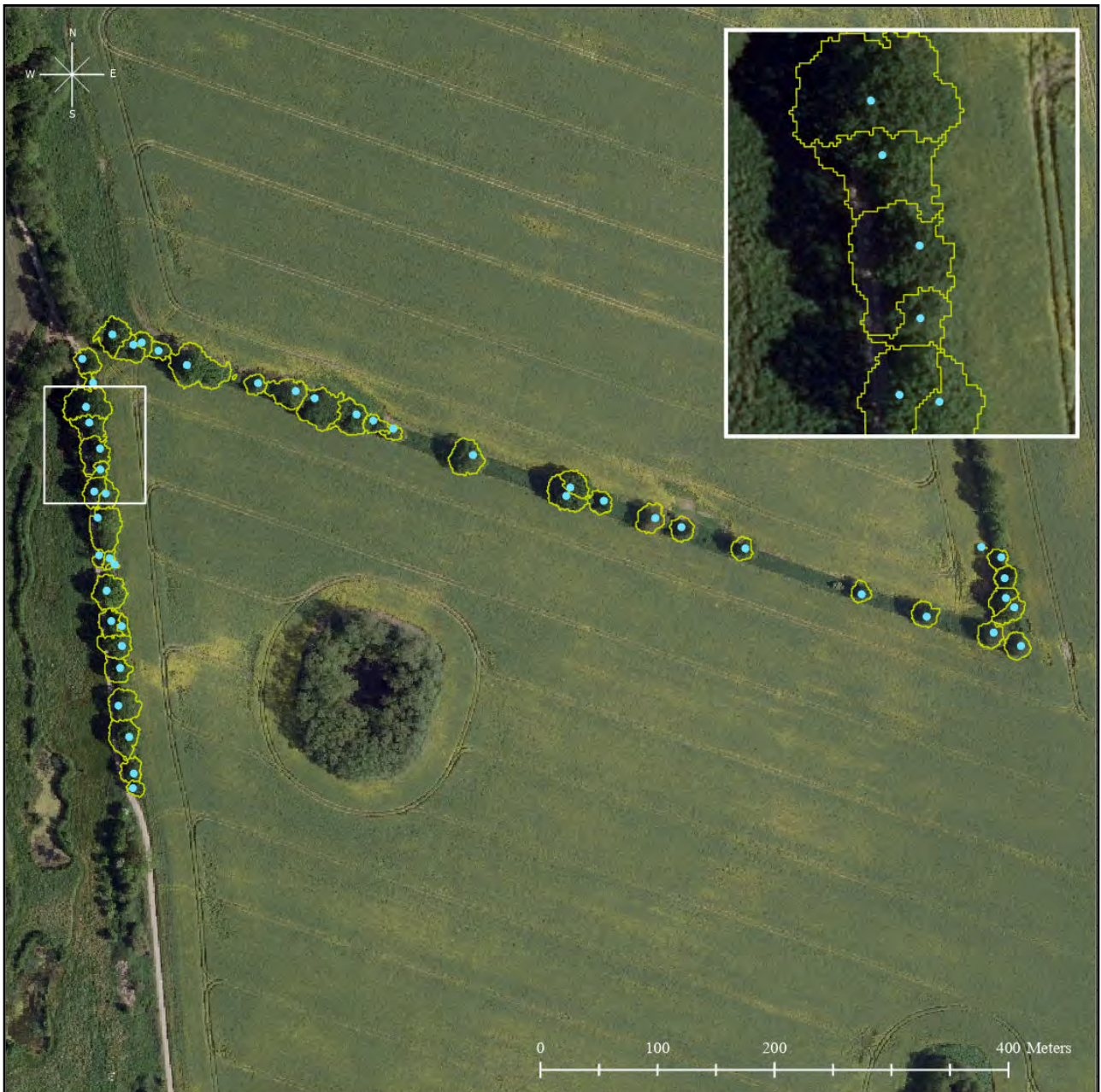
## 15 Optimized Combinations: Ötsra Ramlösa: vwf()

Table 4. The 15 vwf() parameter combinations that achieved zero detection error on both reference plots (Site 1, 7 trees; Site 2, 4 trees). The final columns show how each combination performed when applied to the Östra Ramlösa Field Survey (43 trees), where all combinations overestimated stem count by 5–15 trees. The selected combination highlighted in green (slope = 0.05, intercept = 3.00) produced the lowest error on Välluv and was selected for accuracy assesment and application to the Krokstorp Field Study.

#	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
Slope	0.050	0.050	0.050	0.050	0.075	0.075	0.100	0.100	0.100	0.125	0.125	0.125	0.150	0.150	0.150
Intercept	2.25	2.50	2.75	3.00	2.00	2.25	2.50	1.75	2.00	2.25	1.50	1.75	1.25	1.50	1.00
Error	15	11	8	5	15	10	7	15	9	6	15	8	12	7	11

# Optimized $wf()$ Combination Applied to Östra Ramlösa

- Detected Tree Crown
- Detected Tree Top



**Figure 41.** The optimized  $wf()$  parameter combination ( $slope = 0.05$ ,  $intercept = 3.00$ ) produced the lowest error in Östra Ramlösa, detecting 48 trees against the ground truth of 43.

## 4.2. Point Cloud-Based Tree Detection and Segmentation using lidR

To address the limitations of CHM-based detection observed in the previous step, a secondary segmentation was performed using the `lidR::lidRseg()` algorithm, which operates directly on the 3D point cloud.

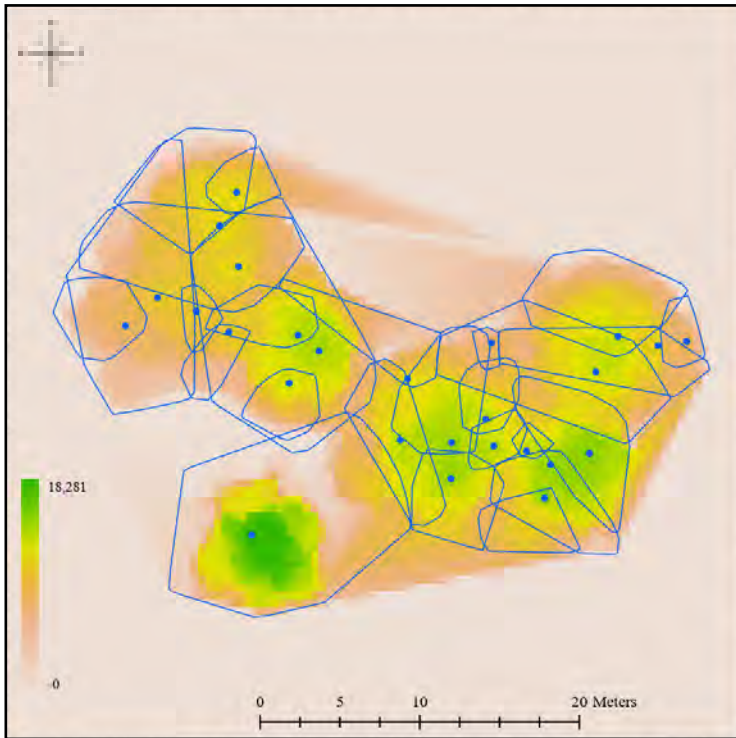
Initial testing of the `lidR::lidRseg()` algorithms, with default thresholds at the two reference plots and the 2025 survey area produced heavy oversegmentation in all three sites. The algorithm produced 26 detected tree tops at Plot 1, 13 at Plot 2 (see Fig. 42) and 280 at the Östra Ramlösa field survey, producing a heavy oversegmentation at all sites. The results of the grid search, testing 252 combinations of algorithm parameters `dt1`, `dt2` and `Zu`, at the two test plots and the 2025 Östra Ramlösa field survey are presented in the heat maps (Fig. 43, Fig. 44 and Fig. 45).

In the results of the search in Plot\_1, 200 of the 252 tested combinations (79.4%) achieved an absolute difference of 0, meaning the algorithm detected exactly 7 trees, matching the field-validated count. Over-detection was only observed at the smallest `dt1` values (1.5–2.0m), where up to 12 trees were detected. From `dt1`  $\geq$  3.0m onward, the detection stabilized entirely, and the result was largely insensitive to the choice of `Zu`. Plot\_2 did not produce any results that achieved an absolute difference of 0. Instead, 232 of 252 combinations (92.1%) achieved the lowest recorded error of 1, consistently detecting 5 trees against a ground truth of 4. Again, over-detection was confined to the smallest `dt1` value (1.5m), which produced 8 detections.

The full 252-combination grid search was selected for the Östra Ramlösa field survey as well. Only 8 of the 252 tested combinations (3.1%) managed to achieve the lowest recorded error, detecting exactly 59 trees, which represents an absolute difference of 16 from the ground truth of 43 trees (see Table 5). A clear pattern emerged regarding the algorithm's sensitivity to distance thresholds. The heat map and the underlying data demonstrate that smaller `dt1` values (1.5m to 2.5m) resulted in massive oversegmentation, in some cases detecting over 200 "trees".

Accuracy only began to stabilize when the initial search radius (`dt1`) was significantly widened. The 8 optimal combinations all utilized large `dt1` values between 7.0m and 8.0m, paired with a relatively low height threshold (`Zu` = 10). The corresponding `dt2` values for these optimal runs ranged from 8.5m up to 11.0m. However, even with rigorous parameter optimization, the point cloud-based `lidR::lidRseg()` algorithm failed to eliminate oversegmentation entirely, consistently identifying more tree crowns than were physically present on the site.

## Default Values of `li2012()` Algorithm

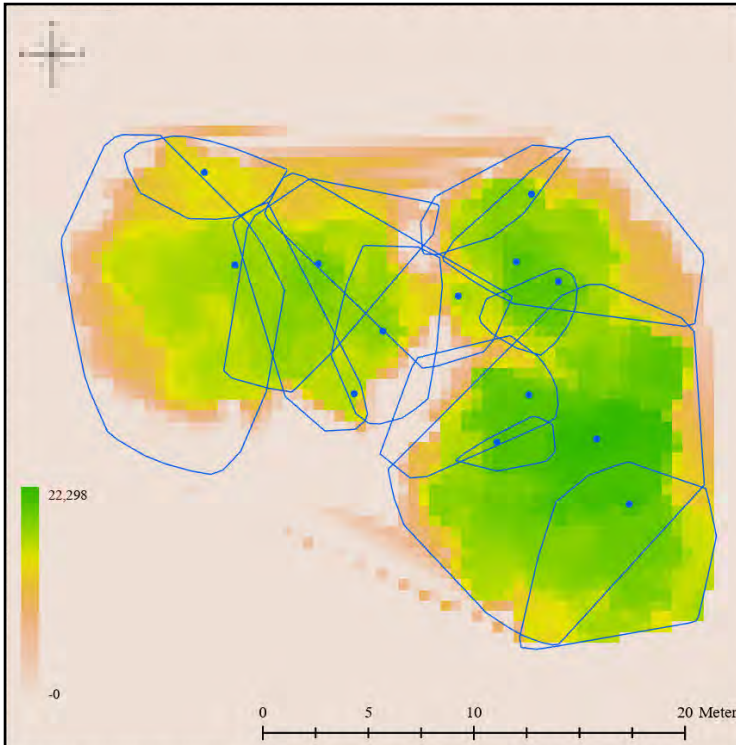


- Detected Tree Crown
- Detected Tree Top

### Plot\_1

Field Validated Tree Count: 7

`wf()` Detected Tree Count: 2



### Plot\_2

Field Validated Tree Count: 4

`wf()` Detected Tree Count: 13

**Figure 42.** Applying the default thresholds of the `li2012()` algorithm to the reference plots resulted in oversegmentation. In Plot\_1, 26 trees were detected compared to a ground truth of 7; in Plot\_2, 13 trees were detected compared to a ground truth of 4. Note how `li2012()` delineates crowns as convex hulls around segmented point clusters, resulting in geometrically regular outlines compared to the irregular watershed-based polygons produced by `mcws()`.

## Grid Search: Plot\_1: li2012()

15	19	6	2	1	1	0	0	0	0	0	0	0	0	0
14	16	4	1	0	0	0	0	0	0	0	0	0	0	0
13	11	3	1	0	0	0	0	0	0	0	0	0	0	0
12	9	2	0	0	0	0	0	0	0	0	0	0	0	0
11	5	1	0	0	0	0	0	0	0	0	0	0	0	0
10	2	0	0	0	0	0	0	0	0	0	0	0	0	0
	1.5	2.0	2.5	3.0	3.5	4.0	4.5	5.0	5.5	6.0	6.5	7.0	7.5	8.0

**Figure 43.** Grid search results for the li2012() algorithm at Plot 1 (ground truth = 7 trees, hmin = 5 m). Each cell shows the lowest absolute detection error across all tested dt2 offsets for a given dt1 × Zu combination. Color scale is consistent across all grid search figures.

## Grid Search: Plot\_2: li2012()

15	3	2	2	1	1	1	1	1	1	1	1	1	1	1
14	2	1	1	1	1	1	1	1	1	1	1	1	1	1
13	2	1	1	1	1	1	1	1	1	1	1	1	1	1
12	2	1	1	1	1	1	1	1	1	1	1	1	1	1
11	1	1	1	1	1	1	1	1	1	1	1	1	1	1
10	1	1	1	1	1	1	1	1	1	1	1	1	1	1
	1.5	2.0	2.5	3.0	3.5	4.0	4.5	5.0	5.5	6.0	6.5	7.0	7.5	8.0

**Figure 44.** Grid search results for the li2012() algorithm at Plot\_2 (ground truth = 4 trees, hmin = 5 m). Each cell shows the lowest absolute detection error across all tested dt2 offsets for a given dt1 × Zu combination. Color scale is consistent across all grid search figures.

## Grid Search: Östra Ramlösa: li2012()

15	198	86	48	27	21	20	19	17	18	18	18	17	17	17
14	168	71	44	26	21	20	19	17	18	18	18	17	17	17
13	128	58	35	23	20	19	18	17	18	18	18	17	17	17
12	100	49	29	22	20	19	19	18	18	18	18	17	17	17
11	69	41	28	21	19	19	19	18	18	18	18	17	17	17
10	48	31	25	20	19	19	19	18	18	18	17	16	16	16
	1.5	2.0	2.5	3.0	3.5	4.0	4.5	5.0	5.5	6.0	6.5	7.0	7.5	8.0

**Figure 45.** Grid search results for the li2012() algorithm in Östra Ramlösa (ground truth = 43 trees, hmin = 5 m). Each cell shows the lowest absolute detection error across all tested dt2 offsets for a given dt1 × Zu combination. Color scale is consistent across all grid search figures.

## 8 Optimized Combinations: Östra Ramlösa: : li2012()

**Table 5.** Best-performing parameter combinations from the `li2012()` grid search on the Östra Ramlösa Field Survey (ground truth = 43 trees), sorted by runtime. All eight combinations achieved the minimum error of 16 trees (detected = 59). Fixed parameters: `R = 2 m`, `hmin = 5 m`, `speed_up = 10`. The combination `dt1 = 7.0`, `dt2 = 9.0` was selected for accuracy assesment and DBH screening in Krokstorp.

#	1	2	3	4	5	6	7	8
<code>dt1</code>	7.0	8.0	7.0	7.5	8.0	8.0	7.5	7.5
<code>dt2</code>	9.0	11.0	10.0	10.5	10.0	9.0	9.5	8.5
<code>Zu</code>	10	10	10	10	10	10	10	10
<b>Error</b>	<b>16</b>	<b>16</b>	<b>16</b>	<b>16</b>	<b>16</b>	<b>16</b>	<b>16</b>	<b>16</b>
<b>Runtime</b>	<b>128.5</b>	128.7	129.2	129.4	129.4	129.7	130.3	134.8

Among the eight optimal parameter sets, the final selection for subsequent testing was based on computational efficiency. The combination utilizing `dt1 = 7.0`, `dt2 = 9.0`, and `Zu = 10`, yielded the fastest processing time (128.5 seconds) and was therefore established as the optimal baseline. To further test whether the local maximum search radius (`R`) affected the tree detection results, three additional runs were performed using the optimized baseline. With the distance and height thresholds fixed, the `R` variable was adjusted to 4, 6, and 8, respectively. Visual examination of the outputs demonstrated that altering the search radius had no impact on the overall count, as all three `R` values consistently detected exactly 59 trees (see Table 6). Thus, the optimized baseline with `R` at default settings formed the final `li2012()` result of: `li2012(dt1 = 7.0, dt2 = 9.0, R = 2, Zu = 10, hmin = 5, speed_up = 10)` (see Fig. 46).

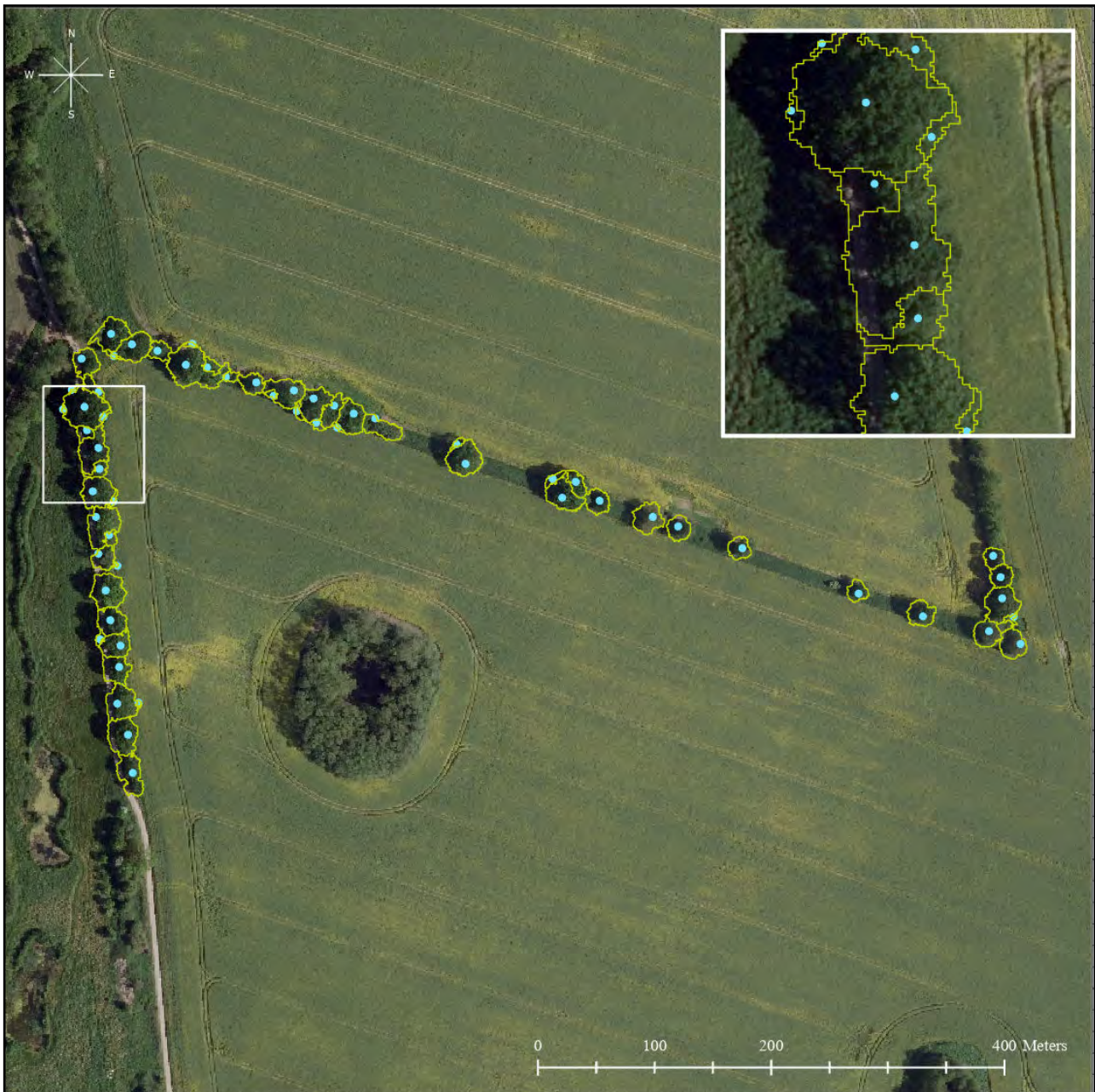
## Sensitivity Test: Östra Ramlösa: Parameter R: li2012()

**Table 6.** Sensitivity test of the `R` parameter in `li2012()` applied to the Östra Ramlösa Field Survey (ground truth = 43 trees). `dt1`, `dt2`, and `Zu` were held constant at the optimal values; only the search radius `R` was varied. Detection count was identical across all four `R` values, indicating that the algorithm's output is insensitive to `R` within this range for this dataset. `R = 2 m` was retained as the default for all subsequent runs.

#	1	2	3	4
<code>dt1</code>	7.0	7.0	7.0	7.0
<code>dt2</code>	9.0	9.0	9.0	9.0
<code>Zu</code>	10	10	10	10
<code>R</code>	2	4	6	8
<b>Error</b>	<b>16</b>	<b>16</b>	<b>16</b>	<b>16</b>

# Optimized `li2012()` Combination Applied to Östra Ramlösa

- Detected Tree Crown
- Detected Tree Top



**Figure 46.** The optimized `li2012()` parameter combination ( $dt1=7.0$ ,  $dt2=9.0$ ,  $Zu=10.0$ ,  $R=2.0$ ,  $hmin=5m$ ) produced the lowest error in Östra Ramlösa, detecting 59 trees against the ground truth of 43.

## 4.3. Accuracy Assessment

Spatial accuracy was evaluated using a buffer-based matching approach, against the field validated tree count of 43 trees in Östra Ramlösa. First, 5 m buffer zones were created around each of the 43 field-inventoried tree positions in ArcGIS Pro. The number of algorithm-detected treetops falling within these buffers was recorded, and results were compared across both the **vwf()** and the **li2012()** results in the Östra Ramlösa survey area (see Table 7).

The optimized **vwf()** configuration achieved a recall of 86.0%, detecting 37 of the 43 field-validated tree positions. The run detected six *false negatives* and eleven *false positives*, resulting in a precision score of 77.1% and an overall F-score of 0.813.

The optimized **li2012()** configuration achieved a recall of 95.3%, detecting 41 of the 43 field-inventoried trees. The run detected two false negatives and 18 false positives, resulting in a precision score of 69.5% and an overall F-score of 0.804.

A visual inspection of the detected trees was conducted in conjunction with the accuracy assessments, comparing them to data from site visits. To ensure a fair comparison of the results, the crowns were segmented using the same method following tree-top detection, employing the **mcws()** algorithm in ForestTools. The results of the two segmentations are shown in Figure 47 and Figure 48. Upon closer inspection of the **li2012()** detection, it can be seen that virtually all 18 false positives have small crown structures and are located either at the outer edge of a large crown or wedged between two crowns, which could mean that they are either part of the bigger crown structures or smaller trees that were not inventoried during the field survey (see Fig. 47).

**Table 7.** Accuracy assessment results for the optimised **vwf()** and **li2012()** algorithms applied to the Östra Ramlösa field survey (GT = 43 trees). The two algorithms now show near-identical F-scores (~0.81 vs ~0.80), but with opposite error profiles: **vwf()** is more precise (fewer false positives) while **li2012()** has higher recall (fewer missed trees). **li2012()**'s high FP count (18) drives its precision down to 69.5% despite detecting 41 of 43 trees.

Method	TP	FN	FP	Recall	Precision	F-Score
<b>vwf()</b>	37	6	11	86%	77.1%	0.813
<b>li2012()</b>	41	18	2	95.3%	69.5%	0.804

# Accuracy Assessment of $\text{vwf}()$ in Östra Ramlösa

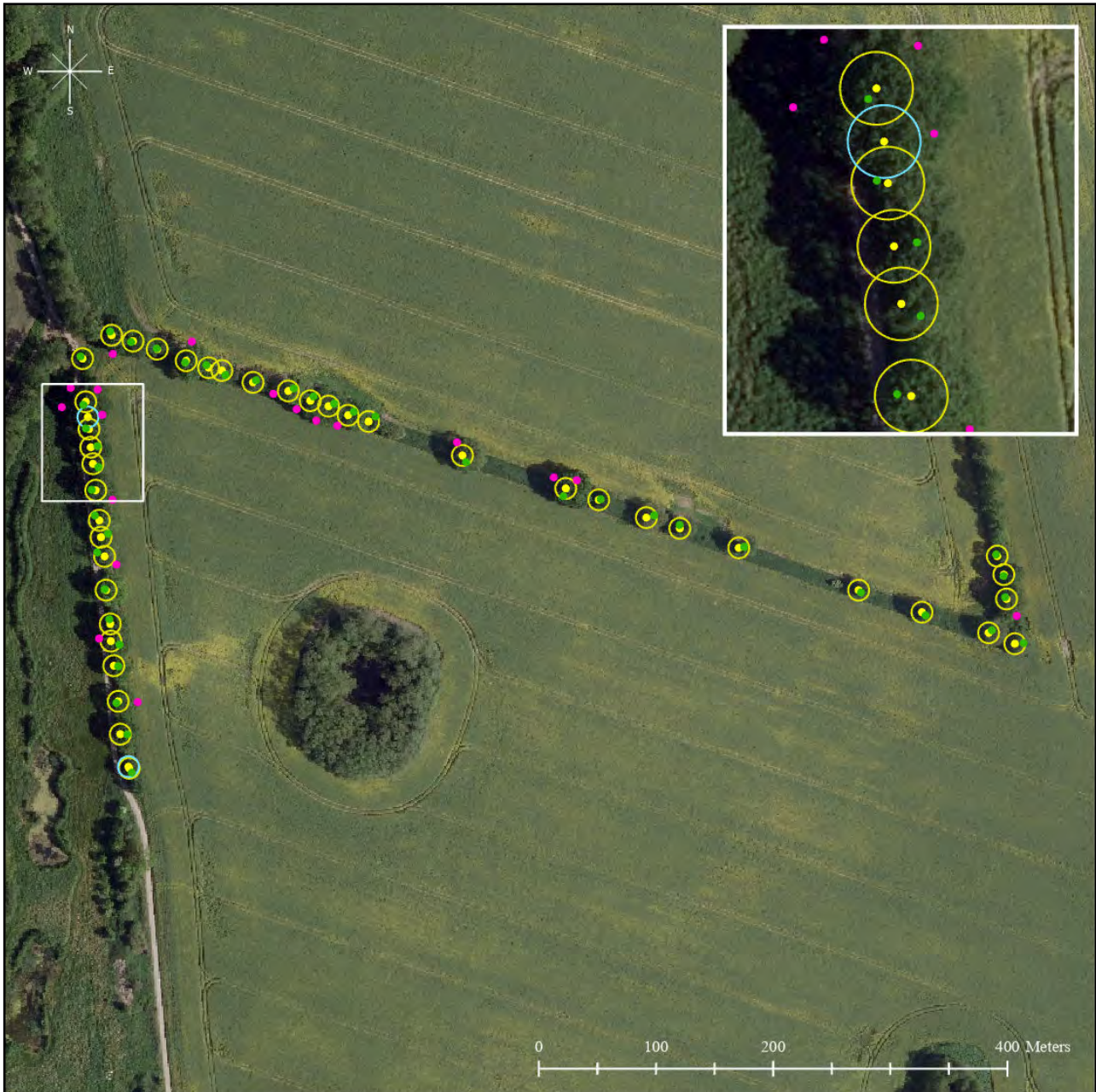
- Field Validated Tree Crown
- Field Validated Tree Top
- False Negative
- False Positive
- True Positive



**Figure 47.** Accuracy assessment of the optimised  $\text{vwf}()$  algorithm ( $\text{slope} = 0.05$ ,  $\text{intercept} = 3.0$ ,  $\text{minHeight} = 5$ ) applied to the Östra Ramlösa validation stand (GT = 43 trees). Yellow circles represent 5 m radius buffers around field-surveyed tree positions (yellow points). Green points indicate detected treetops classified as true positives (TP = 37); magenta points indicate false positives (FP = 11). Cyan buffers containing no detected point represent false negatives (FN = 6). The inset highlights a dense hedgerow section where both under- (cyan buffer) and over-segmentation (magenta point) occurs. Recall = 86.0%, Precision = 77.1%, F-score 0.813.

# Accuracy Assessment of `li2012()` in Östra Ramlösa

- Field Validated Tree Crown
- Field Validated Tree Top
- False Negative
- False Positive
- True Positive



**Figure 48.** Accuracy assessment of the optimised `li2012()` algorithm ( $dt1 = 7.0$ ,  $dt2 = 9.0$ ,  $Zu = 10$ ,  $R = 2$ ,  $hmin = 5$ ) applied to the Östra Ramlösa validation stand (GT = 43 trees). Yellow circles represent 5 m radius buffers around field-surveyed tree positions. Green points indicate detected treetops classified as true positives (TP = 41); magenta points indicate false positives, detections falling outside any ground truth buffer (FP = 18). Cyan buffers containing no detected point represent false negatives (FN = 2). The inset highlights a dense hedgerow section where both under- (cyan buffer) and over-segmentation (magenta point) occurs. Recall = 95.3%, Precision = 69.5%, F-score = 0.804.

## 4.4. Extracting DBH and Screening for Legally Protected Trees

Based on the established priority thresholds for crown area, the segmented trees were classified to screen for high value and legally protected individuals.

In Krokstorp, **vwf()** classified 217 of 901 detected crowns (24%) as High Value. **li2012()** classified 214 of 576 detected crowns (37.3%) as High Value and identified no crowns exceeding the Protected threshold (see Fig. 48, Fig. 49 and Table 8). The two methods diverge most in the "standard" class, **vwf()** detects nearly twice as many small-crowned trees (684 vs 362). This discrepancy is methodological: at the minimum detection height of 5 m, the **vwf()** window function yields a search radius of only **3.3 m** ( $w = 0.05 \times 5 + 3.0$ ), making the algorithm sensitive to minor CHM surface variation and prone to splitting larger crowns into multiple detections. **li2012()** operates on the 3D point cloud and merges spatially proximate points into single segments, suppressing this effect. The standard-class counts should therefore be interpreted with caution and are not directly comparable between the two methods. Agreement in the high-value class, where crown areas are large enough to be unambiguously delineated, is considerably more reliable.

It should be noted that not all trees identified as worthy of special protection in the Krokstorp field survey had a DBH exceeding 100 cm, some qualified through cavities and other structural characteristics rather than size alone. In comparison between the segmenting results (Fig. 50 & Fig. 51) and the field survey, it can be noted that the **li2012()** methods performed better in segmenting the crowns when comparing with the field validated trunk positions. Furthermore, the field validated crown edge positions aligned with the mapped canopy cover, strengthening the idea that both methods would be well suited in producing a canopy cover map if not focusing on segmenting individual trees.

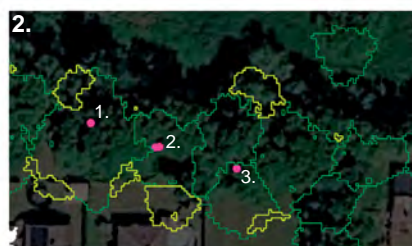
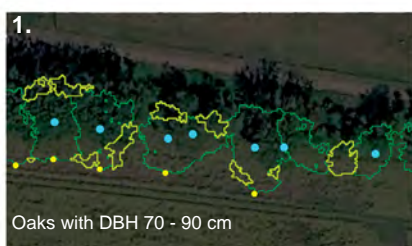
**Table 8.** Number of detected trees per protection class in the Krokstorp study area (Krokstorp), as estimated by **vwf()** and **li2012()** using crown area thresholds derived from Coombes et al. (2019).

Protection class:	Protected > 490.87 m <sup>2</sup>	High Value 78.54–490.87 m <sup>2</sup>	Standard ≤ 78.54 m <sup>2</sup>	Total Count
<b>vwf()</b>	0	217	684	901
<b>li2012()</b>	0	214	362	576

The two methods diverge most in the "standard" class, **vwf()** detects nearly twice as many small-crowned trees (684 vs 362). This discrepancy is methodological: at the minimum detection height of 5 m, the **vwf()** window function yields a search radius of only **3.3 m** ( $w = 0.05 \times 5 + 3.0$ ), making the algorithm sensitive to minor CHM surface variation and prone to splitting larger crowns into multiple detections.

**li2012()** operates on the 3D point cloud and merges spatially proximate points into single segments, suppressing this effect. The standard-class counts should therefore be interpreted with caution and are not directly comparable between the two methods. Agreement in the high-value class, where crown areas are large enough to be unambiguously delineated, is considerably more reliable.

# Estimated Tree Protection Classes: $wvf()$ : Krokstorp



1. Cherry, *Prunus avium*, DBH: 48 cm with cavity
2. Multi stemmed Oak, *Quercus robur*, DBH: 110 cm
3. Cherry, *Prunus avium*, DBH: 52 cm with cavity

### Field Survey:

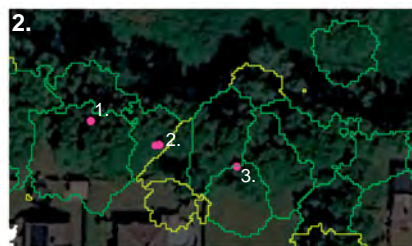
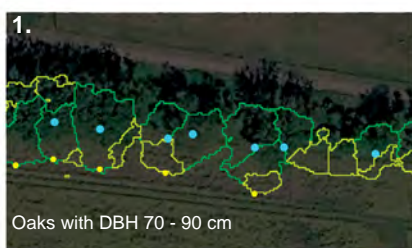
- Crown Edge
- Tree Worthy of Special Protection
- Tree of Municipal Interest

### Technical Study:

- Detected Tree Crown, Area > 78.54 m<sup>2</sup>
- Detected Tree Crown, Area ≤ 490.87 m<sup>2</sup>

**Figure 49.** Delineated tree crowns in the Krokstorp study area, detected using the optimised  $wvf()$  algorithm ( $slope = 0.05$ ,  $intercept = 3.0$ ,  $minHeight = 5$ ). In total, 901 crowns were delineated; 217 were classified as high value and 684 as standard. No crowns exceeded the protected-tree threshold (490.87 m<sup>2</sup>). Insets: clusters of large trees relevant to the field survey; see Figure 51 for field photographs.

# Estimated Tree Protection Classes: 1i2012(): Krokstorp



- 1. Cherry, *Prunus avium*, DBH: 48 cm with cavity
- 2. Multi stemmed Oak, *Quercus robur*, DBH: 110 cm
- 3. Cherry, *Prunus avium*, DBH: 52 cm with cavity

### Field Survey:

- Crown Edge
- Tree Worthy of Special Protection
- Tree of Municipal Interest

### Technical Study:

- Detected Tree Crown, Area > 78.54 m<sup>2</sup>
- Detected Tree Crown, Area ≤ 78.54 m<sup>2</sup>

**Figure 50.** Delineated tree crowns across the Krokstorp study area (Påarp) as detected by the optimised 1i2012() algorithm (dt1=7.0, dt2=9.0, Zu=10, R=2, hmin=5). In total, 576 crowns were delineated, of which 214 are classified as high value and 0 as potentially protected. The inset shows a section where large trees stand in close proximity to smaller ones. see Figure 51 for field photographs.

## Inventory of high-conservation-value trees: Krokstorp



**Figure 51.** The photographs illustrate the character of the trees present:

(bottom) The large multi-stemmed oak, typical of the older specimens along the site boundary.

(left) The tree-lined road corridor forming the eastern edge of the study area. This inventory served as the reference for interpreting detected crown clusters in the LiDAR analysis.

Photo: Hanna Norberg, Helsingborgs satd (2024)

## 5. Discussion

*The results of this study are discussed in relation to the three research questions: (1) What determines whether trees are preserved in spatial planning? (2) How are trees currently addressed throughout the planning and design process? and (3) How can ALS point clouds support decision-making regarding existing trees?*

### 5.1 The Institutional Conditions Shaping Tree Preservation

The interview study reveals that the preservation of trees in spatial planning is not primarily a technical problem; it is a political and organisational one. Trees survive when they are formally protected under the Swedish Environmental Code, when ecological expertise is involved early enough to establish binding constraints, and when the economic argument for preservation outweighs the cost of designing around the tree. When none of these conditions are met, trees are consistently deprioritised, regardless of the frameworks in place to protect them.

Several interviewees described penalty clauses as an insufficient deterrent; in cases where construction is sufficiently profitable, environmental fines are absorbed as a standard project expense rather than treated as a genuine constraint (Ekström, pers. comm. 13 February 2026). The result is that damage is paid for rather than avoided, and the tree is lost regardless. The case described by Krantz (pers. comm. 17 February 2026), where 8 million SEK of tree damage was settled at 1.5 million SEK due to a contractual penalty ceiling, illustrates how readily even substantial environmental costs can be contained within an acceptable project budget.

A parallel weakness exists in the ecological logic of compensation itself. Ridell (2019) argues that compensation in Sweden is reduced to a numerical exercise, where the felling of a mature tree is offset by the planting of a new one, despite widespread acknowledgement that newly planted trees are an insufficient substitute for mature ones (Gilhen-Baker et al., 2022; Hilbert et al., 2019; Bruhn et al., 2026). Together, these two mechanisms confirm what Isaksson and Storbjörk (2012) describe as the systematic disarming of environmental assessments: trees are permitted to influence the process only as long as they do not challenge fundamental development goals.

Furthermore, the Swedish parliament is arriving at the same conclusion as Isaksson and Storbjörk (2012): there is a need for greater transparency in national spatial planning (Sveriges Riksdag, 2025). The majority of practitioners, municipal and private, demonstrate genuine commitment to tree preservation, increasingly reinforced by the regulatory weight of the EU Nature Restoration Law (Regulation (EU) 2024/1991) and the new Swedish standard SS 990002:2025 (Kruuse pers. comm., 19 February 2026; Svensson pers. comm., 25 February 2026). The challenge lies not in the absence of institutional will, but in the established structural conditions that make that will difficult to act on, even where new regulations strengthen the case for preservation (Isaksson & Storbjörk, 2012; Persson, 2013). Norberg (pers. comm., 12 February 2026) and Olsson (pers. comm., 24 March 2026) describe planning processes that span years, and Krantz (pers. comm., 2026) describes an institutional division of responsibility, while Kaartinen et al. (2012) and Schrotter & Hürzeler (2020) describe base maps and digital models in which trees are drawn as dimensionless points.

These findings contrast with the clean, structured planning process shown in Trädkontoret's handbook (Bruhn et al., 2026), which could make the process seem as linear as its flowcharts suggest. Changing the established digital baselines used by municipalities would require dedicated guidance, time, and budget, and even if those were available, the necessary licence updates and supporting infrastructure would take years to implement.

## 5.2 What Accuracy Means at the Planning Scale

The two detection methods used in the technical study produced near-identical F-scores: **vwf()** at 0.813 and **li2012()** at 0.804, while exhibiting opposite error profiles. **vwf()** missed more trees (FN=6) but generated fewer false ones (FP=11), whereas **li2012()** missed almost none (FN=2) but over-detected significantly (FP=18). In detailed development planning, where every square metre holds significant financial value, such discrepancies risk the data being dismissed as insufficiently reliable. However, visual inspection of the **li2012()** detections suggests that the majority of false positives are either oversegmentation at the outer edges of larger crowns or understory vegetation passing the height filter, most probably the former. Lu (pers. comm., 25 February 2026) noted that a research project of this kind would typically require revisiting the field to compare the segmentation results against the trees on site. Although this study used field-validated site visits, a return to the Östra Ramlösa survey area would be necessary to accurately characterise **li2012()**'s precision: to verify whether any trees were excluded from the municipality's original inventory, and whether the algorithm's false positives correspond to real, uninventoried trees.

This raises a fundamental question about how accuracy should be interpreted in a planning context. When using methods such as the 5-metre buffer to assess accuracy, a perfect match is defined as the tree's highest point being in exactly the same position as the base of the trunk. This assumes that the tree is straight and has a single leader, which is not the case for naturally growing deciduous trees, which often have two or more tops in their crown (Pretzsch et al., 2015). As Kaartinen et al. (2012) note, representing tree crowns as round shapes is often misleading, and even a spatial accuracy analysis like the one conducted in this study can be biased by the assumption of a circular form. Rather than validating detected treetops against trunk positions alone, future studies should record the spatial extent of each crown, including its highest visible point and crown extent, as the primary reference geometry. This would allow accuracy metrics to reflect the actual detection performance of the algorithm rather than its correspondence to a trunk-centred inventory convention that was never designed for LiDAR validation.

For the purpose of early-stage tree screening, where failing to flag a legally protected tree carries greater consequences than flagging a non-qualifying candidate, **li2012()**'s high-recall profile is arguably preferable despite its lower precision. The objective is not 100% accuracy, but to provide sufficient spatial evidence that the municipality allocates budget for a certified arborist before the architectural lock-in effect occurs. When applied to the DBH assessment in Krokstorp, this reasoning proved consistent. Comparing the results against high-resolution aerial images, **vwf()** appears to have produced a probable oversegmentation of the area, while **li2012()**'s crown delineations correspond more accurately. Despite this, both methods identified a near-identical number of High Value crowns: 217 and 214 respectively, suggesting that parameter optimization against large-canopy reference trees transferred meaningfully to the full study area.

## 5.3 ALS at the Landscape Scale

The previous section examined the limitations of automated tree detection at the level of individual trees, where algorithmic models struggle to represent the complex reality of vegetation structure. These limitations should not, however, detract from what point cloud data does exceptionally well. Where individual tree classification is constrained by allometric assumptions, species variability, and the structural anomalies of veteran trees, the general canopy layer that LiDAR captures is precisely the kind of data well suited for use as a base layer: a spatially continuous, temporally comparable record of where canopy cover exists, where it does not, and how it changes between scans (Fekete and Cserep, 2021; Lu and Pankratz, 2024).

This is significant because spatial planning is framed at the landscape rather than the individual scale, and so is the planning of green structures (Boverket, 2022; Boverket, 2026). Green corridors, stepping stones, and the continuity of canopy connecting fragmented habitats are central concepts in EU Nature Restoration Law, Regulation (EU) 2024/1991 and the 3-30-300 principle (Boverket, 2023) alike, yet they cannot be evaluated from inventories of single trees, parks, or even forested areas.

Östberg et al.'s (2015) *Alnarpsmodellen* and the i-Tree tool argue that trees need a monetary value to be tangible within an economic decision-making framework. Van Stan et al. (2025), however, argue that assigning a price reduces the tree to an object of comparison, which is rarely in the tree's favour. Article 8 of Regulation (EU) 2024/1991 mandates no net loss of canopy cover by 2030, with particular weight placed on continuity, a metric that cannot be assessed through individual tree valuation, but is directly visible at the landscape scale that a city-wide canopy coverage map captures.

For municipalities pursuing European biodiversity targets, this is where LiDAR's strongest contribution lies. Holopainen et al. (2013) note that ALS scans can monitor the gain and loss of canopy cover with a resolution that no manual inventory can match. Periodic scans identify ecologically critical green structures, and they provide objective spatial data for cases where the protection zones mandated by the Swedish standard apply, or where contested removals reach administrative or legal review.

Within this broader application, individual tree detection retains a useful but more secondary role: as an early-stage screening tool for flagging potentially protected trees in a defined planning area. Based on the understanding that its results function as a trigger for arboricultural inspection rather than a definitive classification. The strength of the workflow lies in coupling the two scales; landscape-level continuity monitoring as the primary application, and individual tree screening as a targeted secondary use, rather than treating either as a substitute for the other.

## 5.4 Limits of Individual Tree Detection

The fact that no detected crown exceeded the 490.87 m<sup>2</sup> threshold, despite field-validated trees of that size being present on site, suggests that allometric models better suited to Swedish conditions are needed. Coombes et al. (2019) found a near-uniform linear relationship across four species and growing conditions; Pretzsch et al. (2015) argue this breaks down logarithmically for older, solitary trees. The technical study supports Pretzsch et al. (2015). When the Coombes model is applied to veteran Swedish multi-stemmed oaks, its reliability diminishes for the trees that are most ecologically significant. As Pretzsch et al. (2015) demonstrate, the relationship between crown area and trunk diameter follows a logarithmic rather than linear function for older, solitary trees, and threshold values derived from a circular crown assumption become increasingly inaccurate as crown morphology departs from regularity. This compounds the filtering bias described by Sithole & Vosselman (2004) and Yan et al. (2018): deadwood in the crown, which is itself a qualifying characteristic for legal protection, reduces the visible crown area in the point cloud, causing the algorithm to assign a lower classification to precisely the trees that carry the highest ecological value.

Holopainen et al. (2013) argue that increased point density makes it possible to retrieve individual trees with stem diameter and age information attached. Even though this study used a high-resolution dataset, there is no guarantee of retrieving such measurements. Bara (2025) argues that open data is a two-tier system; if this study had been conducted with the open data from Lantmäteriet, with a pulse density almost one tenth of that of the private point cloud provided by Helsingborgs stad, the accuracy would arguably have been even lower than the results presented here. This means that the methodology depends on access to costly high-resolution datasets. Furthermore, Bara (2025) also points to the GDPR compliance issues connected to high-resolution point clouds, which can prevent municipalities from sharing such data with consultants on specific projects, a further constraint on the proposed methodology.

These limitations reflect a broader tension within the framework of tree protection in Sweden. Protection is defined primarily in terms of individual specimens, a specific trunk diameter, a specific age, a specific structural characteristic (Naturvårdsverket, 2012). This framework performs adequately when the protected element is discrete and measurable. It performs less well for the ecological relationships that determine a tree's actual conservation value (Gilhen-Baker et al., 2022; Hilbert et al., 2019). A veteran oak does not provide habitat in isolation; the species it supports depend on the continuity of the surrounding vegetation structure: the open field margin, the ditch vegetation, the adjacent shrub belt that maintains microclimate conditions at the base of the trunk. Removing the surrounding trees while formally preserving the veteran oak may satisfy the letter of the protection framework while eliminating the ecological conditions that made the tree valuable in the first place. This is a dimension of conservation that no crown-detection algorithm can evaluate, and one that reinforces the conclusion that automated screening must function as a trigger for physical inspection rather than a substitute for it.

Creating a more accurate tool would require allometric relationships for all relevant species across open, closed, and paved growing conditions, as well as a method for identifying each individual tree's species in order to apply the correct model. Colour spectral analysis holds potential for distinguishing species from an ortho photo (Zhang et al., 2025), but even a tool flexible enough to meet these requirements would still depend on continuous data input and would remain poorly designed for trees with deadwood, structural

anomalies, or growth patterns that depart from the training data. This is precisely the underlying challenge: conditions that are ecologically common, a partially collapsed crown, a hollow trunk, a multi-stemmed veteran, become anomalies the moment they deviate from the model's expected structure (Sithole & Vosselman, 2004; Yan et al., 2018). It may be for this reason that point clouds are currently most reliably applied to mass calculations and the positioning of buildings and infrastructure, predictable, static objects that do not change over time. Trees do not belong to that category.

## 5.5 ALS Data in the Planning Process

While the technical study demonstrates that these methods can be applied efficiently with limited prior experience, the literature and interview study show that practical implementation within a municipal framework requires a realistic assessment of organisational conditions. A municipal planner managing numerous active cases on a constrained budget is unlikely to have the time or mandate to operate and maintain segmentation scripts independently (Norberg, Krantz, Dahlén, pers. comm., 2026). Furthermore, non-specialists are often constrained by the hardware required for large-scale analysis, which is costly and not typical at the consumer level (Svensson and Lu, pers. comm., 2026). This suggests a possible role for specialist expertise, including industrial ecology engineers, geodata consultants, and landscape architects with GIS competence, capable of delivering LiDAR-based tree screening as a commissioned planning service at the rezoning stage. Municipalities do not need to run the scripts themselves; however, they must possess sufficient commissioning competence to specify the output, interpret the results critically, and embed the findings in the planning process before building footprints are established.

There is a related risk in the increasing accessibility of these tools. As automated workflows make LiDAR analysis progressively easier for non-specialists (Urech, Ahn & Lee, 2026), the interpretation of results may become detached from an understanding of their limitations (Lu, pers. comm., 2026). An algorithmic output that assigns a crown area and a DBH class to each detected polygon conveys a precision that the underlying method does not fully support. The method must therefore be accompanied by a clear statement of its accuracy limitations rather than deployed as a definitive classification tool in contexts for which it was not designed.

Furthermore, municipalities are already navigating substantial volumes of policy documents, green structure plans, and strategic guidelines. While planners are generally well-aware of these documents, the sheer number of requirements, which are sometimes also conflicting, makes prioritization a persistent challenge in active planning processes (Dahlén, pers. comm., 2026). The value of introducing LiDAR-based screening is not to add another analytical layer to this documentation burden, but to change the fundamental starting point of the design process. If trees are represented as three-dimensional volumes in the primary planning map before infrastructure routing begins, the spatial constraints they impose are structurally present at the moment decisions are made, rather than surfacing as retrospective objections to plans already finalised.

## 5.6 The Importance of Early Spatial Data

As Isaksson and Storbjörk (2012) demonstrate, environmental assessments are frequently limited in their transformative potential; they are permitted to influence the planning process only as long as they do not challenge fundamental development goals. The Swedish parliament's call for greater coordination, transparency, and the capacity to weigh competing interests in the planning process (Sveriges Riksdag, 2025), acknowledges a structural deficit that tree preservation has long been subject to. Trees are not lost through a single decisive moment but gradually, at every stage of the process: represented as abstract green zones in the comprehensive plan, reduced to accommodate infrastructure in the local development plan, and ultimately exchanged for new ones in the same or another location, not because the tree lacks value, but because the space required for its survival was never secured in the earlier stages and because mature trees' value as infrastructure is constantly undermined.

As Persson (2013) and Isaksson & Storbjörk (2012) argued, the municipal planning monopoly means that the trajectory of a development project is effectively set at the moment a site is agreed upon, and the cost of revision increases at every subsequent stage. Early spatial data is therefore not only in the interest of tree preservation; it serves the developer equally. If a county administrative board identifies, during or after the planning process, that a protected species or a tree qualifying as worthy of special protection was present on site but omitted from the Environmental Impact Assessment, the consequences for all parties are severe: delayed approvals, mandatory revisions, and potential legal liability. Furthermore, as Gilhen-Baker et al (2022), Hilbert et al. (2019) and Bruhn et al. (2026) argue, the planting of new trees is an insufficient substitute for mature trees.

Flagging ecologically sensitive areas before a rezoning application is assessed reduces this risk for everyone involved. Integrating LiDAR-derived canopy data into this earliest stage does not resolve the structural conditions that determine how trees are treated in Swedish spatial planning. However, it introduces objective spatial evidence at the moment when the cost of acting on such evidence is still low enough to change the design. A three-dimensional canopy map that represents mature trees as physically present volumes in the primary planning base reframes the default condition of the design process. By making trees visible the question changes from how to remove what is in the way, and becomes how to build on what we already have.

## 6. Conclusion

The preservation of mature trees can no longer be treated as an act of goodwill; it is a critical ecological imperative supported by increasingly strict European and national mandates. Yet the current spatial planning process consistently fails these trees, not because the institutions involved lack commitment, but because the structural conditions of the process make preservation difficult.

This thesis demonstrates that high-resolution ALS data can support planning decisions as an effective early screening tool for large-scale crown extent mapping. With further development informed by species-specific allometric knowledge, it could also help flag ecologically critical areas and individual trees.

Both the **vwf()** and **li2012()** algorithms proved capable of large-scale canopy screening in complex peri-urban environments, achieving F-scores of 81.3% and 80.4% respectively. The crown-area screening successfully identified high-value candidates across the study area, with 217 and 214 crowns respectively exceeding the 78.54 m<sup>2</sup> threshold corresponding to a DBH of 40 cm. However, neither method detected any crown exceeding the 490.87 m<sup>2</sup> protected threshold corresponding to a DBH of 100 cm, despite field-validated trees of that size being present on site.

The detection parameters were optimized using the Östra Ramlösa survey area, which contained several free-standing high-value oaks but no trees above the protected threshold. It is therefore unsurprising that both methods performed most reliably at detecting high value trees but not protected; since the thresholds were trained on the valuable tree type. Detecting giant trees with a DBH exceeding 100 cm would likely require optimization against a reference dataset that includes them. This result is consistent with what Beucher and Meyer (1993) observed regarding image segmentation more broadly: that the output is not the primary step in image understanding, but its consequence. The algorithm did not fail to detect protected trees; it was never taught to look for them.

The results of the technical study raise a question about what the screening method is intended to achieve. In the peri-urban agricultural landscape of southern Sweden, woody vegetation has been reduced over decades of large-scale intensive agriculture to scattered field margins and isolated stands. In this context, distinguishing between trees of differing protection status may be less important than ensuring all mature trees are spatially present in the planning process before decisions are made. A veteran oak does not provide habitat in isolation; the continuity of the surrounding vegetation structure determines whether the species it supports can survive alongside it. A screening tool that flags individual crowns by size, without capturing these relational values, necessarily understates the ecological stakes of the decisions it is meant to inform.

Automated LiDAR-based tree detection cannot replace the assessment of a tree expert, ecologist or arborist conducting a site visit. However, it serves as a first step toward ensuring that site visits happen before infrastructure is placed, while the question is still where to build, rather than how to limit the damage. By representing mature trees with their actual crown extent in the primary base map used in comprehensive and spatial planning, not as an optional layer but as a permanent one, alongside roads and buildings, spatial data shifts the default condition of design. This thesis argues for precisely this shift in framing: the loss of mature trees must no longer be accepted as an unfortunate but necessary concession to development, but recognized instead as an unacceptable cost to biodiversity, urban resilience and human health.

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An aerial photograph of a city is overlaid with a semi-transparent green filter. The image features white and yellow-green outlines of buildings, streets, and parks. Numerous small, circular tree icons are scattered across the landscape, particularly in the lower right and bottom center areas. The overall aesthetic is clean and modern, emphasizing urban planning and green infrastructure.

## Making Trees Visible

— Legislation, Policy and LiDAR in Spatial Planning

# Appendix

## A - F

## Interview Questions

*“The interview is structured so that — first, I’ll ask about your background, then about tree preservation in projects, and finally, we’ll discuss 3D geodata related to trees.”*

---

### Phrasing

---

#### Background questions

1. Is it okay if I record this interview?
2. What is your name?
3. What is your job title?
4. How long have you been working?
5. What did you study, and where?
6. Do you consider yourself a tree expert?

*In the sense that you feel confident making informed decisions about a tree’s needs in various situations without consulting a professional of any kind?*

7. Are you comfortable downloading and using 3D geodata in your work?

*This may include raw LiDAR data, raster data, contour lines, point clouds, or other 3D geodata*

8. Have you worked on, or do you have experience with, projects in which vegetated land has been developed for buildings or facilities?

*This may include: drainage ponds, parking lots, solar farms, industrial facilities, residential buildings, roads, etc.*

9. Have you worked with or do you have experience using 3D geodata in projects where land covered with vegetation has been developed for buildings or infrastructure?

---

Yes to Q. 8

#### Questions regarding tree protection in projects involving the development of vegetated land

10. In projects where land covered with vegetation is being developed—what factors typically determine whether or not existing vegetation is preserved?

*This may include factors such as time, finances, knowledge, and other resources in the workplace*

11. When you’re deciding which vegetation to preserve or remove, is there a specific methodology you follow?

*Is it often linked to labels such as “trees worthy of special protection,”*

*“cultural-historical environments,” “beautiful or cherished vegetation,” “special habitats,” or “ecosystem services,” or what is the most common reason vegetation is identified as worthy of protection as early as the planning phase?*

- *Do you develop your own guidelines for each new project, or do you rely on standards such as The Swedish Standard?*
- *At what stage of the project do you conduct an environmental assessment, and how much of it is devoted to discussing vegetation?*

**12. What methods have you used to protect and preserve trees in various projects?**

- *Have you conducted on-site tree inventories, and if so, how did you go about it?*
- *Have you conducted digital tree inventories, and if so, how did you go about it?*
- *How do the different inventory methods complement each other?*
- *Have you conducted root mapping, and if so, how did you go about it?*
- *Are there other methods you are familiar with and would like to try?*

**13. How do landscape architects, developers, and the municipality collaborate on tree preservation?**

- *Most municipalities operate differently—what has been your experience?*

**14. Are there any circumstances that you find challenging when working with tree protection?**

*These may include: lack of time, unclear guidelines from the client, financial constraints, collaboration, etc.*

Yes to Q. 9

**Questions about 3D geodata**

**15. What kind of data have you used?**

*Do you use programs like Google Earth Pro and the Google Maps 3D feature? Do you use Lantmäteriet’s LiDAR data as terrain in 3D visualizations or for other purposes? Have you ever tried doing your own 3D scans with a smartphone or a handheld scanner?*

*LiDAR: Was it a privately or municipally funded aerial scan? What was the resolution of the scan? Was the data classified, or did you have to segment it yourself? etc.*

**16. What made you start working with the data?**

- *Was it your own idea, or did someone else suggest it?*
- *Do others around you handle the data the same way you do, or does everyone do it their own way?*

**17. How did you use the data, and how has it been useful to you?**

*What would you like to investigate? Is it tree height, crown spread, trunk location, trunk diameter, tree species, visualization and 3D models, visualization of tree inventories, or analyses such as green volume calculations, etc.?*

**18.** Were there any circumstances that you found challenging while working with the data?

*This could include: the level of detail in the data, its age, the time of year it was collected, etc.*

- *Did the use of the data actually lead to better decisions or better protection of vegetation?*

**19.** Do you use any resources or digital tools when working with new data or new software?

*This could include quick reference guides, YouTube or in-house tutorials, AI tools that write code, or other resources.*

**20.** Is there anything else you'd like to add that we haven't covered?

---

## Local Development Plan: Östra Ramlösa, Stage 1



**Figure 4:** Image taken from the plan description of the LDP covering Östra Ramlösa. Lussebäcken forms the backbone of the area covered by the Östra Ramlösa planning program. Tree-lined avenues and stone walls mark old property boundaries in the landscape and are subject to general biotope protection. The proposal is to let the tree-lined avenues and stone walls, together with the stream, form the framework and structure of the development (Helsingborgs stad 2024, p. 7).

# R-Script: Treetop Detection and Segmentation, Forest Tools

```
library(lidR)
library(ForestTools)
library(sf)
library(terra)

# — SETTINGS (change site_name for each new site)


---


site_name <- "Site2_vwf_opti"
las_path <- "C:/Users/User/Documents/file.laz"
output_dir <- "C:/Users/User/Documents/output_location"

if (!dir.exists(output_dir)) dir.create(output_dir, recursive = TRUE)

# Filenames automatically include site_name
chm_path <- file.path(output_dir, paste0("chm_", site_name, ".tif"))
treetops_path <- file.path(output_dir, paste0("treetops_", site_name, ".shp"))
crowns_path <- file.path(output_dir, paste0("crowns_", site_name, ".shp"))

# — Processing


---


las <- readLAS(las_path)

# — Height normalisation


---


las <- normalize_height(las, tin())
las <- filter_poi(las, Z >= 0, Z <= 50)

# Keep highest point per 25 cm cell - perfect for CHM, much less memory
las <- decimate_points(las, highest(res = 0.25))

chm <- rasterize_canopy(
  las,
  res = 0.5,
  algorithm = pitfree(
    thresholds = c(0, 2, 5, 10, 15),
    max_edge = c(0, 1.5),
    subcircle = 0.2
  )
)

win_fun <- function(x) { x * 0.05 + 3 }
treetops <- vwf(chm, winFun = win_fun, minHeight = 5)
crowns <- mcws(treetops, chm, minHeight = 5)

# — Output


---




---


plot(chm)
```

# C

```
writeRaster(chm, chm_path, overwrite = TRUE)
st_write(treetops, treetops_path, delete_layer = TRUE)
writeVector(as.polygons(crowns), crowns_path, overwrite = TRUE)

cat("Done! Files saved as:\n",
    chm_path, "\n",
    treetops_path, "\n",
    crowns_path, "\n")
```

## R-Script: Treetop Detection and Segmentation, lidR

```
library(lidR)
library(ForestTools)
library(sf)
library(terra)
library(raster)

# — SETTINGS


---


site_name <- "site_name"
las_path <- "C:/Users/User/Documents/file.laz"
output_dir <- "C:/Users/User/Documents/output_location"

if (!dir.exists(output_dir)) dir.create(output_dir, recursive = TRUE)

chm_path <- file.path(output_dir, paste0("chm_", site_name, ".tif"))
treetops_path <- file.path(output_dir, paste0("treetops_", site_name, ".shp"))
crowns_path <- file.path(output_dir, paste0("crowns_", site_name, ".shp"))
las_seg_path <- file.path(output_dir, paste0("las_seg_", site_name, ".las"))
log_path <- file.path(output_dir, paste0("log_", site_name, ".txt"))

# — Start timer


---


start_time <- Sys.time()

# — Processing


---


las <- readLAS(las_path)
las <- normalize_height(las, tin())
las <- filter_poi(las, Z >= 0, Z <= 50)

# — Treetop detection with li2012() (3D point cloud)


---


las <- segment_trees(las, li2012(
  dt1 = 7, dt2 = 9, R = 8, Zu = 10, hmin = 8, speed_up = 10
))
treetops <- crown_metrics(las, func = .stdtreemetrics, geom = "point")

# — CHM for crown segmentation


---


chm <- rasterize_canopy(
  las,
  res = 0.5,
  algorithm = pitfree(
    thresholds = c(0, 2, 5, 10, 15),
    max_edge = c(0, 1.5)
  )
)
```

# D

```
# — Crown segmentation with mcws() using li2012 treetops as markers —————
# mcws needs raster (not SpatRaster) and SpatialPointsDataFrame (not sf)
chm_raster <- raster::raster(chm)
treetops_2d <- st_zm(treetops, drop = TRUE, what = "ZM")
treetops_sp <- as(treetops_2d, "Spatial")
crowns <- mcws(treetops_sp, chm_raster, minHeight = 2, format = "polygons")

# — Convert crowns back to sf for clean shapefile writing
—————
crowns <- st_as_sf(crowns)
treetops <- treetops_2d # already flattened above

# — Stop timer
—————

end_time <- Sys.time()
runtime <- end_time - start_time

# — Output
—————

plot(chm)
writeRaster(chm, chm_path, overwrite = TRUE)
st_write(treetops, treetops_path, delete_layer = TRUE)
st_write(crowns, crowns_path, delete_layer = TRUE)
writeLAS(las, las_seg_path)

# — Log file
—————

log_text <- paste0(
  "Site: ", site_name, "\n",
  "LAS file: ", las_path, "\n",
  "Started: ", start_time, "\n",
  "Finished: ", end_time, "\n",
  "Runtime: ", format(runtime), "\n",
  "Treetop algorithm: li2012(dt1=8, dt2=9, R=4, Zu=5, hmin=8, speed_up=10)\n",
  "Crown algorithm: mcws() watershed on pitfree CHM (res=0.5)\n",
  "Trees detected: ", nrow(treetops), "\n"
)
writeLines(log_text, log_path)
cat("Done!\n", log_text)
```

## R-Script: Grid Search, Forest Tools

```

# =====
# VWF Grid Search – Site 1 (GT = 7) & Site 2 (GT = 4)
# Based on chm+tree_detection_plowright.R
# Varying: slope, intercept | Fixed: hmin = 5 m
# =====

library(lidR)
library(ForestTools)
library(sf)
library(terra)
library(dplyr)
library(ggplot2)

# ---- Search paths & constants -----
site1_path <- "C:/Users/User/Documents/file1.laz"
site2_path <- "C:/Users/User/Documents/file2.laz"
out_dir <- "C:/Users/User/Documents/output_location"
dir.create(out_dir, recursive = TRUE, showWarnings = FALSE)

GT1 <- 7
GT2 <- 4
HMIN <- 5

# ---- Logging -----
log_path <- file.path(out_dir, "gridsearch_vwf.log")
log_con <- file(log_path, open = "wt")
tee <- function(...) {
  msg <- paste0(...)
  cat(msg, "\n")
  cat(msg, "\n", file = log_con)
}

tee("VWF Grid Search started: ", format(Sys.time(), "%Y-%m-%d %H:%M:%S"))

# ---- Pipeline per site -----
prepare_chm <- function(las_path, label) {
  tee("\n[", label, "] Reading LAS...")
  las <- readLAS(las_path)
  tee("[", label, "] Points: ", nrow(las@data))

  las <- normalize_height(las, tin())
  las <- filter_poi(las, Z >= 0, Z <= 50)
  las <- decimate_points(las, highest(res = 0.25))

  tee("[", label, "] Building CHM...")
  chm <- rasterize_canopy(
    las,
    res = 0.5,

```

## R-Script: Grid Search, Forest Tools

```

algorithm = pitfree(
  thresholds = c(0, 2, 5, 10, 15),
  max_edge   = c(0, 1.5),
  subcircle  = 0.2
)
)
tee("[", label, "] CHM done.")
chm
}

chm1 <- prepare_chm(site1_path, "Site1")
chm2 <- prepare_chm(site2_path, "Site2")

# ---- Parameter grid -----
slopes      <- seq(0.05, 0.40, by = 0.025)
intercepts  <- seq(1.00, 5.00, by = 0.25)
combos      <- expand.grid(slope = slopes, intercept = intercepts)
N           <- nrow(combos)

tee(sprintf("\nCombinations: %d (slope x intercept: %d x %d)",
           N, length(slopes), length(intercepts)))

# Factory function to avoid closure trap in loop
make_win_fun <- function(slope, intercept) {
  force(slope); force(intercept)
  function(x) slope * x + intercept
}

# ---- Grid search loop -----
results      <- vector("list", N)
partial_path <- file.path(out_dir, "gridsearch_vwf_partial.csv")
t_start      <- proc.time()["elapsed"]

for (i in seq_len(N)) {

  slope_i <- combos$slope[i]
  int_i   <- combos$intercept[i]
  win_fun <- make_win_fun(slope_i, int_i)

  t0 <- proc.time()["elapsed"]

  out_row <- tryCatch({
    ttops1 <- vwf(chm1, winFun = win_fun, minHeight = HMIN)
    ttops2 <- vwf(chm2, winFun = win_fun, minHeight = HMIN)
    n1      <- nrow(ttops1)
    n2      <- nrow(ttops2)
    elapsed <- proc.time()["elapsed"] - t0
  })
}

```

## R-Script: Grid Search, Forest Tools

```

data.frame(
  slope      = slope_i,
  intercept  = int_i,
  ws_at_h5   = round(slope_i * 5 + int_i, 3),
  ws_at_h15  = round(slope_i * 15 + int_i, 3),
  ws_at_h30  = round(slope_i * 30 + int_i, 3),
  detected_s1 = n1,
  detected_s2 = n2,
  diff_s1     = n1 - GT1,
  diff_s2     = n2 - GT2,
  abs_diff_s1 = abs(n1 - GT1),
  abs_diff_s2 = abs(n2 - GT2),
  total_abs_diff = abs(n1 - GT1) + abs(n2 - GT2),
  runtime_sec = round(elapsed, 2),
  status      = "ok"
)
}, error = function(e) {
  elapsed <- proc.time()["elapsed"] - t0
  data.frame(
    slope = slope_i, intercept = int_i,
    ws_at_h5 = NA, ws_at_h15 = NA, ws_at_h30 = NA,
    detected_s1 = NA, detected_s2 = NA,
    diff_s1 = NA, diff_s2 = NA,
    abs_diff_s1 = NA, abs_diff_s2 = NA,
    total_abs_diff = NA,
    runtime_sec = round(elapsed, 2),
    status = paste0("error: ", conditionMessage(e))
  )
})

results[[i]] <- out_row

if (i %% 10 == 0 || i == N) {
  tee(sprintf("[%3d/%d] slope=%.3f int=%.2f -> S1=%s S2=%s total_diff=%s (%.1f
s)",
           i, N, slope_i, int_i,
           ifelse(is.na(out_row$detected_s1), "ERR", out_row$detected_s1),
           ifelse(is.na(out_row$detected_s2), "ERR", out_row$detected_s2),
           ifelse(is.na(out_row$total_abs_diff), "NA", out_row$total_abs_diff),
           out_row$runtime_sec))
}

if (i %% 25 == 0) {
  write.csv(bind_rows(results[1:i]), partial_path, row.names = FALSE)
}
}

results_df <- bind_rows(results)

```

## R-Script: Grid Search, Forest Tools

```
# ---- Save results -----
full_csv <- file.path(out_dir, "gridsearch_vwf_results.csv")
write.csv(results_df, full_csv, row.names = FALSE)
tee("\nAll results: ", full_csv)

top10 <- results_df %>%
  filter(status == "ok") %>%
  arrange(total_abs_diff, abs_diff_s1, abs_diff_s2) %>%
  head(10)
write.csv(top10, file.path(out_dir, "gridsearch_vwf_top10.csv"), row.names = FALSE)
tee("Top 10: ", file.path(out_dir, "gridsearch_vwf_top10.csv"))

tee("\n--- Top 10 ---")
print(top10[, c("slope", "intercept", "ws_at_h5", "ws_at_h30",
               "detected_s1", "detected_s2", "total_abs_diff")])

# ---- Heatmaps -----
tee("\nGenerating heatmaps...")
plot_df <- results_df %>% filter(status == "ok")

theme_gs <- theme_minimal(base_size = 12) +
  theme(panel.grid = element_blank())

# Heatmap: total_abs_diff
best_total <- plot_df %>% arrange(total_abs_diff, abs_diff_s1) %>% slice(1)
p1 <- ggplot(plot_df, aes(x = slope, y = intercept, fill = total_abs_diff)) +
  geom_tile(colour = "white", linewidth = 0.25) +
  geom_point(data = best_total, aes(x = slope, y = intercept),
            colour = "red", shape = 8, size = 5, stroke = 1.5, inherit.aes = FALSE)
+
  scale_fill_viridis_c(name = "S|diff|", direction = -1) +
  scale_x_continuous(breaks = slopes) +
  scale_y_continuous(breaks = intercepts) +
  labs(title = "VWF grid search – total |detected - GT| (Site 1 + Site 2)",
        subtitle = sprintf("GT: Site1=%d, Site2=%d | hmin=%d m | Red star = best",
                             GT1, GT2, HMIN),
        x = "slope", y = "intercept") +
  theme_gs
ggsave(file.path(out_dir, "heatmap_total_abs_diff.png"), p1, width = 10, height = 7,
        dpi = 150)

# Heatmap: Site 1
best1 <- plot_df %>% arrange(abs_diff_s1) %>% slice(1)
p2 <- ggplot(plot_df, aes(x = slope, y = intercept, fill = abs_diff_s1)) +
  geom_tile(colour = "white", linewidth = 0.25) +
  geom_point(data = best1, aes(x = slope, y = intercept),
```

## R-Script: Grid Search, Forest Tools

```

    colour = "red", shape = 8, size = 5, stroke = 1.5, inherit.aes = FALSE)
+
  scale_fill_viridis_c(name = "|diff|", direction = -1) +
  scale_x_continuous(breaks = slopes) +
  scale_y_continuous(breaks = intercepts) +
  labs(title = sprintf("VWF - Site 1 |detected - %d|", GT1), x = "slope", y =
"intercept") +
  theme_gs
ggsave(file.path(out_dir, "heatmap_site1.png"), p2, width = 10, height = 7, dpi =
150)

# Heatmap: Site 2
best2 <- plot_df %>% arrange(abs_diff_s2) %>% slice(1)
p3 <- ggplot(plot_df, aes(x = slope, y = intercept, fill = abs_diff_s2)) +
  geom_tile(colour = "white", linewidth = 0.25) +
  geom_point(data = best2, aes(x = slope, y = intercept),
    colour = "red", shape = 8, size = 5, stroke = 1.5, inherit.aes = FALSE)
+
  scale_fill_viridis_c(name = "|diff|", direction = -1) +
  scale_x_continuous(breaks = slopes) +
  scale_y_continuous(breaks = intercepts) +
  labs(title = sprintf("VWF - Site 2 |detected - %d|", GT2), x = "slope", y =
"intercept") +
  theme_gs
ggsave(file.path(out_dir, "heatmap_site2.png"), p3, width = 10, height = 7, dpi =
150)

tee("Heatmaps saved.")

# ---- Done -----
tee(sprintf("\nTotal runtime: %.1f minutes", (proc.time()["elapsed"] - t_start) /
60))
tee("Finished: ", format(Sys.time(), "%Y-%m-%d %H:%M:%S"))
for (ln in capture.output(sessionInfo())) tee(ln)
close(log_con)

cat("Done! Files saved to:", out_dir, "\n")

```

## R-Script: Grid Search, lidR

```
library(lidR)
library(sf)
library(terra)
library(ggplot2)

# — SETTINGS (change site_name for each new site)


---


site_name <- "Site_name"
las_path <- "C:/Users/User/Documents/file.laz"
output_dir <- "C:/Users/User/Documents/output_location"
ground_truth <- 43 # field-inventoried tree count

if (!dir.exists(output_dir)) dir.create(output_dir, recursive = TRUE)

# Output paths
results_csv <- file.path(output_dir, paste0("grid_results_", site_name, ".csv"))
top10_csv <- file.path(output_dir, paste0("top10_", site_name, ".csv"))
scatter_path <- file.path(output_dir, paste0("scatter_", site_name, ".png"))
log_path <- file.path(output_dir, paste0("log_", site_name, ".txt"))

# — Start timer


---


total_start <- Sys.time()

# — Load and prepare point cloud ONCE


---


cat("Loading and normalising point cloud...\n")
las <- readLAS(las_path)
las <- normalize_height(las, tin())
las <- filter_poi(las, Z >= 0, Z <= 50)

# — Build parameter grid


---


# dt1: 1.5 to 8.0 (step 0.5)
# dt2: dt1 + 1, dt1 + 2, dt1 + 3
# Zu: 10 to 15 (step 1)
# hmin = 8, R = 2 (locked)
dt1_values <- seq(1.5, 8.0, by = 0.5)
dt2_offsets <- c(1, 2, 3)
Zu_values <- seq(10, 15, by = 1)
hmin_fixed <- 8
R_fixed <- 2
speed_up <- 10

grid <- expand.grid(
  dt1 = dt1_values,
  dt2_offset = dt2_offsets,
  Zu = Zu_values
```

# F

```
)
grid$dt2 <- grid$dt1 + grid$dt2_offset
grid$hmin <- hmin_fixed
grid$R <- R_fixed

cat("Grid contains", nrow(grid), "parameter combinations.\n\n")

# — Run grid search


---


results <- data.frame(
  dt1      = numeric(),
  dt2      = numeric(),
  Zu       = numeric(),
  hmin     = numeric(),
  R        = numeric(),
  detected  = integer(),
  diff     = integer(),
  abs_diff  = integer(),
  pct_match = numeric(),
  runtime_sec = numeric(),
  status    = character(),
  stringsAsFactors = FALSE
)

for (i in seq_len(nrow(grid))) {
  params <- grid[i, ]
  iter_start <- Sys.time()

  cat(sprintf("[%d/%d] dt1=%.1f, dt2=%.1f, Zu=%d, hmin=%d, R=%d ... ",
             i, nrow(grid), params$dt1, params$dt2, params$Zu,
             params$hmin, params$R))

  result <- tryCatch({
    las_seg <- segment_trees(las, li2012(
      dt1      = params$dt1,
      dt2      = params$dt2,
      R        = params$R,
      Zu       = params$Zu,
      hmin     = params$hmin,
      speed_up = speed_up
    ))
    treetops <- crown_metrics(las_seg, func = .stdtreemetrics, geom = "point")
    list(detected = nrow(treetops), status = "ok")
  }, error = function(e) {
    list(detected = NA_integer_, status = paste("error:", e$message))
  })

  iter_end <- Sys.time()
}
```

# F

```
runtime_sec <- as.numeric(difftime(iter_end, iter_start, units = "secs"))
diff_val    <- result$detected - ground_truth
abs_diff_val <- abs(diff_val)
pct_match   <- (result$detected / ground_truth) * 100

results <- rbind(results, data.frame(
  dt1      = params$dt1,
  dt2      = params$dt2,
  Zu       = params$Zu,
  hmin     = params$hmin,
  R        = params$R,
  detected = result$detected,
  diff     = diff_val,
  abs_diff = abs_diff_val,
  pct_match = round(pct_match, 1),
  runtime_sec = round(runtime_sec, 2),
  status    = result$status,
  stringsAsFactors = FALSE
))

cat(sprintf("detected=%s, runtime=%.1fs\n",
           ifelse(is.na(result$detected), "NA", result$detected),
           runtime_sec))

# Free memory between iterations
if (exists("las_seg")) rm(las_seg); gc(verbose = FALSE)
}

# — Stop timer


---


total_end    <- Sys.time()
total_runtime <- total_end - total_start

# — Save full results


---


write.csv(results, results_csv, row.names = FALSE)

# — Top 10 results table


---


top10 <- results[order(results$abs_diff, results$runtime_sec), ][1:10, ]
write.csv(top10, top10_csv, row.names = FALSE)

cat("\n===== TOP 10 RESULTS =====\n")
print(top10, row.names = FALSE)

# — Scatter plot: Zu (y) vs dt1 (x), coloured by abs_diff


---


results_ok <- results[results$status == "ok", ]
```

# F

```
p <- ggplot(results_ok, aes(x = dt1, y = Zu, colour = abs_diff)) +
  geom_jitter(width = 0.1, height = 0.1, size = 3, alpha = 0.8) +
  scale_colour_viridis_c(option = "plasma", direction = -1,
                          name = "abs_diff\n(|detected - GT|)") +
  scale_x_continuous(breaks = dt1_values) +
  scale_y_continuous(breaks = Zu_values) +
  labs(
    title = paste0("Grid search: li2012() detection error across dt1 x Zu"),
    subtitle = paste0("hmin = ", hmin_fixed, " m, R = ", R_fixed,
                      " m, ground truth = ", ground_truth, " trees"),
    x = "dt1 (m)",
    y = "Zu (m)"
  ) +
  theme_minimal(base_size = 12) +
  theme(
    plot.title = element_text(face = "bold"),
    plot.subtitle = element_text(colour = "grey40")
  )
```

```
ggsave(scatter_path, p, width = 9, height = 6, dpi = 300)
print(p)
```

```
# — Log file
```

---

```
n_runs <- nrow(results)
n_ok <- sum(results$status == "ok")
n_errors <- sum(results$status != "ok")
best_diff <- min(results$abs_diff, na.rm = TRUE)
n_at_best <- sum(results$abs_diff == best_diff, na.rm = TRUE)
mean_iter <- mean(results$runtime_sec, na.rm = TRUE)

log_text <- paste0(
  "=====  
"Site: ", site_name, "\n",
  "LAS file: ", las_path, "\n",
  "Ground truth: ", ground_truth, " trees\n",
  "\n",
  "Started: ", total_start, "\n",
  "Finished: ", total_end, "\n",
  "Total runtime: ", format(total_runtime), "\n",
  "Mean per iteration: ", round(mean_iter, 2), " s\n",
  "\n",
  "----- Parameter ranges -----  
"dt1: ", paste(dt1_values, collapse = ", "), " m\n",
  "dt2: dt1 + ", paste(dt2_offsets, collapse = ", "), " m\n",
  "Zu: ", paste(Zu_values, collapse = ", "), " m\n",
  "hmin: ", hmin_fixed, " m (fixed)\n",
  "====="
```

# F

```
"R:      ", R_fixed, " m (fixed)\n",
"speed_up: ", speed_up, "\n",
"\n",
"----- Run summary -----\n",
"Total combinations: ", n_runs, "\n",
"Successful runs:     ", n_ok, "\n",
"Failed runs:         ", n_errors, "\n",
"\n",
"----- Best result -----\n",
"Lowest abs_diff:    ", best_diff, "\n",
"Combinations tied at best: ", n_at_best, "\n",
"\n",
"----- Top 10 -----\n"
)

top10_text <- capture.output(print(top10, row.names = FALSE))
log_text  <- paste0(log_text, paste(top10_text, collapse = "\n"), "\n")

writeLines(log_text, log_path)

cat("\n===== DONE =====\n")
cat("Total runtime:", format(total_runtime), "\n")
cat("Files saved to:", output_dir, "\n")
cat(" - Full results: ", basename(results_csv), "\n")
cat(" - Top 10:       ", basename(top10_csv), "\n")
cat(" - Scatter plot: ", basename(scatter_path), "\n")
cat(" - Log file:     ", basename(log_path), "\n")
```