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Masters Thesis

Simulation of Tree Root Growth in a 3D Model of Amsterdam

Author:
Iris Reitsma

Daily Supervisor:
Nicole Archangel

Examiner:
Dr. Robert Belleman

Second Assessor:
Dr. Jaap Kaandorp

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Declaration of Authorship

I, Iris Reitsma, declare that this thesis, entitled 'Simulation of Tree Root Growth in a 3D Model of Amsterdam' and the work presented in it are my own. I confirm that:

- This work was done wholly or mainly while in candidature for a research degree at the University of Amsterdam.
- Where any part of this thesis has previously been submitted for a degree or any other qualification at this University or any other institution, this has been clearly stated.
- Where I have consulted the published work of others, this is always clearly attributed.
- Where I have quoted from the work of others, the source is always given. With the exception of such quotations, this thesis is entirely my own work.
- I have acknowledged all main sources of help.
- Where the thesis is based on work done by myself jointly with others, I have made clear exactly what was done by others and what I have contributed myself.

Signed:

ireitsma

Date: June 16, 2022

“The roots of education are bitter, but the fruit is sweet.”

Aristotle

UNIVERSITY OF AMSTERDAM

Abstract

Faculty of Science
Informatics Institute

Master of Science in Computational Science

Simulation of Tree Root Growth in a 3D Model of Amsterdam

by Iris REITSMA

Root systems of trees are hard to monitor, while it is essential to know where and how they grow for city development and to maintain the urban trees healthy. We created a model that estimates how much root volume trees need now and in the future and converts this volume to 3D cylinders to include them in 3D Amsterdam. We try out three methods that vary in their required input parameters: the static, tree dictionary, and tree growth methods. We investigate if the model can provide accurate and valuable insight into the location and the impact of tree roots and validate and compare the three methods for three diverse subregions in Amsterdam: *het Wallengebied*, *IJburg* and *Sarphatipark*. We did this based on predictive capabilities, ground radar scans of real root systems, and damage reports involving roots. We found that the model is capable of giving a general indication of the space that the roots require but that, in some cases, it is necessary to reshape the cylinders to provide a more accurate indication of the location of the roots. In addition, we found that the model can be used to investigate which areas are prone to root lifting in the future. The three methods perform similarly in estimating the current root volumes. However, the static and tree growth method are expected to respectively under- and overestimate the future root volumes. Therefore, we used the tree dictionary method to estimate the root volumes that the trees need to stay healthy for the whole city of Amsterdam.

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This thesis internship at the municipality of Amsterdam has come to an end. I very much enjoyed the past few months and was lucky to meet many new people who helped me with my project. Without them, this thesis would not have been possible.

I would like to start by saying that I am incredibly thankful to my examiner Rob Belleman because he was willing to supervise this project while it was not a listed one. In addition, our weekly meetings helped me greatly, and he provided valuable feedback on my project and report. Additionally, this project would not have been possible without my second assessor Jaap Kaandorp, who took the time to assess my work and to have friendly discussions with me about root growth models (unfortunately, I did not find the time to try out DLA models). I am also extremely grateful to my daily supervisor Nicole Archangel for the valuable guidance, sprint planning, and feedback on my project and report. I learned a lot from her about Agile and Scrum methodologies, which I am sure will be helpful in many other moments in my career.

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Contents

List of Figures

List of Tables

Abbreviations

CSL	**C**omputational **S**cience **L**ab
UvA	**U**niversiteit **v**an **A**msterdam
LOD	**L**evel **Of** **D**etail
GHG	**G**emiddeld **H**oogste **G**rondwaterstand (average highest groundwater level)
BGT	**B**asisregistratie **G**rootschalige **T**opografie (basic register large-scale topography)
WMTS	**W**eb **M**ap **T**ile **S**ervice
OGC	**O**pen **G**eospatial **C**onsortium
GPS	**G**lobal **P**ositioning **S**ystem
WGS	**W**orld **G**eodetic **S**ystem
RD	**R**ijks **D**riehoeks (coordinates)
AHN	**A**ctueel **H**oogtebestand **N**ederland (height map of the Netherlands)
DSM	**D**igital **S**urface **M**odel
DTM	**D**igital **T**errain **M**odel
BAG	**B**asisregistratie **A**dressen en **G**ebouwen (register addresses and buildings)
NAP	**N**ormaal **A**msterdams **P**eil (Amsterdam Ordnance Datum)
UTD	**U**rban **T**ree **D**atabase
d.b.h.	**d**iameter at **b**reast **h**eight
HDD	**H**eating **D**egree **D**ays
CDD	**C**ooling **D**egree **D**ays
USDA	**U**nited **S**tates **D**epartment of **A**griculture
RIVM	**R**ijks**I**nstituut voor **V**olksgezondheid en **M**ilieu (national institute for health and environment)
WUR	**W**ageningen **U**niversity & **R**esearch

KNMI	**K**oninklijk **N**ederlands **M**eteorologisch **I**nstituut (Royal Dutch Meteorological Institute)
glTF	**g**raphics **l**anguage **T**ransmission **F**ormat
UI	**U**ser **I**nterface
SIA	**S**ignalen **I**nformatievoorziening **A**msterdam (signals information supply Amsterdam)
RGB	**R**ed **G**reen **B**lue
RGBA	**R**ed **G**reen **B**lue **A**lpha
HSV	**H**ue **S**aturation **V**alue
DXF	**D**rawing **E**xchange **F**ormat
API	**A**pplication **P**rogramming **I**nterface
VTK	**V**isualization**T**ool **K**it
GIS	**G**eographic **I**nformation **S**ystem

Chapter 1

Introduction

Urban trees have many effects on their surroundings. They improve the air quality in cities by removing fine particles and gaseous pollutants such as CO_2 from the atmosphere [10, 11]. They block solar radiation from heating surfaces and increase the urban albedo, which reduces heat storage, and therefore they moderate heat stress and reduce the urban heat island effect [12]. Trees intercept and store rainfall and increase the permeability of the soil, which can help reduce drainage problems [11, 13, 14]. They also reduce noise pollution in two ways. Firstly, they lessen the traffic noise of busy streets. Secondly, they add more positively rated noises to the city soundscape, such as rustling leaves and bird sounds [15]. Trees attract these birds and various other wildlife such as squirrels and insects. They do so by providing as a food source, shelter, or brooding habitat [11, 16]. Thus, trees improve the quality of life of both humans and all other kinds of biodiversity in cities.

Besides these supporting services of trees, they add to the aesthetic value of the street scene [15]. Amsterdam is a city with many trees. Some trees even have a monumental status because of their aesthetic value or, for example, historical significance. It is estimated that there is at least one tree for each city's inhabitants. This is a lot in comparison to cities like Paris, where it is estimated that there is only one tree for every 22 inhabitants [9]. To maintain the beneficial and aesthetic effects of the trees, it is essential to monitor and take good care of them [17].

The city of Amsterdam monitors its trees every three years. There are over 260000 trees managed and registered by the municipality, which can be viewed in this interactive map[1] [9]. This dataset excludes privately managed trees by, for example, cemeteries, trees in larger green areas, and trees in private gardens. It contains attributes such as species,

[1]https://maps.amsterdam.nl/bomen/?LANG=nl

height, and plantation year. The municipality thus well monitors the aboveground characteristics of these trees.

However, the root systems of the trees are not or cannot be monitored as often. Although they are not often monitored, it is essential to know where and how roots grow. Think of when a city wants to design new (subsurface) infrastructure. In this case, it is crucial not to damage the roots since that can have a significant impact on the tree, not only on its health but also on its stability [11]. These factors increase the risk of storm damage caused by trees to buildings, cars, or even people [17]. In addition, trees can damage subsurface infrastructure such as sewers and the above surface infrastructure such as sidewalks and quay walls [11, 17, 18]. Especially in older cities such as Amsterdam, where the subsurface space is already quite full, and the roots cannot grow very deep because of the high groundwater levels, it is crucial to map the subsurface space that should be preserved for the tree roots to keep the trees healthy.

For this thesis, we created a model that estimates how much root volume trees need, based on the aboveground parameters of the trees that the municipality of Amsterdam monitors. We created three methods that use slightly different input parameters. They model the estimated root volume as 3D cylinders and also predict how much volume the roots need in the future. This is necessary for the future development of a city because it provides insight into the underground that is currently missing. This model is not only beneficial for Amsterdam but also for other cities and areas with high groundwater levels. Besides, it provides insight into the subterranean ecology and the applicability of a simplified modeled version of a real-world system, like roots, in general.

Visualizing the results of the model in an appropriate program can help infrastructure planners design new plans so that both the trees and infrastructure will not disturb each other. The platform that we use to display the model results is 3D Amsterdam[2], which is a 'digital twin' of Amsterdam that the municipality is developing, see Figure 1.1. There is an increasing demand for displaying city data in 3D, so Amsterdam and also cities like Utrecht and Rotterdam are developing digital twins. These platforms can potentially be used to visualize new neighborhoods to citizens, determine the solar potential of roofs, and show data like heat stress in the city. In addition, a 3D city model is very suitable for simulations of, for example, wind streams, crowds, and flooding. This way, digital twins can play an important role in decision- and policy-making.

The 3D Amsterdam team is making the model as realistic as possible by, for instance, using point cloud scans of buildings to detect bay windows and passages, which they can include in 3D Amsterdam. The 3D model has an option to view the subsurface area of the city, currently only displaying the sewers. The 3D team wants a better representation

[2]https://3d.amsterdam.nl/

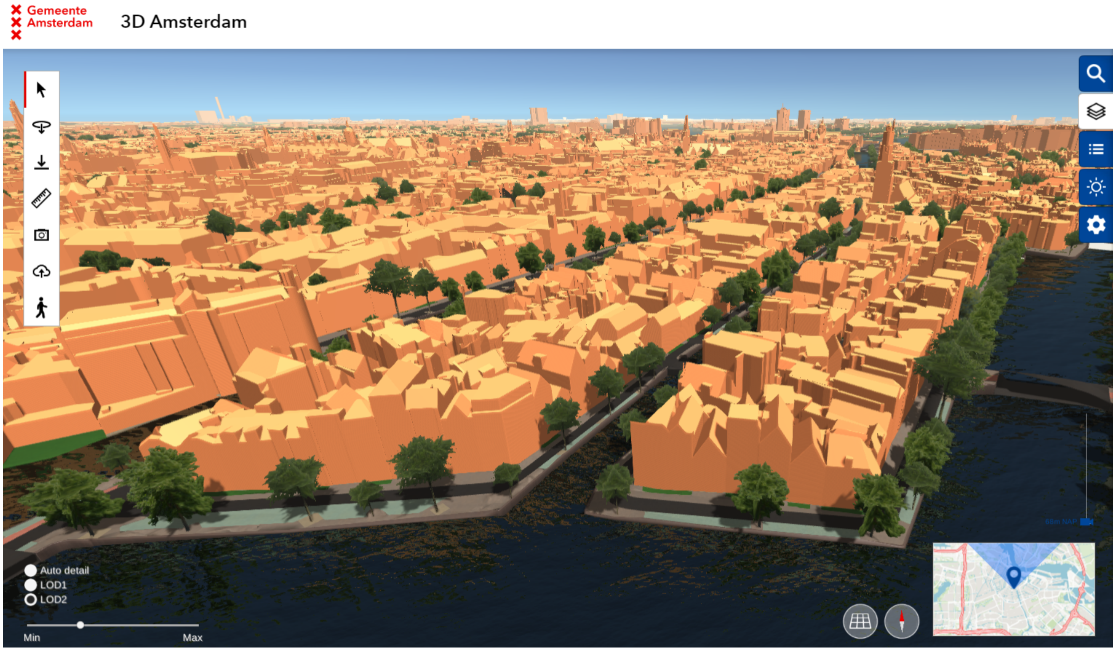


FIGURE 1.1: A screenshot of the 3D Amsterdam website. The buildings can be seen in orange, and the trees consist of three 2D images. In addition, various UI elements and functionalities of the website can be seen.

of the subsurface in their model since the municipality does not have good insight into this space and it is getting full. Tree roots are one of the categories that they want to add because these roots are very abundant in the subsurface space. The trees managed by the municipality are visible in the 3D model, simplified by three 2D image planes based on their species, see Figure 1.1. With the result of our tree root model, the estimated root volumes of these trees can also be added to the 3D Amsterdam model and can be visualized over time.

Our root model is initially tested for three subregions in Amsterdam. The first one is *het Wallengebied*, an older area in need of redevelopment and where the problem of a full subsurface is very occurrent. The second one is *IJburg*, a new building area, and the third one is *Sarphatipark*, a park in the middle of the city. These last two areas were selected such that the model is tested for diverse city areas. The central question that we address in this report is *Can a simulation of tree root growth in a 3D model of a city provide accurate and valuable insight into the location and impact of the roots?*

To answer this question, we produced and created:

1. A literature overview of the factors that influence and limit root growth.
2. A structured overview of the data and relations needed as input for the model.
3. A model that determines how much volume the roots need at an arbitrary year for a particular tree.

4. Code that converts the root volume to a geometrical shape and saves this in the suitable format that can be included in the 3D Amsterdam model.

5. A visualization of the root volume growth in the 3D Amsterdam model with a corresponding user interface (UI) to control the visualized data.

6. A comparison between the performance of the three different methods.

7. A validation and comparison of the model output with real tree and root data.

8. An evaluation of the model's usefulness in determining the current and future impact of the roots.

9. An output dataset containing the current and future estimated root volumes for the trees in the municipality dataset.

A review of the relevant literature is given in Chapter 2. Chapter 3 describes the methods and how they are included in the model. Chapter 4 presents the experiments that we did and the results of the model, and it also immediately discusses these results. Chapter 5 gives the conclusions, and in Chapter 6, we provide recommendations for future work.

Chapter 2

Literature Review

2.1 Types of roots

Originally, three main types of roots were identified: taproots, heart roots, and lateral (surface) roots, see Figure 2.1 [19]. In a tap root system, a robust main root grows vertically down in the area below the trunk. In a heart root system, roots of various sizes grow diagonally down from the trunk. In a lateral or surface root system, horizontal roots grow sideways from the trunk, extending just below the soil surface, while small roots descend vertically from these roots. The initial root system of a seedling consists of a taproot. From this taproot, lateral roots grow to form a branched structure [19].

These systems help describe the characteristics of roots. However, tree species and soil conditions influence the specific growth conditions of tree roots. The classifications are often not retained, and many exceptions occur [20]. For example, urban trees usually have less available space for their roots, which can cause them to deviate from these systems.

A common misconception about tree roots is that they grow in a similar structure as the branches, while in reality, roots grow more shallow and widespread. In general, roots do not occur below two meters deep in the soil. In deep and loose soils, they might grow deeper, but typically 90 to 99% of the roots of a tree are located in the upper one meter of soil [21].

2.2 Soil properties

The soil conditions influence the root growth of trees. The environmental constraints from the soil on roots have been classified into four groups [20]. The first group is the

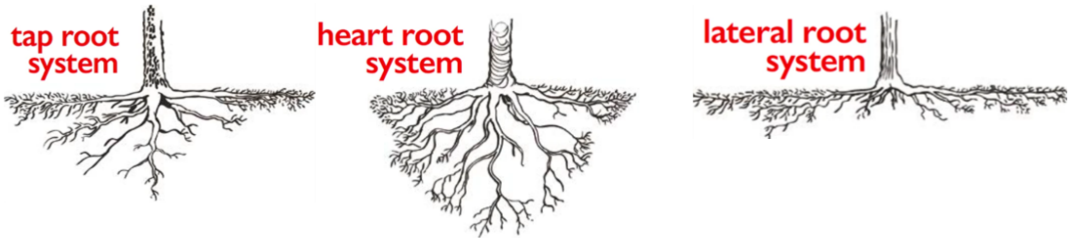


FIGURE 2.1: An illustration of the three main types of tree roots that were originally identified: taproots, heart roots, and lateral roots [1].

mechanical resistance of the soil. Roots cannot grow too deep into the soil with a high bulk density, like compact clay soil or very stony soil. The second constraint group is the aeration of the soil. Roots need oxygen for respiration, so root growth stops if oxygen levels become too low due to compact soil or the presence of other gases. The third group is the fertility of the soil. Soils without sufficient fertility produce root systems with poorly branched surface roots and no roots descending deeper into the soil. The fourth group is the moisture of the soil. If a tree is located in a dry area, this can cause shallow roots to intercept more rainfall. If there exists a subsurface supply of water, roots can grow towards it if they can penetrate. On the other hand, waterlogging, or excess water, depletes the soil of oxygen. This creates anaerobic conditions, so roots typically grow very shallow and widespread in soils with high water tables [20].

In Amsterdam, the upper meters of the soil consist primarily of sand and various ground heightening materials [22]. These are not always suitable for trees, so usually, if a new tree is planted in Amsterdam, an underground area is dug out. This soil is replaced with tree-specific substrates like tree soil, tree sand, or tree granulate.[1] Tree soil is the most suitable for trees, but it cannot support infrastructures like pavements and roads. Therefore, tree soil is usually only used for trees in the open ground [11]. Tree sand can support light loads and, together with tree granulate, moderate loads. Heavy loads such as roads need to be supported by tree granulate [8, 11].

2.3 Groundwater level

The most crucial factor for root growth in Amsterdam is the high groundwater level, which roots cannot grow below since this does not provide enough oxygen [23]. The groundwater levels in Amsterdam are highly regulated. This is because many of the houses are located on wooden poles. If the groundwater levels become too low, these poles run dry, which can cause them to rot. But if the levels become too high, this can

[1]Other soil substrates such as humus compost or mulch are also used as e.g. top layer, but the most commonly used soil substrates are tree soil and tree sand [11].

lead to drainage problems after rainfall. Because of the high groundwater levels, trees in Amsterdam can almost always reach the groundwater with their roots [11]. Because the groundwater levels being highly are regulated, we also assume that the groundwater levels will remain similar in the coming years. Groundwater measurements are done by Waternet and are available on this website[2] [24].

The assumption that the groundwater levels will remain similar in the coming years is supported by the climate scenarios from the Koninklijk Nederlands Meteorologisch Instituut (KNMI, the Royal Dutch Meteorological Institute). They created four scenarios, which are combinations of two different values for the global temperature rise: 'Gematigd' (G, moderate) and 'Warm' (W, hot), and two possible changes of the airflow pattern: 'Lage waarde' (L, low value) and 'Hoge waarde' (H, high value) [25]. Thus, the W_H-scenario predicts the most drastic changes, and the G_L-scenario the least extreme changes. These scenarios involve changing precipitation amounts, which can cause the groundwater levels to change. For the G_L-scenario, the KNMI calculated for a test location in Amsterdam that the lowest groundwater level in the driest summers at the end of the century would be around 5cm higher than their current value. In the W_H-scenario, which includes longer periods of drought, the groundwater level at the end of the century will remain the same or around 5cm lower [25]. 5cm is not much compared to the root depth and horizontal root extension, which are in the order of meters. Also, these 5cm changes are the most extreme scenarios. These scenarios thus support the assumption that the groundwater levels remain similar.[3]

When groundwater is the limiting factor in root depth, the depth that roots can grow to depends on the difference between the ground level and groundwater level. This difference is called relative or rootable depth. The higher the groundwater level, the smaller the rootable depth because of the low oxygen levels. If the groundwater is sufficiently high and no other factors limit root growth, roots typically grow until the average highest groundwater level (or Gemiddeld Hoogste Grondwaterstand, GHG, in Dutch) [11, 23]. This GHG can be calculated by averaging the three highest groundwater level measurements over the period April 1 - March 31 (hydraulic year). The average of these yearly values over a period of at least eight years is the GHG [26]. Thus, this GHG determines the root depth.

[2]https://maps.waternet.nl/kaarten/peilbuizen.html

[3]Besides climate change, the groundwater level is also dependent on the policy of the counties. In periods of persistent drought, the counties can accommodate the farmers by raising the groundwater level. However, this is not expected to influence the groundwater level in cities a lot, nor trees because of the short period of these interventions.

2.4 Estimated root volume of trees

The volume that trees require for their roots to grow depends on many parameters related to the tree. Norminstituut Bomen (Norm Institute Trees) created a tool called Rekenprogramma Boommonitor (Tree Monitor Calculation Tool), which is based on the moisture balance in the soil [2]. This tool relates the most important parameters to the volume estimated for the roots and is available for licensees such as students and the municipality. The most important parameters are soil profile type, tree height, crown diameter, and circulation time of a tree.

Soil profile entails the infrastructural function of the area in which the tree is located. Trees in the open ground require less volume than a similar tree beside a busy road. This is because closed pavements reduce the flow of oxygen and water into the soil. Besides, the best soil for trees cannot be used underneath roads since it cannot support the traffic [8]. The trees thus need a larger amount of volume to take in the same amount of nutrients. Furthermore, a tree needs more roots and hence more volume if it cannot access the groundwater. If the tree can reach the groundwater level, it is ensured water provision. If it cannot access the groundwater level, it needs more root volume to compensate the water provision with rainwater. Based on Section 2.3, we make the assumption that all trees in Amsterdam can reach the groundwater level.

This report uses four categories of soil profile type: open ground (with tree soil), light load, moderate load, and heavy load. Section 2.2 explains the corresponding soil properties of these loads in more detail. The category open ground contains areas like green spaces, light load contains sidewalks and bike paths, moderate load contains parking spaces, and heavy load contains roads. Appendix A has a list with the classification of the most occurring soil profile types, subdivided by the load category. These classifications are based on the classes mentioned in Handboek Bomen 2018 (Tree Manual 2018) [8]. Sometimes the soil profile type could not be classified, for example when the location of the tree is misplaced in water or a building. These situations are listed in Section A.5.

Two other important parameters related to the estimated root volume are the height and crown size of a tree. For the height input, the trees are divided into four classes by the Handboek Groen (Green manual) and Handboek Bomen 2018 [8, 11]. This division is essential when choosing trees in urban design concerning, for example, the width of the street and the distance to the facade [11]. Trees of the first class of height are higher than 15 meters. Trees of the second class of height are between 8 and 15 meters, and trees of the third class of height are smaller than 8 meters. The last class consists of

TABLE 2.1: The tree crown class subdivision for each height class, based on Handboek Bomen 2018 [8].

crown class:	small	regular	broad
height class 1 (> 15m)	< 10m	10 - 15m	> 15m
height class 2 (8 - 15m)	< 8m	8 - 12m	> 12m
height class 3 (< 8m)	< 5m	5 - 8m	> 8m
shape/pollard trees	< 3m	3 - 5m	> 5m

shape and pollard trees, which can vary in height but get pruned regularly[4]. The trees are then subdivided based on their crown diameter, which is the diameter of the crown when looked from above. There are three crown classes: small, regular, and broad. The exact ranges for the crown diameter differ for each height class. Table 2.1 gives an overview of these crown classes.

The output of the calculation tool Boommonitor looks like Figure 2.2. This specific example is for a tree of the first height class with a regular crown, located in a lightly loaded soil. The output consists of three levels of ambition for the root volume: optimal ('optimaal'), reasonable ('redelijk'), and marginal ('marginaal'). The marginal volume indicates the minimal volume that should be assigned to the tree roots. The reasonable volume indicates more realistic growth conditions for the tree, and the optimal volume provides the optimal growth conditions for a tree. The calculation tool outputs the necessary root space in cubic meters and in square meters (in this case for when the rootable depth is 1m) [8].

The final important parameter for determining how much volume should be assigned to the tree roots is the circulation time ('omloop') of a tree, which is also visible in Figure 2.2 [8]. For this, the distinction between regular and fast-growing trees is important. If a tree is a regular grower, the circulation numbers in the calculation tool output are 20, 40, 60, and 80 - 120 years, just as in Figure 2.2. If a tree is a fast grower, the circulation numbers are 15, 25, 35, and 45 - 60 years. Trees classified as fast-growing in this report are of genera *Populus*, *Salix*, and *Alnus* [8]. The estimated root volume of these trees thus also increases faster over time.

2.5 Tree growth over time

The numbers from the calculation tool Boommonitor are dependent on tree height and crown size. In the tool itself, the tree species determine this height and crown size, assuming the final values that a matured tree of a species will have. However, it can

[4]Shape trees are not used by default in Amsterdam since they require intensive management and pruning. Pollard trees are not used in streets but can be planted in e.g., parks [11].

Boominfo ?

Beoogde omloop (cyclus):

Regulier (duurzaam groeiend)	20	40	60	80	jaar

Benodigde doorwortelbare ruimte (m^3) en grondvlak (m^2): ?

(ambitieniveau) Optimaal	**13.2**	**22.6**	**28.3**	**33.9**	**m^3**
	13.2	*22.6*	*28.3*	*33.9*	*m^2*
(ambitieniveau) Redelijk	**10.6**	**18.1**	**22.6**	**27.1**	**m^3**
	10.6	*18.1*	*22.6*	*27.1*	*m^2*
(minimum niveau) Marginaal	**7.9**	**13.6**	**17**	**20.3**	**m^3**
	7.9	*13.6*	*17*	*20.3*	*m^2*

FIGURE 2.2: An example of the root volume output from the calculation tool Boommonitor. There are three levels of ambition for the root volume of a tree: optimal ('optimaal'), reasonable ('redelijk'), and marginal ('marginaal'). The influence of the circulation time ('omloop') can be seen in the top of this figure. Source: Rekenprogramma Boommonitor, Norminstituut Bomen [2].

also be interesting to include the height and crown growth over time. Not only for determining the root volume but also to do other exciting calculations over time related to the urban ecosystem services of a tree. There is even a tool, called i-Tree, that can express these services in monetary value [27].

Scientists of the U.S. Forest Service Pacific Southwest Research Station recorded data from over 140000 trees in 17 cities in 16 different climate regions in the U.S. [28]. From this data, they created allometric growth equations for 171 distinct tree species, which also underpin models such as i-Tree. The data and equations are publicly available in the Urban Tree Database[5] (UTD).

2.5.1 Growth equations

Seven equations were developed for the 20 most abundant tree species in each of the 16 different climate regions. Tree age and crown diameter can be used to predict the diameter at breast height (d.b.h., at 1.37 m). This d.b.h. can be used to predict tree height, crown diameter, crown height, age, and leaf area. Note that the authors refer to tree age as the years after planting. They tested six models with four different weights for each of these seven parameter relations. This was done after removing outliers in

[5] http://dx.doi.org/10.2737/RDS-2016-0005

the data [28]. The tested models are four polynomial models, a log-log model, and an exponential model:

$$
\begin{aligned}
\text{Linear:} \qquad & y_i = a + bx_i + \frac{\epsilon_i}{\sqrt{w_i}} \\
\text{Quadratic:} \qquad & y_i = a + bx_i + cx_i^2 + \frac{\epsilon_i}{\sqrt{w_i}} \\
\text{Qubic:} \qquad & y_i = a + bx_i + cx_i^2 + dx_i^3 + \frac{\epsilon_i}{\sqrt{w_i}} \\
\text{Quartic:} \qquad & y_i = a + bx_i + cx_i^2 + dx_i^3 + e{x^4}_i + \frac{\epsilon_i}{\sqrt{w_i}} \\
\text{Log-log:} \qquad & \ln(y_i) = a + b\ln(\ln(x_i + 1)) + \frac{\epsilon_i}{\sqrt{w_i}} \\
\text{Exponential:} \qquad & \ln(y_i) = a + bx_i + \frac{\epsilon_i}{\sqrt{w_i}}
\end{aligned}
\tag{2.1}
$$

Here y_i is the measurement of tree i that is the dependent variable, and x_i is the independent variable. a is the mean intercept, b the mean slope, ϵ_i is the random error for the tree, and w_i is a known weight that takes one of the following forms: $w_i = 1$, $w_i = 1/\sqrt{x_i}$, $w_i = 1/x_i$, or $w_i = 1/x_i^2$ [28]. For each combination of tree, climate zone, and parameter relation, the resulting best-fitting model is listed in the UTD, together with the fitted coefficients to use in the relation. The weighting for the polynomials is built into the coefficients but not for the log-log and exponential models. More explanation on the development of these tree growth equations and examples on how to use them can be found in the paper *Urban Tree Database and Allometric Equations* [28].

2.5.2 Climate comparison with the Netherlands

The equations were developed separately for each of the 16 climate regions since tree growth for a species can be very dependent on the climate [28]. To determine which equations to use for the Netherlands, we compared the 16 different climate regions of the U.S. to the Dutch climate.

The U.S. climate regions are classified based on cooling degree days (CDD) and heating degree days (HDD), which represent the yearly summation of degrees of the average daily temperature above and below 18.5 °C [29]. Also, hardiness zones were taken into account, which are defined by the average annual minimum winter temperature and indicate which plants can survive in a specific zone. There are multiple definitions of hardiness zones. The paper uses the USDA scale from the United States Department of Agriculture, which is the most widely used system [30]. Lastly, annual precipitation was taken into account.

According to a report by the RIVM in 2007, the amount of HDD in the Netherlands in 2003 was 2887 °C [2747, 3027] [31]. The report shows a declining trend in HDD. If this trend continues, the current number of HDD should be around 2700 °C. According to the same report, the amount of CDD in the Netherlands in 2003 was 92.1 °C [62.0, 134.7] [31]. The CDD shows an increasing trend. If this continues the current number of CDD should be around 140 °C. The HDD and CDD are also measured specifically for Amsterdam in the period of 2005-2015. The HDD is 2166 °C and the CDD 37 °C [32]. The USDA hardiness zone of the Netherlands ranges from 7b (close to the German border) to 10a (Waddeneilanden). Most of the Western part of the Netherlands has hardiness zone 8b, while most of the Eastern region has 8a. These zones have average minimum winter temperatures of respectively -9.4 °C to -6.7 °C and -12.2 °C to -9.4 °C [33]. The annual precipitation in the Netherlands is between 800 and 1000mm [34]. For Amsterdam, measurement numbers ranged from 810 to 850mm [35–37].

Comparing the above information with Table 1 in the Urban Tree Database and Allometric Equations paper shows that the most similar U.S. climate is the Pacific Northwest. This climate zone has an amount of HDD and CDD of respectively 2468 and 157, the USDA hardiness zones 8-9, and annual precipitation of 1059mm [28]. This assumption is supported by both the Pacific Northwest and the Netherlands having a temperate oceanic climate [38, 39]. Thus, the tree growth equations associated with the Pacific Northwest should be used for the Netherlands.

2.5.3 Limitations of tree growth equations

The tree growth equations from the UTD have some limitations [28]. One of these limitations is that large sample sizes of trees are needed since tree growth can be very variable depending on environmental factors. Also, trees might be pruned or damaged by pests or storms, making them deviate from their regular growth. Another limitation is that in the UTD, planting dates or tree ages rarely exceed 40 years, and detecting trees from areal imagery used for data acquisition is difficult for images taken before 1990. This makes predictions for older trees less accurate. In addition, tree age information is often hard to acquire. Equations predicting d.b.h. from age could produce negative values, which could cause problems for further calculations [28].

2.6 Roots as geometrical shapes

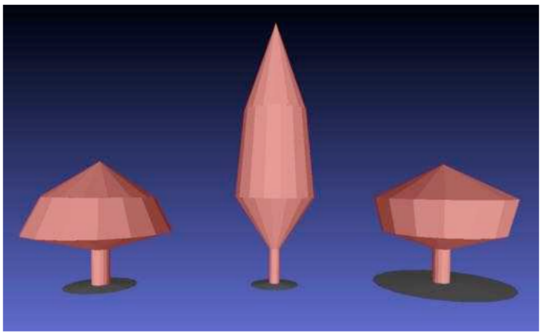
The estimated root volume needs to be converted to a geometrical shape. Modeling roots as their actual shapes can only be done with either destructive methods like digging out the tree or time-consuming techniques such as ground radar scanning. Given that roots keep growing, these measurements have to be repeated often. It is, therefore, more feasible to model roots as 3D geometrical shapes. The geometrical shape then represents the potentially occupied subsurface space by the roots. Cylinders and cones are often used as building blocks for these geometrical shapes [3, 4].

Roots can be represented with different Levels of Detail (LOD). Geometrical descriptions for roots have been proposed as comparable to the CityGML LOD, which is often used as a standard in city models [3]. The different LODs are:

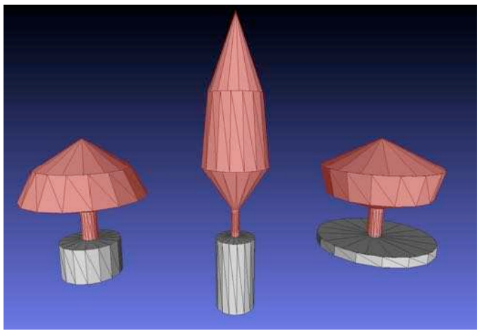
- LOD 0: Project the horizontal root spread on the terrain surface, see Figure 2.3a.
- LOD 1: Basic 3D model in the shape of a cylinder considering lateral root extension and root depth, see Figure 2.3b.
- LOD 2: 3D model with distinctive geometrical shapes like truncated cones, similar to the characteristic shape of the roots, see Figure 2.3c.
- LOD 3 & LOD 4: Models derived from scanned data, see Figure 2.3d. For LOD 3, a convex hull can be built around the data. For LOD 4, more advanced shape reconstructions are needed.

LOD 0 is only suitable for 2D analysis, while with LOD 1, it is already possible to analyze interactions and conflicts with underground infrastructure. The analytical results from LOD 2 should be comparable to LOD 1 [3]. LOD 3 and 4 differ from the former levels since they visualize the actual roots instead of the potential occupation by roots and, therefore, also need data collection.

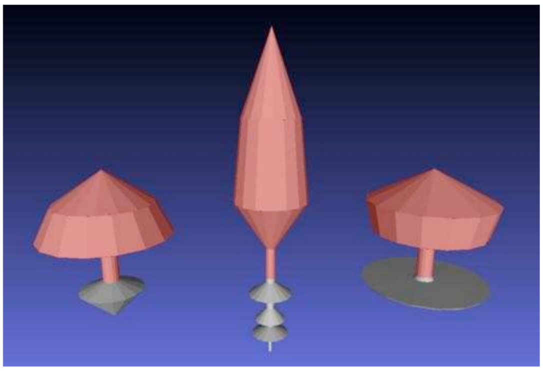
For this thesis, we model the roots with LOD 1, which means that the roots are modeled in the shape of a cylinder. A cylindrical shape for the root volume is applicable for Amsterdam, where the groundwater levels are very high, so most roots are lateral roots. Any other geometrical shape would likely be truncated to a more cylindrical shape by the high groundwater level.



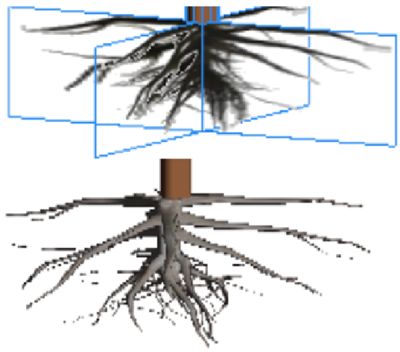
(A) LOD 0 representation for heart roots, taproots and lateral roots [3].



(B) LOD 1 representation for heart roots, taproots and lateral roots [3].



(C) LOD 2 representation for heart roots, taproots and lateral roots [3].



(D) Realistic (LOD 3 or 4) representation of root systems [4].

FIGURE 2.3: Tree roots can be represented using different LODs, matched with the CityGML standards [3, 4].

Chapter 3

Methods

We created three methods to estimate the current and future root volume: the static method, tree dictionary method, and tree growth method. These methods partly use the same input parameters. How the input parameters can be derived is discussed in Section 3.1. How the estimated root volumes are converted to cylinders in a suitable output format is explained in Section 3.2. The three methods to estimate the root volume are discussed in Section 3.3. Section 3.4 describes how the cylinders are included in 3D Amsterdam.

The model is created using Python 3.8.5. The code can be viewed and installed from this GitHub page[1], which also contains descriptions of the different scripts and step-by-step instructions for running the model. The visualization of the root volume growth in the 3D Amsterdam model and the UI for controlling the visualized data are created with Unity 2020.3.29f1 and corresponding programming language C#.

3.1 Derivation of the input parameters

The municipality of Amsterdam monitors its more than 260000 trees every three years. The data for these trees is publicly available in four CSV datasets through this link[2]. We use the Python library Pandas for reading out the CSVs. These datasets contain the tree position, species, tree number, tree type, height, plantation year, tree owner and manager.[3] Not all these parameters are useful for the root volume. We elaborate on the useful ones below.

[1]https://github.com/reitsmairis/tree$_root_model$

[2]https://maps.amsterdam.nl/open_geodata/

[3]The tree datasets are from 2020 and are therefore not entirely up to date. Especially newly planted trees are missing. The municipality is currently working on migrating and improving the quality of the tree datasets, which are planned to be available in the beginning of 2023.

3.1.1 Tree positions

The tree positions ('LNG', 'LAT' in the municipality dataset) determine the location of the root volume cylinders. In addition, the positions are needed for sampling the soil profile type, and also the tree height when it is unknown. This sampling is described in more detail in respectively Section 3.1.7 and Section 3.1.4. The accuracy of the tree positions in the datasets varies; it can differ from 10cm to 10m with the actual tree positions [9].

The municipality measures the location of the trees with the Global Positioning System (GPS), which uses the World Geodetic System (WGS84) as a reference coordinate system. This means that each tree has a latitude and longitude value. Many Dutch datasets and also 3D Amsterdam make use of Rijksdriehoekscoördinaten (central triangle coordinates, abbreviation: RD-coordinates) instead of WGS84. RD-coordinates are projected Cartesian coordinates, as opposed to WGS84, which uses a curved coordinate system. This coordinate system consists of an x-coordinate, which goes from West to East, and a y-coordinate, which goes from South to North. The RD-coordinates are measured in meters. The reference point of these coordinates is the Onze Lieve Vrouwetoren in the city of Amersfoort, which has been chosen so that all coordinates are positive and the y-coordinate is always larger than the x-coordinate. To convert from WGS84 to RD-coordinates and the other way around, we use the Python library Rijksdriehoek 0.0.1[4] [40].

3.1.2 Tree number

The municipality assigns each tree a number ('boomnummer') for identification. We also use this tree number to label the output root volume cylinders, making it easy to match them with the corresponding trees. In addition, this tree number is used to find the corresponding crown diameter in the dataset, which is described in more detail in Section 3.1.5.

Very few trees are not assigned a tree number in the municipality dataset. If this happens, we use the object number ('OBJECTNUMMER') of the tree for the output naming, including the prefix 'objNR'. This is because, otherwise, the geometrical root volumes would be overwritten each time the model encounters a tree without a tree number. However, most of the time that the tree number is lacking, most other tree data is lacking as well, which makes it impossible to estimate the root volume of these trees.

[4] https://pypi.org/project/rijksdriehoek/

3.1.3 Tree species

The scientific names of the species of most trees are known in the municipality dataset as 'Soortnaam_WTS'. They consist of a genus (e.g. *Ulmus*), and species or cultivar (e.g., *Ulmus x hollandica 'Wredei'*). We use this genus to determine if a tree is a fast or regular grower in all three methods and to determine the height and crown in the tree dictionary and tree growth methods. If the species is unknown, only the static method can estimate the root volume.

3.1.4 Tree height

The datasets from the municipality contain a height ('boomhoogte') range of usually 3 meters for the trees (e.g., 12 to 15 meters). For the height input, which is used by the static method, we take the average of those values.

When the tree height is unknown, we use the heightmap Actueel Hoogtebestand Nederland (AHN) to estimate the tree height [41]. This height map is measured by LiDAR data, which is converted to a point cloud, and then to a grid. The most recent version of this height map is AHN4, which was measured between 2020 to 2022. For the tree height, the 0.5m resolution DSM (Digital Surface Model) grid version is used. Such a height map is not very accurate in estimating tree heights since the laser can easily miss the highest point of a tree and we need to sample the height map at the highest location, which is often not precisely on the known tree location. To overcome this problem, we create Gaussian noise around the tree location with a standard deviation of 0.5m to increase the possibility of sampling the tree at its highest measured point. Thus, 20 new sample points are created in addition to the original location of the tree. For each point, the AHN4 is sampled by URL request to the AHN viewer[5] [42] by making use of the Python library Urllib3.

The RIVM also created a dataset with the tree height as a raster map of 10 by 10m, which is also sampled by URL request and can be viewed here[6] [43]. This file was derived from the AHN2 and AHN3 0.5m files, the Basisregistratie Adressen en Gebouwen (BAG, register addresses and buildings) file, and infrared areal pictures. This dataset is older than the AHN4, but it might contain more accurate tree height information since it is combined with other datasets. Besides, since it is aggregated to a 10 by 10m raster, it is not needed to create Gaussian noise since it is much less likely that the highest point of the tree falls within another raster cell.

[5] https://www.ahn.nl/ahn-viewer

[6] https://atlasnatuurlijkkapitaal.nl/boomhoogte-in-nederland

In the end, the maximal returned value out of the AHN4 samples and the RIVM sample is returned as the tree height. This is likely still an underestimation, but it does give some tree height indication when the municipality height is missing.

3.1.5 Crown size

The dataset from the municipality does not contain the crown size of trees. This data is provided by the consultancy agency Cobra Groeninzicht[7] for the three subregions in Amsterdam. Cobra Groeninzicht has its own tree data and matches this with the municipality data based on the tree number assigned by the municipality.

We classify the crown diameter according to the classes displayed in Table 2.1, for which height information is also necessary. Since one of the classes consists of shape and pollard trees, which can vary in height, the tree type also needs to be checked. This is available in the dataset from the municipality as tree type parameter ('boomtype'). Trees from the shape and pollard tree class are labeled as type 'vormboom' (shape tree) or 'knotboom' (pollard tree) in the dataset. This parameter is optional for all three methods because they assume that a tree is from a regular class when the type is not provided.

It could be that the crown size is not determined, or at least not accurately. In the crown dataset, the height is estimated at 3 meters if it is unknown, and the crown diameter is put at 1.971 meters. In this case, we assume that the crown is unknown and cannot be classified, which also means that the static method can not estimate the root volume of the corresponding tree.

3.1.6 Plantation year

The plantation year ('plantjaar') in the municipality dataset is the year that the tree is planted in Amsterdam [9]. The actual age of a tree is not significantly related to this number since a tree can be between 5 and 15 years when it is planted. If the plantation year is unknown (= 0 in the dataset), it is impossible to estimate the root volume with any of the three methods.

3.1.7 Soil profile type

The municipality dataset does not contain the soil profile type or load. This can be determined by using the BGT (Basisregistratie Grootschalige Topografie), which includes

[7] https://www.cobra-groeninzicht.nl/

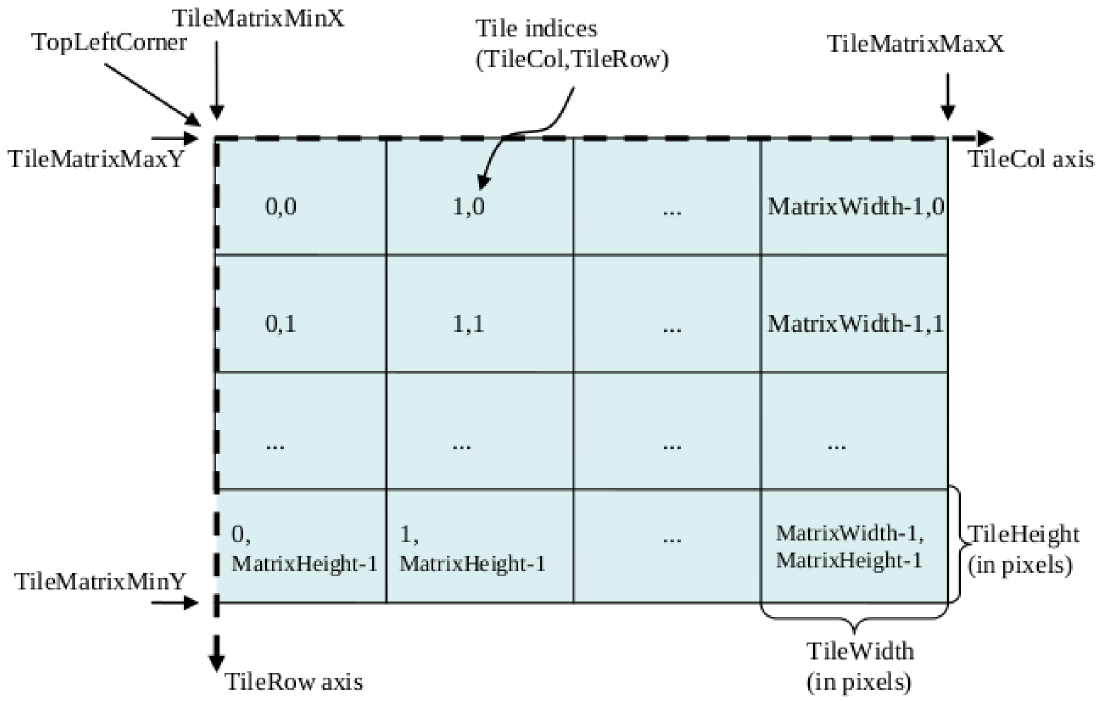


FIGURE 3.1: Tile matrix representation of a WMTS. It consists of multiple tiles indicated by their tileRow and tileColumn. Each tile consists of a number of pixels, defined by the tileWidth and tileHeight in pixels. The topLeftCorner indicates the reference point of the tile matrix. Adopted from the WMTS documentation [5].

the registration of large-scale topographies such as buildings, roads, and watercourses. The BGT is available as Web Map Tile Service (WMTS) according to the OGC (Open Geospatial Consortium) standards. A WMTS file consists of a tile matrix as visualized in Figure 3.1. This tile matrix subdivides into multiple tiles if a user zooms in. This means that some computation is required when consulting the BGT value at a point location since the RD-coordinate of that point needs to be converted to a corresponding tile and pixel within that tile. We explain this procedure below, which is based on the information from the WMTS documentation [5].

Firstly, we need the reference point of the tile matrix. For this purpose, the topLeftCorner is often used, which is visualized in the upper left corner of Figure 3.1. This topLeftCorner defines the x and y offset of this matrix corner in RD coordinates. These coordinates can be retrieved from the GetCapabilities request on the WMTS, giving for the topLeftCorner: offsetX $= -285401.92$, offsetY $= 903401.92$. Secondly, the zoom level needs to be matched with the corresponding denominator that defines the scale of a tile, which can also be retrieved from the GetCapabilities request. This denominator is defined with respect to a standardized rendering pixel size of 0.28 by 0.28mm [5]. We use the highest zoom level of 14, corresponding to a denominator of 750. The span of a pixel can then be determined by

$$\text{pixelSpan} = (\text{pixelSize} \cdot \text{denominator})/\text{metersPerUnit}, \tag{3.1}$$

where metersPerUnit is 1 for the RD-coordinate system.

We then need the span of a tile, which follows from multiplying the span of a pixel by the tileWidth in pixels (which is equal to the tileHeight for the BGT), which is 256 according to the GetCapabilities request. Thus:

$$\text{tileSpan} = \text{tileWidth} \cdot \text{pixelSpan}. \tag{3.2}$$

With this information, we can determine the row and column of the tile matrix that correspond to an RD-coordinate (x, y):

$$\begin{aligned} \text{tileColumn} &= (x - \text{offsetX})/\text{tileSpan}, \\ \text{tileRow} &= (\text{offsetY} - y)/\text{tileSpan}. \end{aligned} \tag{3.3}$$

What remains is the pixel coordinate (i, j) within that tile, which can be determined by using the decimals of the rows and columns and multiplying this with the tileWidth in pixels:

$$\begin{aligned} i &= (\text{tileColumn} - \text{floor}(\text{tileColumn})) \cdot \text{tileWidth}, \\ j &= (\text{tileRow} - \text{floor}(\text{tileRow})) \cdot \text{tileWidth}. \end{aligned} \tag{3.4}$$

With these tile and pixel coordinates, we can make a GetFeatureInfo request of the BGT for a tree position, which returns the BGT properties at the coordinate of the tree.

We firstly check these properties by function, such as “voetpad” (sidewalk). The second check is for appearance, of which “groenvoorziening” (green space) is an example. If both do not occur in the properties, the type is also checked, which can be, for example, “bordes” (platform) or “waterloop” (watercourse). We also check if the properties contain the key “bag_pand”, in which case it is a building. Appendix A contains a list of which soil profile type corresponds to these combinations of properties. If the value of the BGT could not be determined or classified, the root volume can not be estimated.

3.2 Volume to Cylinders

The estimated tree root volume needs to be converted to a geometrical shape, in this case, a cylinder with a height and a radius. The cylinder height is determined by the rootable depth, for which we need the groundwater level and the ground level. The cylinder height and volume together determine the radius of the cylinder. This section describes these steps and the derivation of these parameters in more detail.

3.2.1 Groundwater and interpolation

The groundwater measurements are available on this website[8] from Waternet [24]. They are measured with respect to the Normaal Amsterdams Peil (NAP, Amsterdam Ordnance Datum). Waternet measures this by hand six times a year at about 2500 locations. Besides that, automatic daily measurements occur at a few hundred sites. These groundwater measurements need to be converted to a GHG value to determine the rootable depth. To convert the measures to GHG, we first need to convert the dates and years from the dataset to hydraulic years. Then, the three highest groundwater values in a hydraulic year belonging to one monitoring well are averaged, and this average value is again averaged over the different hydraulic years, as explained in more detail in Section 2.3. This way, we can calculate the GHG for each of the monitoring wells.

The groundwater levels are measured at point locations (monitoring wells) within Amsterdam. Since the trees can be located between those wells, they need to be interpolated. This type of multivariate interpolation is also called spatial interpolation, which can be done in various ways. In this report, we use the Delaunay triangulation method for interpolation, which creates a mesh formed by triangles. This has the advantage of not having to loop over the measurement points for every tree since the mesh can be stored and readout for a tree at any moment. Delaunay triangulation creates a surface of triangles based on the input points so that no point lies inside the circumscribed circle of any triangle, which is visualized in Figure 3.2. While doing so, it maximizes the smallest angle of all the angles of the triangles to avoid triangles with a long or thin shape.

In the model, the Delaunay triangulation is done using the Vedo module, a Python module that can be used for scientific analysis of 3D objects which is based on the Visualization Toolkit (VTK) and NumPy [44]. This module has a function called delaunay2D, which creates the Delaunay triangulation of the input GHG points. To determine the GHG at the location of a tree, we determine the intersection point of the Delaunay mesh and a line through the coordinate of the tree perpendicular to the coordinate plane, which can be easily done by applying the intersectWithLine function from Vedo to the line and mesh. This returns a 3D coordinate of intersection, of which the x and y entries represent the location of the tree and the z entry the interpolated GHG value at the location of the tree.

[8] https://maps.waternet.nl/kaarten/peilbuizen.html

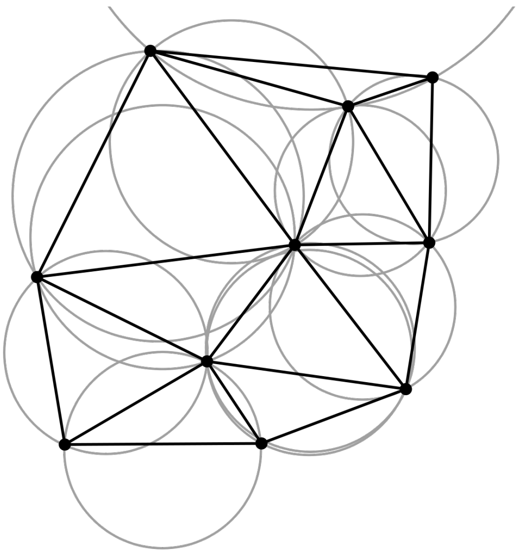


Figure 3.2: A mesh resulting from Delaunay triangulation on a set of vertices [6]. The circumscribed circles of the triangles are also shown. No point lies inside such a circle.

3.2.2 Ground level height

The ground level height is determined by using the AHN4 0.5m grid again, just as sampling the tree height described in Section 3.1.4 [41]. However, this time we used the DTM (Digital Terrain Model), so the objects on the ground were excluded. Again, a URL request is made to the AHN viewer[9] for the location of the tree [42]. The AHN4 value could be unknown, while the AHN3 value is known because they have been measured using different or higher flight paths [41]. In these cases, the AHN3 0.5m DTM value is sampled instead.

If both the AHN4 and AHN3 values are unknown, we sample the values of the four adjacent grid cells. This is done by adding and subtracting 0.5m to the x and y coordinates of the tree. We firstly try to do this with the AHN4, and if these values are still all unknown, we use the AHN3 as backup again. The average of the returned ground level values is taken as the ground level height for the tree location. In the rare case that the values of the four adjacent grid cells are also unknown for both the AHN3 and AHN4, the root volume of the corresponding tree can not be estimated.

3.2.3 Cylinder output

With the previous sections, we have all the necessary information to convert an estimated root volume to a cylinder. The height h of a cylinder is determined by the relative or

[9]https://www.ahn.nl/ahn-viewer

rootable depth at the location of a tree, which is the difference between the ground level and the GHG:

$$h = \text{ground level} - \text{GHG}. \tag{3.5}$$

If also the estimated root volume V of a tree is known, this determines the radius r of the cylinder:

$$V = \pi r^2 h, \text{ so } r = \sqrt{\frac{V}{\pi h}}. \tag{3.6}$$

A cylinder object is represented by multiple points on two circles at a different z height. One of these circles is located at the ground level, the other at the groundwater level. The location of the tree determines the x and y coordinates of the cylinder by

$$\begin{aligned} x_i &= x_{\text{tree}} + r \cdot \cos{(i \cdot \theta)}, \\ y_i &= y_{\text{tree}} + r \cdot \sin{(i \cdot \theta)}, \end{aligned} \tag{3.7}$$

where $i \in [0, N-1]$ with N the number of points on one circle and $\theta = 2\pi/N$. In this report, $N = 15$ is used, such that the total number of vertices for a cylinder is 30.

To be included in the 3D Amsterdam model, we need to store the cylinders in CityJSON format. CityJSON is an OGC standard used to encode 3D city models [45]. It is a JSON object with the following members for the root volume cylinders:

- "type": "CityJSON".
- "version": 1.0 is used.
- "CityObjects": Contains key-value pairs. The keys represent the IDs of the objects, and the value is the object. This object is explained in more detail below.
- "vertices": Array of coordinates of each vertex in the object (in this case cylinders). Their position is used as the index to which the CityObjects geometry refers.

The CityObjects contain the cylinders and are stored using the following members:

- "type": This should be one of the defined possibilities mentioned here[10]. For the root cylinders, we chose SolitaryVegetationObject.

[10] https://www.cityjson.org/specs/1.1.1/

- "attributes": Can be used to list information about the object.
- "geometry": Contains the Geometric Objects. They have a type, which is MultiSurface for the cylinders. They also define the LOD, which is 1. And most importantly, they have boundaries in which each surface is represented by an array of an array. The indices in these arrays refer to the vertices and define the surfaces this way.

CityJSONs can be opened with the viewer ninja[11]. In addition, we include the root cylinders in 3D Amsterdam, which is built with Unity. Including the root CityJSONs in Unity or ninja showed z-fighting, a flickering effect of the polygons 'fighting' to be shown. This is a 3D rendering problem that occurs when multiple polygons are very close to each other. The z-fighting thus happens because the three root volume cylinder layers that we estimate for the different ambition levels have the same height. To reduce this effect, one and two centimeters are added to the topside and downside of respectively the middle cylinder (reasonable ambition level) and inner cylinder (marginal ambition level). This introduces a height difference, so the z-fighting disappears.

3.2.4 Cylinder boundaries

The interpolated mesh of GHG values could be inaccurate for areas where groundwater measurements are sparse. If the ground level varies significantly in those areas, this could lead to unrealistic or even negative values for the rootable depth. Therefore, we set boundaries for the upper and lower cylinder height. In Section 2.1, we explained that roots in general do not grow below two meters deep, and 90 to 99% of the roots are located in the upper 1 meter of soil [21]. In consultation with the tree experts of the municipality, it was chosen to have 1.25m as the maximal rootable depth and, consequently, cylinder height. The minimal rootable depth is set to 25cm to avoid too small or negative rootable depth values.

In consultation with the tree experts, no upper boundary for the root volume is chosen. This is because urban trees do not often reach the age where their root growth is negligible. It is advised to reserve a volume of at least 25m^3 for trees of the first and second height class and 15m^3 for trees of the third height class [11]. However, if the tree is not assigned a very long circulation time, this could be unnecessary. Also, if a tree is assigned a long circulation time, it needs more volume for its roots. For these reasons, no boundaries are applied to the estimated root volume.

[11] https://ninja.cityjson.org/#

3.3 Three estimation methods

Section 3.1 explained the necessary input parameters for the model. This section explains how these input parameters are used by the three different methods to estimate the root volume of trees.

3.3.1 Root volume

The root volume for a tree of which the necessary parameters are known can be estimated by inter-and extrapolating the data (as in Figure 2.2) from the calculation tool Boommonitor. Doing this linearly gives an initial root volume at the plantation and a growth rate of the root volume per year for each combination of input parameters of the tool (height class, crown class, and soil profile type). We do this calculation for fast growing trees and regular growing trees, and for all three ambition levels. The output numbers of the tool do not always increase perfectly linear since roots might grow faster when a tree is younger, but averaging the growth rate gives a good indication of the root volume. We use these numbers in combination with the circulation time of a tree to couple the known tree parameters to an estimated root volume. All three methods output three cylinders per tree per year, which correspond to the three different ambition levels for the root volume.

3.3.2 Static method

The first method to estimate the root volume is the static method. This method retrieves the tree height and crown size from the datasets from 2020 as described in sections 3.1.4 and 3.1.5. This method then classifies the height and crown of the tree based on these measurements. With the plantation year of the tree, it is possible to determine the circulation of the tree in an arbitrary year. This circulation, the BGT value, and the interpolated root volume numbers then give the estimated root volume for an arbitrary year. This root volume can be converted to a cylinder using the rootable depth, for which the GHG level and ground level are needed. The GHG levels are derived and interpolated as described in Section 3.2.1 and the rootable depth is determined as described in Section 3.2.3. Figure 3.3 shows the pipeline for the static method.

Although species is also one of the input parameters in Figure 3.3, this parameter is only used to determine if the tree is a fast or regular grower. If the species is unknown, this method estimates the root volume assuming a regular growing tree. Therefore, for this method, the species information is not required, which could be seen as an advantage.

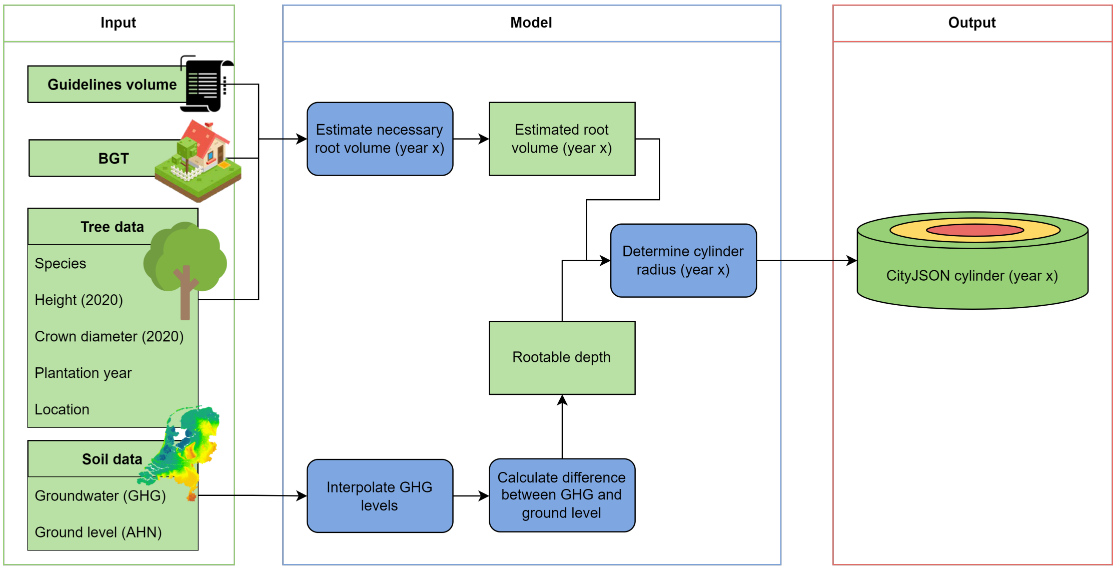


Figure 3.3: Pipeline for the static method for calculating the root volume cylinder sizes. The left box shows the inputs of the model, and the right box the three output cylinders corresponding to the ambition levels. The model box shows how to go from the input to the output.

The static method assumes that a tree will be in the same crown and height classes for the rest of its life, based on the datasets for 2020. This is a disadvantage of the method since trees grow and could therefore reach higher crown and height classes in a later stadium of their life. This assumption could be valid for trees that have already reached their expected height and crown, but especially younger trees are likely to grow to other classes.

The static method is the only method that uses the actual tree height and crown diameter from the datasets of the municipality and Cobra Groeninzicht, which are from 2020. This could make the predictions for 2020 more accurate than the methods that do not use this information. However, the more one deviates from this year, the more the problem above arises, and the less accurate the classification is. This could be overcome by updating the datasets frequently, but the model will probably still work best for the years corresponding to these datasets and not for estimating the volume for future years.

3.3.3 Tree dictionary method

The second method is the tree dictionary method, which is based on how the calculation tool Boommonitor determines the root volume [2]. This method classifies the tree height and crown class based solely on its species. This is possible since it is known what final height and crown size a tree has when it is fully grown for most species.

Table 3.1: The 15 most occuring tree genera in Amsterdam, starting with the most abundant genus [9].

Top 15	Scientific name	Dutch name	English name	Amount
1	*Ulmus*	Iep	Elm	31327
2	*Tilia*	Linde	Linden	26195
3	*Acer*	Esdoorn	Maple	25641
4	*Fraxinus*	Es	Ash	19217
5	*Platanus*	Plataan	Plane	15413
6	*Quercus*	Eik	Oak	14047
7	*Populus*	Populier	Poplar	12900
8	*Alnus*	Els	Alder	12372
9	*Betula*	Berk	Birch	11277
10	*Salix*	Wilg	Willow	11252
11	*Prunus*	Kers	Cherry	11245
12	*Carpinus*	Haagbeuk	Hornbeam	6492
13	*Crataegus*	Meidoorn	Hawthorn	6078
14	*Robinia*	Acacia	Locust	5647
15	*Aesculus*	Paardenkastanje	Horse chestnut	4021

For Amsterdam's 15 most occurring genera, we created a dictionary containing the final crown and height class as in Table 2.1, and the final height and crown size, for all species and cultivars of these genera. These genera are listed in Table 3.1, starting with the most abundant one [9]. In total, this tree dictionary contains the height and crown information for 225 tree species. The dictionary was created based on the information from various online tree databases, handbooks, and catalogs. The most important ones are the calculation tool Boommonitor [2], Handboek Groen [11], tree producers Ebben Nurseries [46] and Van den Berk Nurseries [47], and the Wageningen University and Research (WUR) Temperate Species Tree Database and Street Trees [48, 49]. Other sources are Bomenwijzer [50], Bomenbieb [51], Landscape Plants [52], Gardenia [53], and the North Dakota Tree Handbook [54]. If the final height or crown values or classes for a species are unknown or not included in the dictionary, it is impossible to estimate the root volume with this method.

This method thus looks at the species of a tree and divides the tree into a height and crown class based on this. Using the plantation year of the tree, it is possible to determine the circulation of the tree in an arbitrary year. This circulation, the BGT value, and the interpolated root volume numbers then give the estimated root volume for the arbitrary year. This root volume can be converted to a cylinder using the rootable depth, for which the GHG level and ground level are needed. The GHG levels are derived and interpolated as described in Section 3.2.1 and the rootable depth is determined as described in Section 3.2.3. Figure 3.4 shows the pipeline for the tree dictionary method. Note that it is very similar to the pipeline for the static method shown in Figure 3.3, but they both use different input data relating to the tree. The tree dictionary method

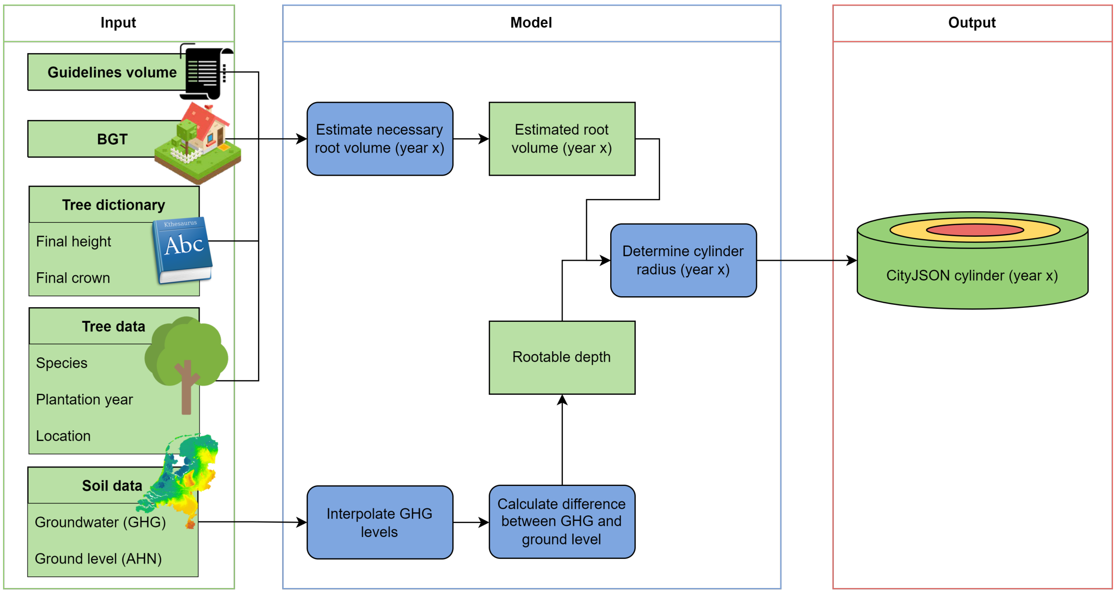


FIGURE 3.4: Pipeline for the tree dictionary method for calculating the root volume cylinder sizes. The left box shows the inputs of the model, and the right box the three output cylinders corresponding to the ambition levels. The model box shows how to go from the input to the output. This figure differs from the static method in Figure 3.3 in the input parameters for the tree data since this tree dictionary method uses the final height and crown sizes contained in the tree dictionary, whereas the static model uses the tree data from 2020.

uses the theoretical final height and crown sizes in the tree dictionary, whereas the static model uses the actual tree measurements from 2020.

An advantage of this method is that it is not necessary to measure many tree parameters, but the corresponding disadvantage could be that it does not consider this actual tree information and parameters.

3.3.4 Tree growth method

The third method is the tree growth method. This method predicts the height and crown size of a tree based on its age. Age, in this case, means the circulation of the tree, and since the municipality knows the plantation year of most trees, the circulation can be calculated for an arbitrary year. The predictions use the equations from the Urban Tree Database (UTD) described in Section 2.5 for the correct tree genus and climate region. The age can predict d.b.h., and this d.b.h. predicts crown diameter and height. This predicted crown diameter and height divide a tree into the corresponding height and crown class. Together with the circulation, the BGT value, and the interpolated root volume numbers, this then determines the estimated root volume. This root volume can be converted to a cylinder using the rootable depth, for which the GHG level and ground level are needed. The GHG levels are derived and interpolated as described in

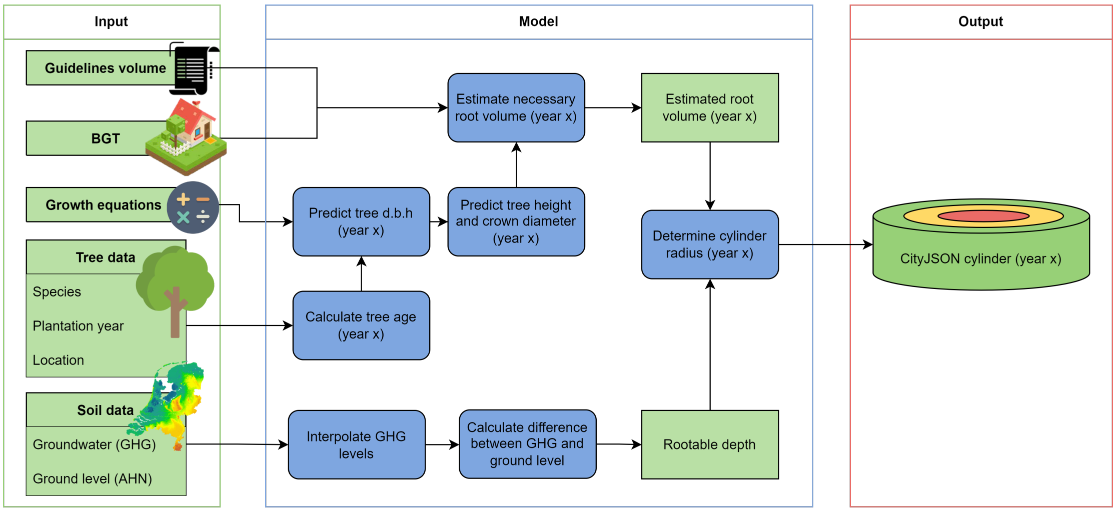


FIGURE 3.5: Pipeline for the tree growth method for calculating the root volume cylinder sizes. The left box shows the inputs of the model, and the right box the three output cylinders corresponding to the ambition levels. The model box shows how to go from the input to the output.

Section 3.2.1. and the rootable depth is determined as described in Section 3.2.3. Figure 3.5 shows the pipeline for the tree growth method.

A disadvantage of this method is that the equations correspond to 20 species only. These are abundant species in America, but not necessarily in the Netherlands. This is why not only species but also overlapping genus is taken into account in the tree growth method. For example, if there is only an equation for *Quercus rubra*, then the same equation is also applied to other trees of genus *Quercus*. The difference in the prediction performance for trees that have equations corresponding to only their genus or whole species is tested in Section 4.2.1. If there is no equation for a particular tree genus, the tree height and crown size, and consequently the root volume, cannot be estimated with this method. Another disadvantage is that the equations are based on urban trees in the US. There could be circumstances that differ from the Netherlands that are not included in the climate comparison, leading to inaccurate predictions.

An advantage of this method is that it also predicts the tree height and crown size over time. These values are essential since they indicate the urban ecosystem services of a tree. These ecosystem services include rainfall regulation and removing pollutants. Tools like i-Tree can even convert these tree services to monetary value [27]. Besides this, the predicted height and crown size can be used to scale trees over time in 3D models like 3D Amsterdam.

3.4 Unity implementation

The previous sections explained how the methods estimate the root cylinder sizes and output these in CityJSON format. This section describes how these CityJSON cylinders can be included in the 3D Amsterdam Unity project.

3.4.1 Tile Bake Tool

The models output the tree root cylinders in CityJSON format, but the 3D Amsterdam project uses a binary format as input. The 3D Amsterdam team created a tool called the Tile Bake Tool to convert CityJSONs to binary format. These binary files are often much smaller and thus use less memory and significantly reduce the loading time in Unity. The binary format is compatible with glTF (Graphics Language Transmission Format), a standard format for 3D scenes and models which can be opened with most 3D editors. The Tile Bake Tool generates a glTF-wrapper such that it also outputs glTF files.

The Tile Bake Tool does not only convert the format of the output root cylinder files; it also prepares the data in 1000 by 1000 meter tiles. This way, Unity can load the correct tiles depending on where the camera looks in the digital environment. Loading the entire city takes more time, but now tiles that are not looked at can be excluded. The Tile Bake Tool is available on the GitHub page of Amsterdam, as CityDataToBinaryModel[12]. It needs a configuration file that specifies the source folder of the CityJSON data and the output folder for storing the binary data. The "config" folder contains examples of this configuration file, the configuration file that we made for the roots is based on the example file for the trees.

3.4.2 Time slider

The Tile Bake Tool splits the root cylinders into 1000 by 1000 meter tiles. These tiles are separated both for the different years for which root volume estimations are done and three ambition levels for the root volumes. Unity creates layers for the different years at the start, based on the provided file path to the binary files, using a tool developed by the 3D Amsterdam team called the "tilehandler". The root growth over time is visualized using a timeline created by the 3D Amsterdam team. This slider connects to the cylinder layers corresponding to different years. When the slider is moved to a new year, the layer corresponding to this year is turned visible, and the layer corresponding

[12]https://github.com/Amsterdam/CityDataToBinaryModel

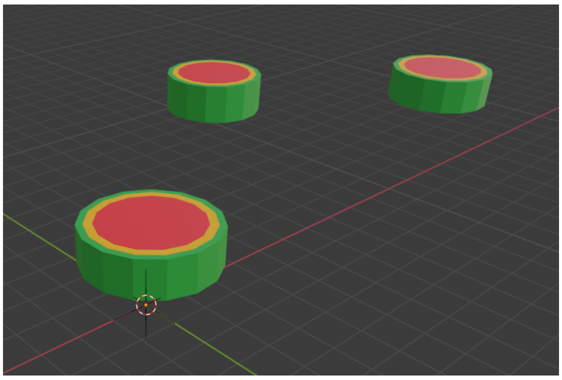


FIGURE 3.6: An example of how the estimated root volume cylinders look. For each tree, volumes corresponding to three ambition levels are estimated: marginal (red), reasonable (orange), and optimal (green).

to the previous year is turned off. This is quicker than loading new layers in Unity when the slider is moved. The implementation of the timeline is very general, such that other layers that also have a time component can be connected to it as well.

3.4.3 Materials

We used a red, orange, and green color for respectively the marginal, reasonable, and optimal ambition levels for the estimated root volume, see Figure 3.6. As an additional UI element, we wanted a slider that controls the transparency of the root cylinders, which can also make them completely transparent if wanted. We first tried to couple a slider to the alpha value of the RGBA (Red Green Blue Alpha) color. However, since the cylinders corresponding to the different ambition levels overlap and their meshes are hollow, this creates unwanted visual effects.

We used dithering to deal with these unwanted effects, which is a way of rendering pixels that creates faux transparency. We did this by creating a shader for each ambition level, which is a script containing the algorithms and a calculation for determining the properties of rendered pixels. The pipeline for the shader can be seen in Figure 3.7. This shader takes the primary material color and a float f as input. The float f is controlled by a standard Unity UI slider and can have a value between 0 and 1. We then use a Unity dithering node with $1-f$ and the screen position as input to determine the Alpha Clip Threshold of the material. Pixels with values below this Alpha Clip Threshold are not rendered. Furthermore, we split the input RGBA color and multiply the alpha with the $1-f$ input, which thus changes the alpha of the material. This means that when the input float f is close to one, almost all pixels are rendered, and if the input float is close to zero, practically no pixels are rendered, and the material appears transparent.

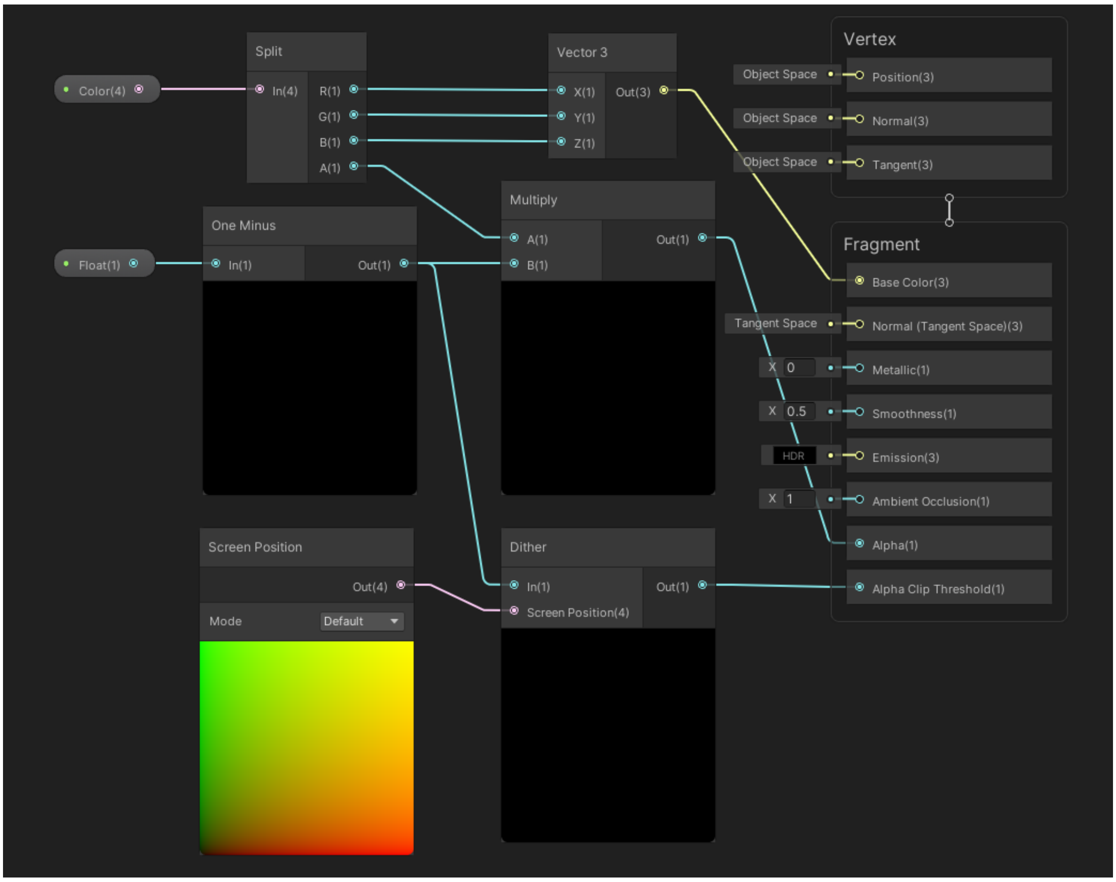


FIGURE 3.7: The pipeline for the shader that is used to create faux transparency with dithering in Unity. This shader takes the basic material color and a float f as input. The float f is controlled by a Unity slider and can have a value between 0 and 1. We use a Unity dithering node with $1 - f$ and the screen position as input to determine the Alpha Clip Threshold of the material, pixels with an alpha below this threshold are not rendered. Furthermore, we split the input RGBA color and multiply the alpha with $1 - f$ input, which thus determines the alpha of the material.

Chapter 4

Experiments, Results and Discussion

The model is firstly tested on the three chosen subregions in Amsterdam: *het Wallengebied*, *IJburg*[1], and *Sarphatipark*. This is because running the model and experiments on all the trees in the dataset of Amsterdam takes a lot of time. The specific bounding box coordinates of the subregions that were used to select the trees are displayed in Table 4.1. After the experiments, we run the model for all the trees in the dataset. This is described in Section 4.5. The visualization in 3D Amsterdam is discussed in Section 4.6. All figures in this chapter are made with Python library Matplotlib.

We used three different approaches to compare the output of the model to the real root situations. The first approach is only applicable to the tree growth method. It compares the height and crown size predicted by this method with the tree height and crown size from the data. The second approach compares the estimated root volume cylinders with ground radar scans of root systems. The third approach compares the estimated root volume cylinders with damage reports by citizens and road inspectors. The first and third approach are done for the three subregions in Amsterdam: *het Wallengebied*,

[1] In subregion *IJburg*, there is an insufficient number of groundwater level measurement points to create a mesh that covers most of the subregion. Therefore, for each point, points with the same value were manually added at ±400m in x and y direction, aligning with the shape of the region.

TABLE 4.1: The bounding box coordinates in WGS84 that were used to select the trees in the different subregions.

	min longitude	min latitude	max longitude	max latitude
het Wallengebied	4.891912	52.366063	4.905603	52.376220
IJburg	4.986429	52.347605	5.008591	52.363305
Sarphatipark	4.892947	52.353315	4.899928	52.355310

Table 4.2: The counts and percentages of trees for which a root volume could be estimated by the three methods, separated by subregion. The total percentages and counts are also displayed for each of the methods.

	Total trees	Static	Tree dictionary	Tree growth
het Wallengebied	1099	63.1% (693)	71.2% (783)	68.0% (747)
IJburg	2216	64.9% (1439)	57.9% (1283)	48.5% (1074)
Sarphatipark	507	68.8% (349)	57.8% (293)	56.4% (286)
Total	3822	64.9% (2481)	61.7% (2359)	55.1% (2107)

IJburg and *Sarphatipark*. The second approach is used for the trees around *Stationsplein* for which the ground radar scans were available. Sections 4.2, 4.3, and 4.4 elaborate on these different approaches and their results.

4.1 Results for the subregions

We created root volume output for the subregions using the three methods: static, tree dictionary, and tree growth. These methods need different input parameters, and therefore it differs per method for how many trees a root volume can be estimated. The counts and percentages of trees for which a root volume could be estimated are displayed in Table 4.2 for each method, separated by subregion. The total counts and percentages for each method are also shown.

The static method was able to estimate the most root volumes in total. Only for *het Wallengebied*, it estimated the least amount of volumes. For the tree dictionary method, the lower count could be explained because it is not working for tree species that are not included in the dictionary with the height and crown classes. The tree growth method cannot estimate root volumes for genera without growth equations. The static method is not dependent on species, only to check if a tree is a fast grower, but if the tree species is unknown, it estimates the root volume for a regular growing tree. Therefore, species is not the limiting factor, but it is the availability of especially the height, crown size, and year of plantation information. Although the static method could estimate the most root volumes, this does not imply that this is the preferred method since we still need to determine the accuracy of the three methods.

The CityJSON output for the subregions can be found on this GitHub page[2] in the output folder. This folder contains the output of all three methods and can be opened with the ninja[3] viewer. For *Sarphatipark* and *IJburg*, the output is generated for 2020. For *het Wallengebied*, the output is generated for 2020, 2025, 2030, 2035, 2040, 2045,

[2]https://github.com/reitsmairis/tree$_r oot_m odel$

[3]https://ninja.cityjson.org/#

2050, 2055, and 2060. This is because for *het Wallengebied*, we included the output in a subpage of 3D Amsterdam. This subpage also includes the slider for controlling time and can be viewed here[4]. The subpage might disappear when the results are available for the whole city and included in the main 3D Amsterdam page, we elaborate on this in Section 4.6.

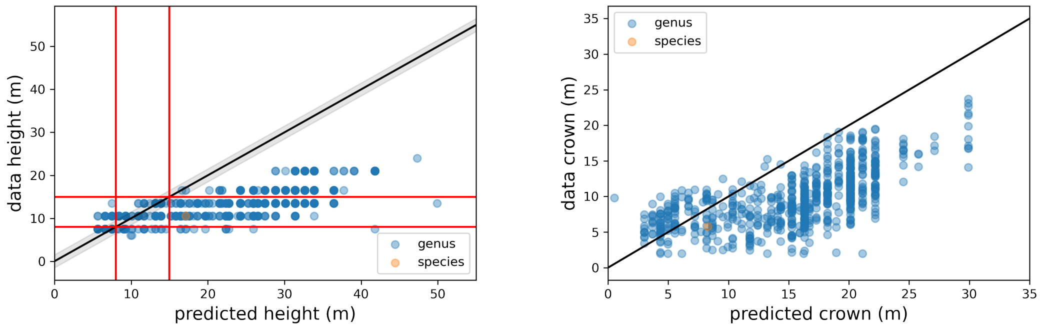
The estimated cylinders are nicely separated and structured along the streets for subregions *het Wallengebied* and *IJburg*. The cylinders rarely overlap in these subregions. In *Sarphatipark*, they are more randomly spread and overlap more frequently. Also, a significant part of the cylinders is very shallow, implying that the GHG is very high at the location of those trees or that the groundwater interpolation did not work well in this park.

4.2 Prediction of height and crown size

The tree growth method predicts the height and crown size of a tree based on its age (since the year of plantation). Since the tree heights and crown sizes are known for 2020, it is possible to verify how well these values can be predicted by the tree growth method. We used this method to predict the 2020 height and crown sizes of the trees in the three subregions in Amsterdam and compared these to the actual measurements for the height and crown size of 2020. This way, these measurements are treated as "ground truth", while they might also deviate from the actual tree height and crown size. However, they are the most realistic available data and can still give a general indication of to what extent they agree with the predicted parameters.

This evaluation is done for trees for which the height is known by the municipality and the crown size by Cobra Groeninzicht. Shape and pollard trees are excluded from this evaluation because their crowns and heights do not follow a natural form, and no good fitted models were found [28]. For the genus *Carpinus*, the equation for predicting the crown size returns negative values when the plantation year of the tree is older than 1992. These outcomes are excluded from this evaluation and probably arise because the Urban Tree Database (UTD) does not contain samples of *Carpinus* older than 1992. One tree in *Sarphatipark* had an unrealistic predicted height of around 100m and crown size of about 55m; this tree is also excluded from the evaluation.

[4]https://3d.amsterdam.nl/?project=boomwortels



(A) Tree height. (B) Tree crown size.

FIGURE 4.1: Measured height and crown size as function of the predicted height and crown size by the tree growth method for subregion *het Wallengebied*. The black line shows where they are equal and contains a shaded area of 3m for the height representing the height measure range of the municipality. The blue points correspond to trees for which a growth equation is available for the genus only; orange points correspond to trees for which an equation is available for the specific species. The red lines mark the boundaries of the different height classes.

4.2.1 General prediction accuracy

Figure 4.1 shows the actual height and crown size as a function of the predicted height and crown size by the tree growth method for subregion *het Wallengebied*, the black line shows where they are equal. Every point corresponds to a tree. For blue points, the UTD only contains equations for the genus of the tree, while for the orange points, equations are available for the specific species. We separated the trees like this to analyze if the tree growth method predicts more accurately for trees of which the equations correspond to the particular species. Since the municipality measures the height in ranges of 3m, this range is added as a shaded area in the scatter plot for the height.

Ideally, all points would fall onto the diagonal black line, meaning that the predicted height is equal to the actual height. Figure 4.1, however, shows that the tree growth method tends to overestimate the height and crown sizes for *het Wallengebied*. This is not necessarily a problem for estimating the root volume since the trees are divided into the height and crown classes as described in Table 2.1. If the predicted height differs from the actual height, but both heights still fall in the same height class, the outcome for the root volume is the same. To visualize this, we draw red lines corresponding to the boundaries of the classes in Figure 4.1a. Trees that fall within the boxes intersecting with the black diagonal line are predicted in the correct height class. In contrast, for trees in other boxes, the height is over-or underestimated so that the height of the tree is classified wrongly. We included Figure 4.2 to support this explanation, this figure is a simplification of Figure 4.1a and outlines in which of the 'boxes' that the red lines create the root volumes are correctly, over-, or underestimated. The red lines in Figure

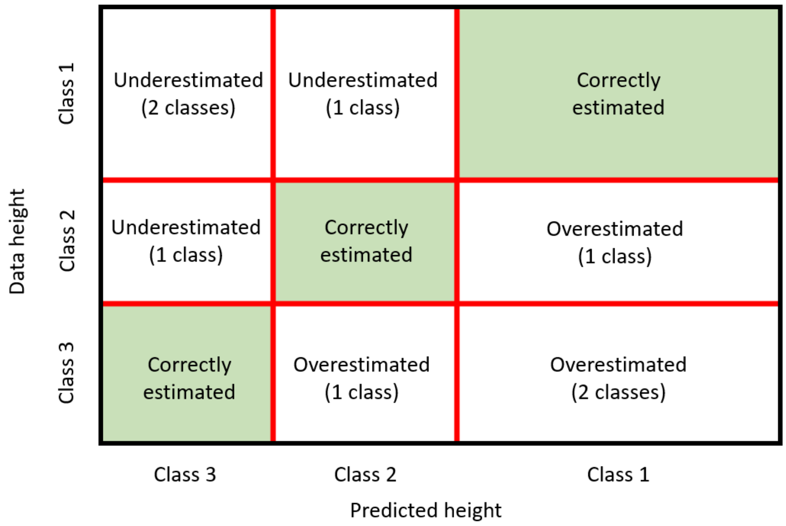


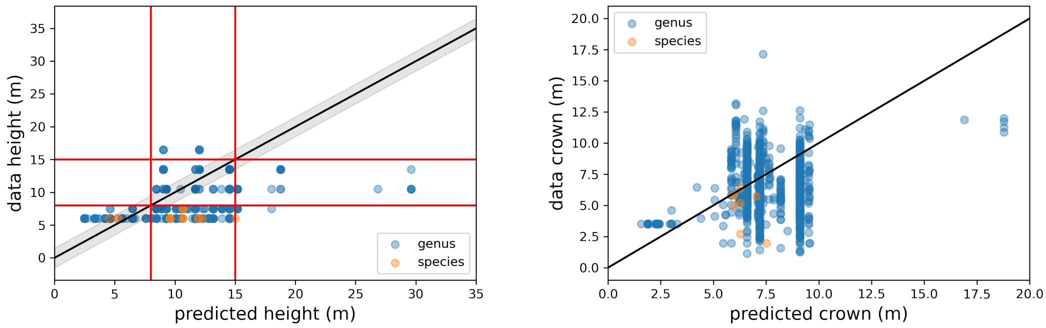
FIGURE 4.2: A simplification of the figures plotting the actual height as a function of the predicted height. It shows in which part of the figures the tree growth method correctly estimates the height class, and when it over- or underestimates the height class.

4.1a show that many trees are classified in the first height class while belonging to the second height class, and are thus overestimated.

Figure 4.3 shows the actual height and crown size as a function of respectively the by the tree growth method predicted height and crown size for subregion *IJburg*. This is a newer area, which implies that the trees are also younger and smaller in comparison to the trees from *het Wallengebied*. The red lines in Figure 4.3a show that many trees are classified in the second height class while they belong in the third height class. Just as in *het Wallengebied*, the tree growth method tends to overestimate the height for subregion *IJburg*. However, from Figure 4.3b, it seems that the crown sizes are also often underestimated.

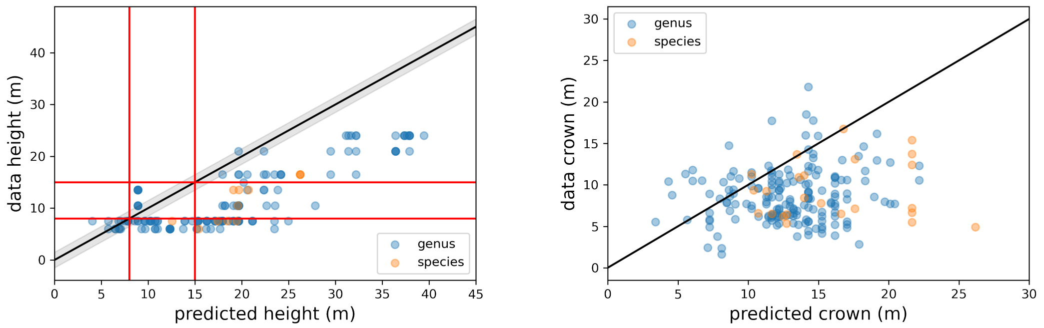
Another difference with *het Wallengebied* is that for *IJburg*, it seems that there are more trees for which equations are available for the specific species instead of only the genera since there are more orange points. Figure 4.3a shows that the height of these trees is often overestimated. The tree growth method thus does not seem to make better predictions for trees of which the equations correspond to the specific species.

Figure 4.4 shows the actual height and crown size as a function of respectively the by the tree growth method predicted height and crown size for subregion *Sarphatipark*. This city park is more than a century old and contains old and large trees. The red lines in Figure 4.4a show that many trees are classified in the first height class while they belong in the second or third height class. The tree growth method tends to overestimate the height class, and from Figure 4.4b the crown also seems to be overestimated often. Just



(A) Tree height. (B) Tree crown size.

FIGURE 4.3: Measured height and crown size as function of the predicted height and crown size by the tree growth method for subregion *IJburg*. The black line shows where they are equal and contains a shaded area for the height of 3m representing the height measure range of the municipality. The blue points correspond to trees for which a growth equation is available for the genus only; orange points correspond to trees for which an equation is available for the specific species. The red lines mark the boundaries of the different height classes.



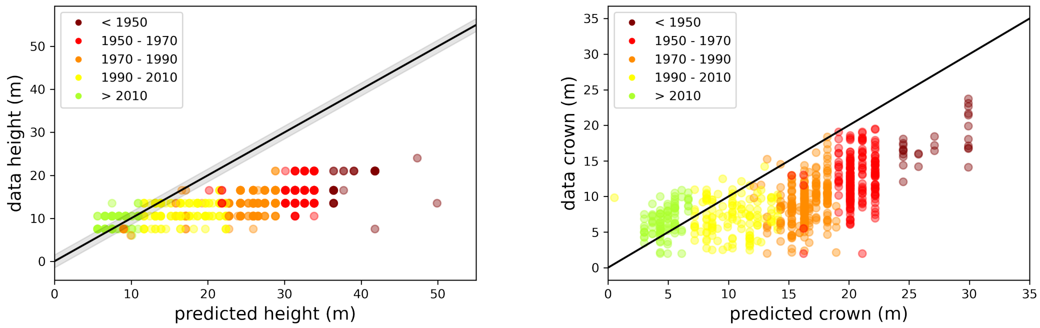
(A) Tree height. (B) Tree crown size.

FIGURE 4.4: Measured height and crown size as function of the predicted height and crown size by the tree growth method for subregion *Sarphatipark*. The black line shows where they are equal and contains a shaded area of 3m for the height representing the height measure range of the municipality. The blue points correspond to trees for which a growth equation is available for the genus only; orange points correspond to trees for which an equation is available for the specific species. The red lines mark the boundaries of the different height classes.

as with *IJburg*, it appears that the tree growth method is not performing better for the trees for which equations are available for the specific species, which are represented by the orange points.

4.2.2 Influence of tree age

We also investigated the influence of tree age on the prediction capability of the tree growth method. Figure 4.5 shows the actual height and crown size as a function of



(A) Tree height. (B) Tree crown size.

FIGURE 4.5: Measured height and crown size as function of the predicted height and crown size by the tree growth method for subregion *het Wallengebied*, colored by plantation year. The black line shows where they are equal and contains a shaded area of 3m for the height representing the height range measure of the municipality.

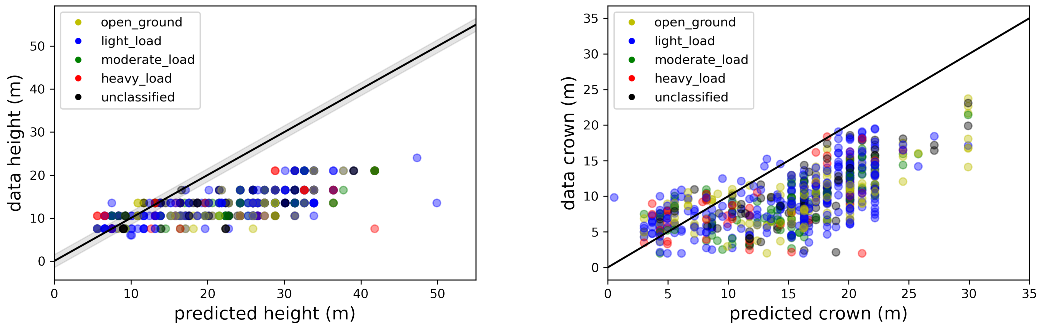
respectively the predicted height and crown size for *het Wallengebied*, colored by plantation year. These figures show that the older the tree, the more the tree growth method overestimates the height and crown size.

Similar figures were created for *IJburg* and *Sarphatipark*, they are included in Appendix B. For new building area *IJburg*, most trees are relatively young, which makes it hard to conclude something about the age influence. For *Sarphatipark*, there seems to be an age influence, but not as clear as for *het Wallengebied*.

The decrease in predicting accuracy with age can be explained because it is difficult to obtain accurate age data for older trees. For the trees in the UTD, plantation dates rarely exceeded 30 to 40 years [28]. The growth equations are thus mainly based on younger trees and do not necessarily reflect the growth of older trees accurately. In general, tree height increases rapidly when the tree is young but levels off when the tree matures. The yearly height increase can even approach zero, and also d.b.h. growth peaks in the early life of a tree [55]. Thus, if the UTD contains only young trees for a species, the slow down in growth is not included in the equations, which explains the overestimation of height and crown size. In addition, the variability of trees increases naturally with aging, which also contributes to increasing uncertainties in the predicted height and crown size [28].

4.2.3 Influence of soil profile type

The influence of the soil profile type on the prediction capabilities of the tree growth method is also investigated. Figure 4.6 shows the actual height and crown size as a function of respectively the predicted height and crown size for *het Wallengebied*, colored



(A) Tree height. (B) Tree crown size.

FIGURE 4.6: Measured height and crown size as function of the predicted height and crown size by the tree growth method for subregion *het Wallengebied*, colored by soil profile type. The black line shows where they are equal and contains a shaded area of 3m for the height representing the height range measure of the municipality.

by the soil profile type. Based on this figure, it is hard to see if there is a pattern. In addition, the low alpha values used for the scatter plot points are insufficient to overcome the bias in the plotting order. This is also the case for the figures for *IJburg* and *Sarphatipark*, which are included in Appendix B. Therefore, we also calculated the percentages of correctly estimated height classes for each soil profile type and the percentages of under- and overestimated height classes. These can be seen in Table 4.3, 4.4, and 4.5 for respectively *het Wallengebied*, *IJburg*, and *Sarphatipark*. These tables also show the total percentages of correctly classified tree heights.

The tables again show that the tree growth method overestimates the height class for many trees, while it rarely underestimates it. The soil profile type for which the most heights were classified correctly is a light load for all three subregions. The soil profile type corresponding to the lowest correctness score is open ground for all three subregions. However, the percentages are close to each other, especially for *het Wallengebied* and *Sarphatipark*. Note that for *Sarphatipark*, there are no trees with heavy load as soil profile type and only two trees with a moderate load. Only for *IJburg*, the percentages are more separated.

An explanation for the difference between the scores could be that the UTD contains mostly trees located in soil profile types of light loads and barely trees in open ground. This would lead to more accurate predictions for trees in lightly loaded soil. This is, however, not very likely, since the paper *Urban Tree Database and Allometric Equations* mentions that the UTD includes both street and park trees [28]. Thus, the soil profile type does not seem to have a significant influence on the prediction capabilities since most percentages are very close to each other. There is no good explanation found for the larger differences in *IJburg*.

TABLE 4.3: The percentage of correctly estimated, underestimated, and overestimated height classes by the tree growth method for each soil profile type for subregion *het Wallengebied*.

Soil profile type	Correct	Underestimated	Overestimated
Open ground	36.5%	2.2%	61.3%
Light load	43.5%	3.1%	53.5%
Moderate load	38.5%	4.3%	57.3%
Heavy load	40.7%	6.8%	52.5%
Total	40.4%	3.1%	56.5%

TABLE 4.4: The percentage of correctly estimated, underestimated, and overestimated height classes by the tree growth method for each soil profile type for subregion *IJburg*.

Soil profile type	Correct	Underestimated	Overestimated
Open ground	18.9%	1.4%	79.8%
Light load	56.9%	-	43.1%
Moderate load	51.2%	-	48.8%
Heavy load	37.5%	-	62.5%
Total	34.0%	0.7%	65.3%

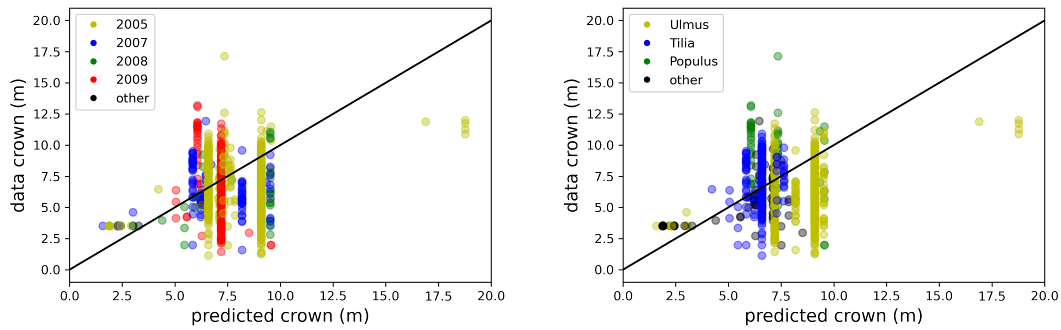
TABLE 4.5: The percentage of correctly estimated, underestimated, and overestimated height classes by the tree growth method for each soil profile type for subregion *Sarphatipark*.

Soil profile type	Correct	Underestimated	Overestimated
Open ground	35.8%	-	64.2%
Light load	47.1%	-	52.9%
Moderate load	-	-	100%
Heavy load	-	-	-
Total	39.4%	-	60.6%

4.2.4 Stratified patterns

Figures 4.1, 4.3, and 4.4 show different patterns. The figures corresponding to the height contain a horizontal pattern. This pattern is a consequence of how the municipality measures its height data; it represents the average of the 3m ranges used. The figures also show a vertical pattern, which is most obvious in Figure 4.1b and 4.3b. A reason behind this pattern could be that trees of the same genus that are planted in the same year have the same predicted value for their crown.

To check if this is indeed the case, we remade Figure 4.3b, corresponding to *IJburg*, now colored based on the year of plantation and genus. The result can be seen in Figure 4.7, which shows the actual crown size as a function of the predicted crown size. Figure 4.7a is colored based on the most occurring plantation years in this subregion. Figure 4.7b is colored based on the most occurring genera. The vertical patterns seem to follow the colored patterns. There are, for example, two distinct vertical red groups



(A) Plantation year. (B) Genera.

FIGURE 4.7: Measured crown size as function of the predicted crown size by the tree growth method for subregion *IJburg*, colored by the most occurring plantations years and genera. The black line shows where they are equal.

that correspond to trees planted in 2009. Figure 4.7b shows that these two red groups are represented by the two genera *Populus* and *Ulmus*.

It also makes sense that the vertical pattern is the most visible for *het Wallengebied* and *IJburg* since trees in streets are often planted in batches, thus having the same plantation year and species. This explains why for the trees in the city park *Sarphatipark*, the pattern is less visible.

The patterns show that, although trees of the same genera are planted in the same year, they can end up with very different heights and crown sizes. Section 4.2.3 shows that differences in soil profile type cannot explain this. A possible explanation could be that these trees of the same genera can be of different species, and if there is no equation for a specific species, the equation for the genera is applied, as explained in Section 3.3.4. For this reason, Figure 4.3b was again remade, now colored for the four most occurring species of genus *Ulmus*. The result can be seen in Figure 4.8. This figure shows that even trees of the same species that are planted in the same year are very variable in crown size. Other influences that can explain the variable height and crown sizes among trees of the same species and age can be crown damage from stressors like storms, pests, or drought [28], but this can not be tested due to a lack of data.

4.2.5 Other explanations for the prediction inaccuracies

Besides the UTD containing mostly data for younger trees, which leads to an increasing overestimation of the height and crown size by the tree growth method with age, there can be various other reasons why the measured and predicted values differ. We used the equations for the US climate region that is most comparable to the Netherlands. This was based on CDD, HDD, hardiness zone, and precipitation. However, more factors

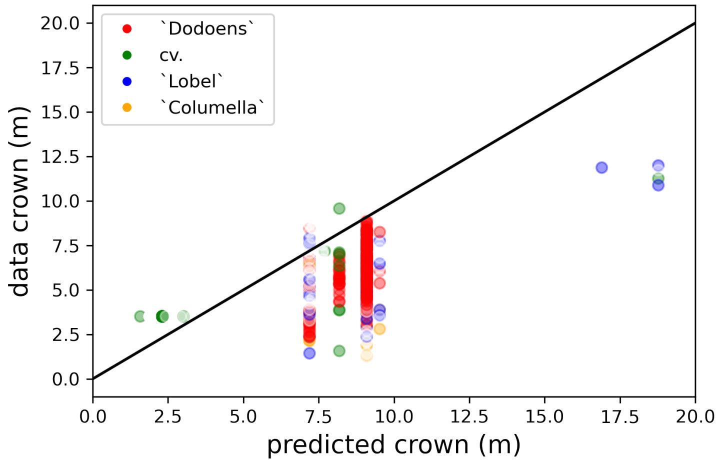


FIGURE 4.8: Measured crown size as function of the predicted crown size by the tree growth method for subregion *IJburg*, colored by the most occurring species of genera *Ulmus*. The black line shows where they are equal.

related to climate might be important that were not taken into account, like latitude, wind speeds, and air quality. In addition, the UTD does not consider some factors that can be very important to tree growth, like soil profile type or groundwater profile.

If the height or crown of the trees are wrongly classified by the tree growth method, this also influences the estimated root volume by this method. The tree growth method overestimates many tree height classes, which means that the corresponding root volumes will also be overestimated.

4.3 Comparison with ground radar scans

In 2018, the knowledge studio for trees and soil Terra Nostra[5] investigated the roots of 22 trees in project area *Stationsplein* in Amsterdam. This area will be redesigned, during which the trees should be maintained without root system damage. The goal of the investigation was to visualize these root systems by making ground radar scans [7].

4.3.1 Ground radar method

A ground radar sends radio waves into the ground, which get reflected by, for example, water and metals. Because tree roots contain a lot of moisture, they can easily be distinguished [56]. An antenna detects the reflected signals and registers the location of the roots. Both 900MHz and 400MHz antennas are used, of which the reach is

[5]https://www.terranostra.nu/nl

TABLE 4.6: The report number, municipality tree number, species, height, and plantation year for the trees for which the ground radar scans were made and municipality data is available [7, 9].

Report number	Number	Species	Height (m)	Plantation year
1	339708	*Ulmus hollandica* 'Commelin'	12-15	1960
2	339709	*Ulmus hollandica* 'Vegeta'	12-15	1960
3	339700	*Ulmus* 'Dodoens'	9-12	1980
4	339701	*Ulmus hollandica* 'Vegeta'	12-15	1970
5	339684	*Ulmus hollandica* 'Belgica'	12-15	1940
6	339681	*Ulmus hollandica* 'Belgica'	15-18	1940
10	339664	*Ulmus* 'Clusius'	9-12	1985
11	339663	*Ulmus hollandica* 'Belgica'	15-18	1920
12	339662	*Ulmus hollandica* 'Belgica'	15-18	1920
13	339650	*Ulmus* 'Lobel'	9-12	1989
14	339649	*Ulmus hollandica* 'Belgica'	18-24	1900
15	348052	*Ulmus* 'Lobel'	9-12	2014
16	347494	*Ulmus* 'Rebona'	9-12	2012
17	348073	*Ulmus* 'Rebona'	6-9	2014
18	339597	*Ulmus hollandica* 'Vegeta'	15-18	1960
19	339596	*Ulmus hollandica*	12-15	1960
20	347493	*Ulmus* 'Rebona'	6-9	2012
21	339599	*Ulmus hollandica* 'Vegeta'	12-15	1960
22	339598	*Ulmus hollandica* 'Commelin'	15-18	1960

respectively 1m and 2-2.5m in depth. The 900MHz antenna can detect roots from 0.5-1cm thick. The 400MHz antenna can detect roots from 1.5-2cm thick. The 900MHz scans contain less noise from freestone, debris, and brickwork [7].

The ground radar is attached below a buggy and directly contacts the surface. The ground radar is controlled via a tablet [56]. For each tree, either circular or linear scan lines were used, with a distance between the lines of around 0.6m. The scan area was kept as large as possible, preferably as large as the tree crown. The root detections are grouped in three layers of depth: 0-30cm, 30-60cm, and 60-100cm. These root detections are then converted to a root density by counting the number of detected roots per area [7].

We investigate the data for the ground radar scans of the 22 trees. There is no municipality data available for three of those trees (with report numbers 7, 8, and 9). They might have been cut down. The information on the other trees is listed in Table 4.6. Notice how all trees are of genus *Ulmus* but of different species. The ages of the trees span a broad range; some trees are over a century old, while others are not even a decade old. This way, we can test our model accuracy using trees of different ages and for the most occurring tree genus in Amsterdam. For the trees in Table 4.6, the three method estimated root volumes for 2018, which is the same year as the scans.

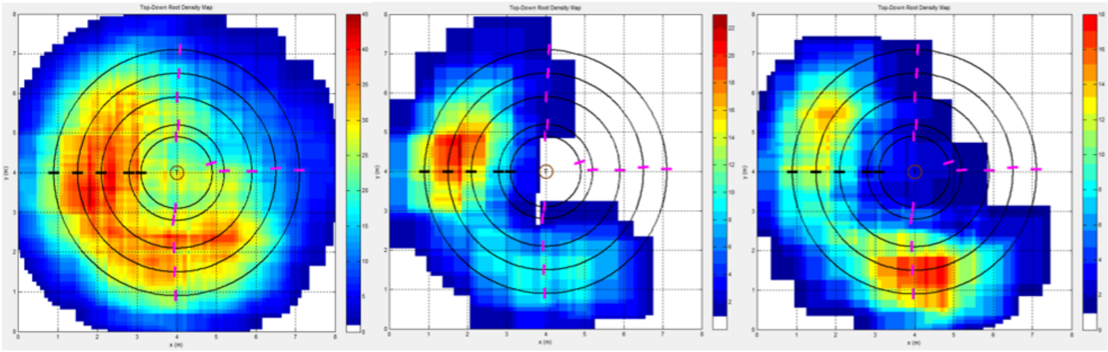


FIGURE 4.9: The top-down ground radar scans for tree with report number 1 for the depth zones 0-30cm (left) 30-60cm (middle) and 60-100cm (right). The scan lines for this tree are circular and are indicated by the black lines. The starting point of the scan lines is indicated by the black dashed line, and with the passing of a quarter circle, the purple dashed lines are drawn. The tree's location is indicated with a circle containing the letter 'T'. The color represents the root density, the red color indicates a relatively large amount of roots per meter, and blue is a relatively low amount. White means that no roots are detected there. The coloring is based on the highest amount of roots per meter and differs per depth zone. Image from Terra Nostra [7].

4.3.2 Comparison with the scan images

Figure 4.9 shows the root density images for the different depth ranges for the tree with report number 1, for which the scan lines are circular. Figure 4.10 shows the images for the tree with report number 6, for which the scan lines are linear. The red color represents a relatively high amount of root detections per meter and differs per depth zone. The colors between the different depth zones thus can not be compared one-to-one.

One of the underlying assumptions of the cylindrical root model is that the root growth is symmetrical in the horizontal directions and similar in the vertical direction. The figures show that the root growth is not perfectly symmetrical in both the horizontal plane and the vertical direction, especially for Figure 4.9. According to the report, the lower root density areas for Figure 4.9 might be caused by the presence of a biking lane, although the report also concludes that for most trees, the 0-30cm zone is intensively rooted, also underneath biking lanes and other pavements [7]. The cylindrical shapes thus do not always accurately indicate the location of the roots, so it might be more accurate to reshape the cylinders when necessary.

Another underlying assumption of the cylindrical root model is that the density of the roots is expected to decrease when moving outward from the tree position. For the upper depth zone in Figure 4.9, the root density seems to decrease with the distance from the tree position in the horizontal plane, but this could also be an effect of the scan lines not being much broader than the area with a high root density.

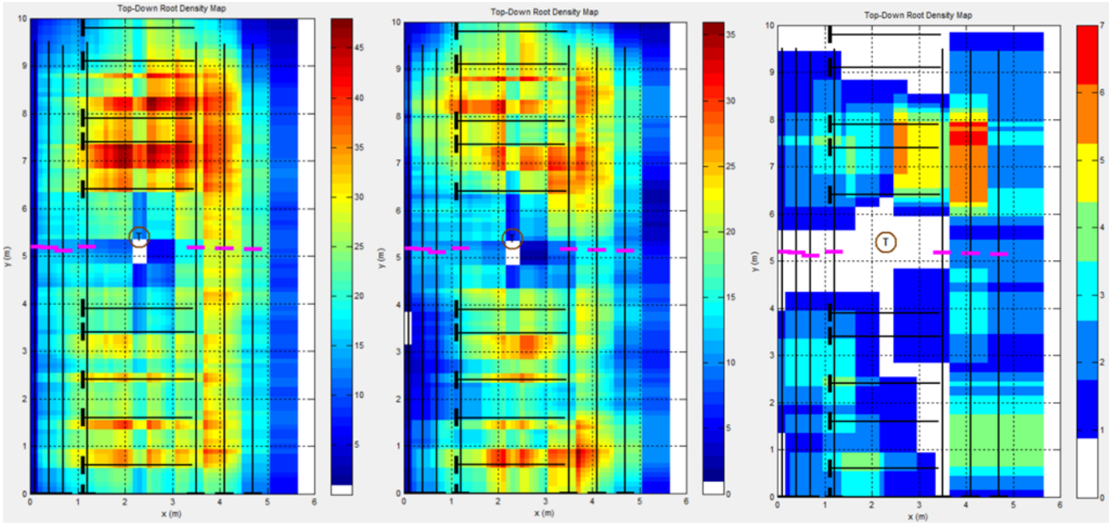


FIGURE 4.10: The top-down ground radar scans for tree with report number 6 for the depth zones 0-30cm (left) 30-60cm (middle) and 60-100cm (right). The scan lines for this tree are linear and are indicated by the black lines. The starting point of the scan lines is indicated by the black dashed line. The tree's location is indicated with a circle containing the letter 'T'. The color represents the root density, the red color indicates a relatively large amount of roots per meter, and blue is a relatively low amount. White means that no roots are detected there. The coloring is based on the highest amount of roots per meter and differs per depth zone. Image from Terra Nostra [7].

4.3.3 Comparison with volume rendering

To compare our model output more quantitatively with the root density images from the report, we counted the pixels corresponding to a high root density and compared this to the estimated root volumes.

First, we aggregate the images corresponding to the three different depth layers using volume rendering. For this, we use ParaView 5.9.1, which is a visualization tool based on VTK. The three images must have the same pixel dimensions. We used IrfanView[6] to crop the images corresponding to the same tree with the same pixel measures. The figures from the Terra Nostra report were used, which correspond to the 900MHz scans.

The volume rendering creates a 3D image from the three 2D images. We then want to select the voxels corresponding to the high root density areas. To do this, it is first needed to convert the RGB (red, green, blue) color to color values represented by one scalar value. We transform the RGB color to HSV (hue, saturation, value), of which hue represents the color. Red has a hue of 0, green of around 0.33, and cyan of 0.5. We use a "Programmable Filter" in Paraview to loop through all the points in the volume rendering image and convert their RGB color to a hue value using the Python library colorsys[7]. The only problem is that white (which corresponds to no root detections) has

[6] https://www.irfanview.com/
[7] https://docs.python.org/3/library/colorsys.html

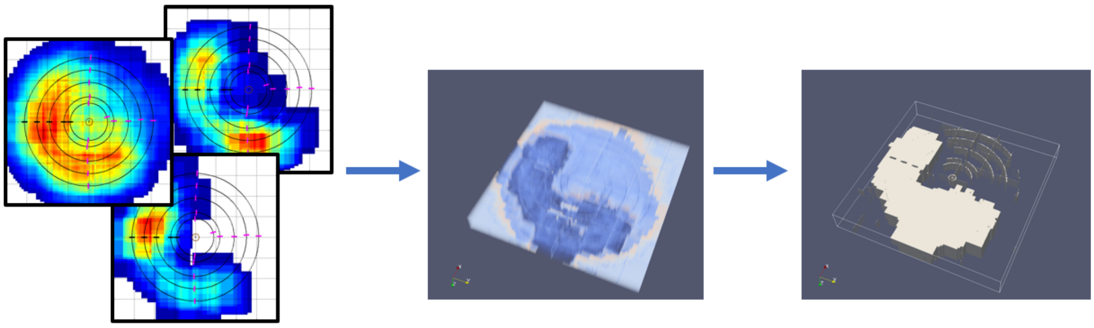


FIGURE 4.11: The volume rendering uses three 2D PNG images (left, images from Terra Nostra [7]) to create a 3D image (middle). The RGB values of the voxels of this 3D image are converted to hue, which represents the color as one scalar. Lastly, only the voxels with a hue value corresponding to sufficient root detection areas are selected (right).

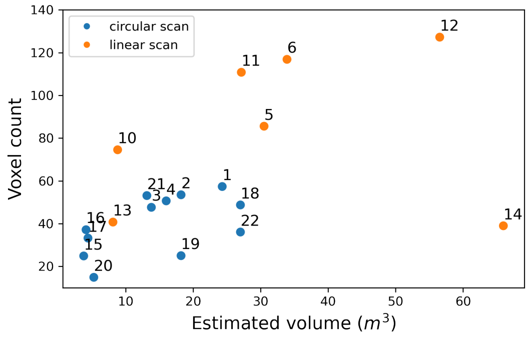
a hue of 0, just like red. To exclude the white points, we set the hue manually to -2 if the RGB color of the point corresponds to white.

The hue values can be used as an output on which a "Threshold" filter is applied to only show points with a hue between 0 and 0.6 to select the areas where sufficient roots are detected. We then count the number of points that are contained in this threshold selection for each tree. The whole process is visualized in Figure 4.11.

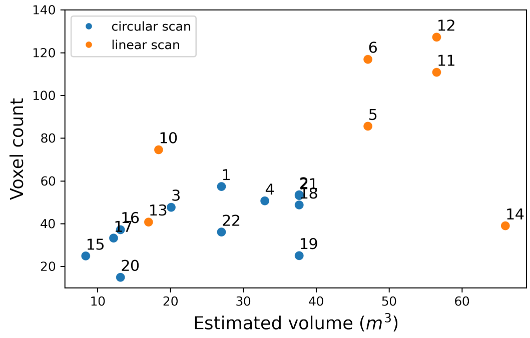
The number of points in the threshold selection cannot be compared immediately one-to-one between all trees since the input images can differ in their number of pixels and the actual area they represent. Therefore, we normalize by dividing by the area in pixel units and multiplying by the area in distance units. The comparison is still not completely reliable since the color bars differ in value for each image and each layer of depth. This means that red represents a different root density for each image and depth layer, although it always represents the highest root density in that image. It is difficult to normalize for these differences since this would involve our conception of the colors.

We compare the normalized amount of points with the optimal estimated root volumes for 2018 for each of the three methods: static, tree dictionary, and tree growth. The result can be seen in Figure 4.12, which is annotated with the report number of the trees and colored by the shape of the scan lines. Ideally, a higher value for the estimated root volume should correspond to a higher normalized voxel count. This is true for some points, implying that the model can give a general indication of how much space the roots require. It seems, however, that there are many exceptions to this pattern.

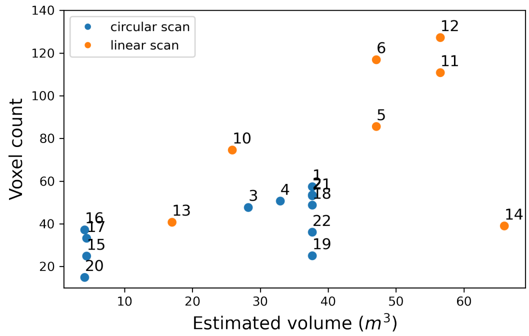
Tree with report number 14 appears to be the most prominent exception from the increasing trend. This is the oldest tree, with a plantation year of 1900. The ground radar scans for this tree can be seen in Figure 4.13. This figure seems to have fewer high-density root areas than, for example, Figure 4.10, which explains the low pixel



(A) Static method.



(B) Tree dictionary method.



(C) Tree growth method.

FIGURE 4.12: The normalized voxel count for the points corresponding to a high root density as a function of the estimated root volume by the static, tree dictionary, and tree growth methods. The annotations represent the report number of the trees. The blue colors represent the trees for which the scan lines were circular; the orange colors represent the trees for which the scan lines were linear.

count. However, the report does mention that the root density for the upper layer is rather intensive. It also notes that roots were detected until the groundwater level at 2.2 meters depth for this tree, while the detections using the 900MHz antenna do not go deeper than 1 meter. This might explain the large gap between the estimated root volume and the low voxel count for tree 14 in Figure 4.12, also since for the other trees in the report, the maximal root depth was found to be more around 1-1.5m.

Figure 4.12 showed a little correlation, but also with many outliers in pixel count that might not represent the actual root volume accurately since the used scans might have missed deep roots. It also could imply that the estimated root volume is not accurate for those trees. Still, based on the many uncertainties using these scans, it is unsure how valuable they are for drawing conclusions about the cylindrical root model and the three different methods.

Terra Nostra also provided the raw data in Drawing Exchange Format (DXF), which could be opened in QGIS 3.22.1[8]. This raw data contains the root detections, which we

[8]https://qgis.org/en/site/

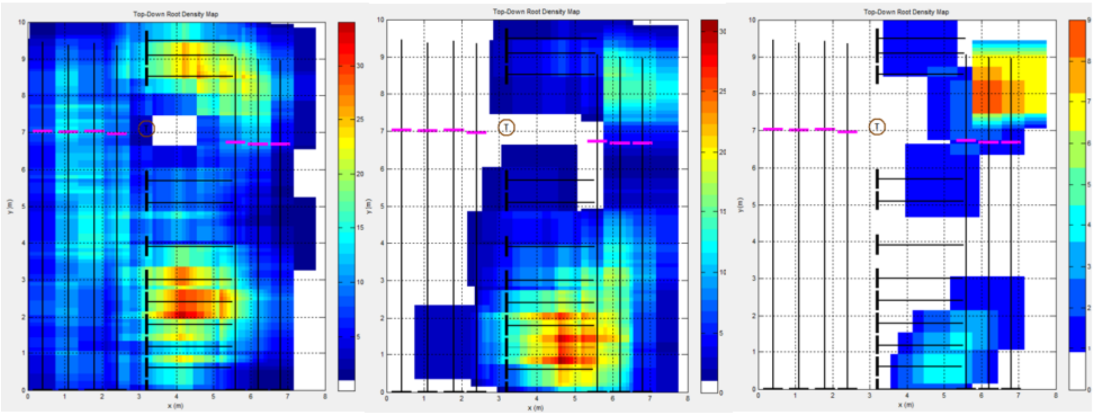


FIGURE 4.13: The top-down ground radar scans for tree with report number 14 for the depth zones 0-30cm (left) 30-60cm (middle) and 60-100cm (right). The scan lines for this tree are linear and are indicated by the black lines. The starting point of the scan lines is indicated by the black dashed line. The location of the tree is indicated with a circle containing the letter 'T'. The color represents the root density, the red color indicates a relatively large amount of roots per meter, and blue is a relatively low amount. White means that no roots are detected there. The coloring is based on the highest amount of roots per meter and differs per depth zone. Image from Terra Nostra [7].

counted for each tree. Like the voxel count from the volume rendering, this count can be compared to the estimated root volumes. This showed a similar pattern as in Figure 4.12, which implies that the volume rendering gives a good root volume indication, despite the different color bars in each image. But these raw detections also do not go deeper than 1 meter, so it is still uncertain whether more roots are located below this depth. In addition, it could be a possibility that roots are located outside of the scanlines, which then are not detected. The figures corresponding to the raw data point count are included in Appendix C.

4.4 Comparison with root damage reports

Besides the ground radar scans, there is little known about the underground root situation. However, there are situations where the influence of roots is visible aboveground as well. This is the case for root lifting, where roots exert pressure on the pavements and roads such that these tear or get uneven. The municipality has multiple ways of recording this root damage: they inspect the roads themselves, and civilians can make notifications about them.

4.4.1 Civilian notifications

The Signalen Informatievoorziening Amsterdam (SIA, signals information supply Amsterdam) is a platform on which civilians can make notifications about, for example, pollution and nuisance in the city. In the old version of the platform, civilians had to choose the notification category themselves. However, since the list of categories was long, the wrong category was often chosen. The new version uses an algorithm that recognizes words in the notification and determines the category based on that. The platform is available through this link[9].

The notifications are collected in an extensive database and can be accessed and analyzed through Tableau[10], which is a visualization platform used for data analysis. In the Tableau platform of the municipality, it is possible to search for words that are contained in the notifications. We looked for “wortel” (root), which also comprises words like “boomwortels” (tree roots) and “wortelopdruk” (root lifting). The locations of the resulting notifications were made available by the municipality and can be used to compare with our model output. The disadvantage of using these notifications is that their locations are added manually by the civilians through the platform, which could lead to an offset to the actual tree or root damage location.

4.4.2 Road inspection records

The department of municipal management (“afdeling stedelijk beheer”) of the municipality of Amsterdam inspects the roads in Amsterdam every other year [57]. If a road is damaged, they also register whether this is because of tree roots. Large areas of damaged roads are registered as shapefiles, while if the damage is very localized to one tree, it gets registered as a point at the location of the tree. The location of these records is more reliable than the civilian notifications. They also classify the severity and magnitude of the damage. The severeness categories are “severe”, “moderate”, and “mild”. The magnitude categories are “large”, “medium”, and “small” [57].

4.4.3 Determination of the intersection score

To compare the damage data with our model output, we define the *intersection score* that estimates what part of the estimated root volume cylinder boundary intersects with infrastructure that is not meant for plant growth. We consider all soil profile types listed underneath “Open ground” in Appendix A to be meant for plant growth. We count how

[9] https://meldingen.amsterdam.nl/
[10] https://www.tableau.com/

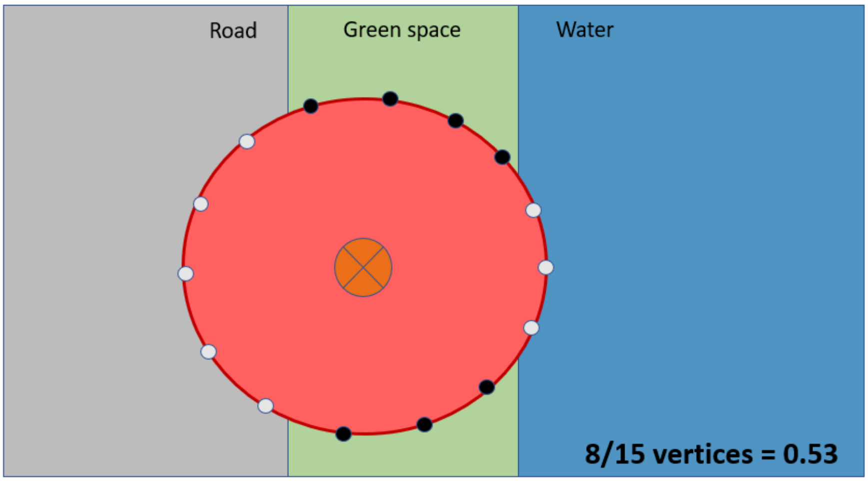


FIGURE 4.14: An example of how the intersection score of the estimated root volume with the infrastructure not meant for plant growth is calculated. The grey and blue area represent roads and a watercourse, and the green area represents the green space. The red circle represents the top-down view of an estimated root volume cylinder. The brown circle with a cross is the tree location. Out of the 15 vertices on the cylinder, 8 fall outside the designated green space, leading to a score of 0.53.

many vertices of an estimated root cylinder fall outside of this category to calculate the score, using the marginal root volume cylinders since they represent what volume the trees need as a minimum. We use the output for the year 2020[11]. A score of 0 means that the root growth is entirely happening in the for trees designated area, and a score of 1 means that the root growth is happening entirely in areas not meant for plant growth. Figure 4.14 gives an example of how to calculate the score. The eight white vertices fall outside the designated green space, giving a score of $8/15 = 0.53$. If the soil profile type (BGT) request for the vertices fails, it is impossible to calculate the intersection score.

4.4.4 Comparison with intersection score by location

Figure 4.15 shows the location of the damage reports and a comparison with the three methods for subregion *het Wallengebied*. For each method, the circles indicate the tree locations and are colored by the value of the intersection score of the corresponding estimated root volume. The red crosses indicate the locations of the civilian notifications. The point data of the road inspection records are visualized with blue crosses, and the shapefiles are included in black to grey, where black represents the most severe damage, and grey represents moderate damage. Another lighter shade indicates mild damage, but almost all damage was classified as severe and moderate in the subregions. The shapefiles are plotted using Python library PyShp.

[11]Most damage reports are from this year or the year before or after, for which the radius will not differ more than a few centimeters.

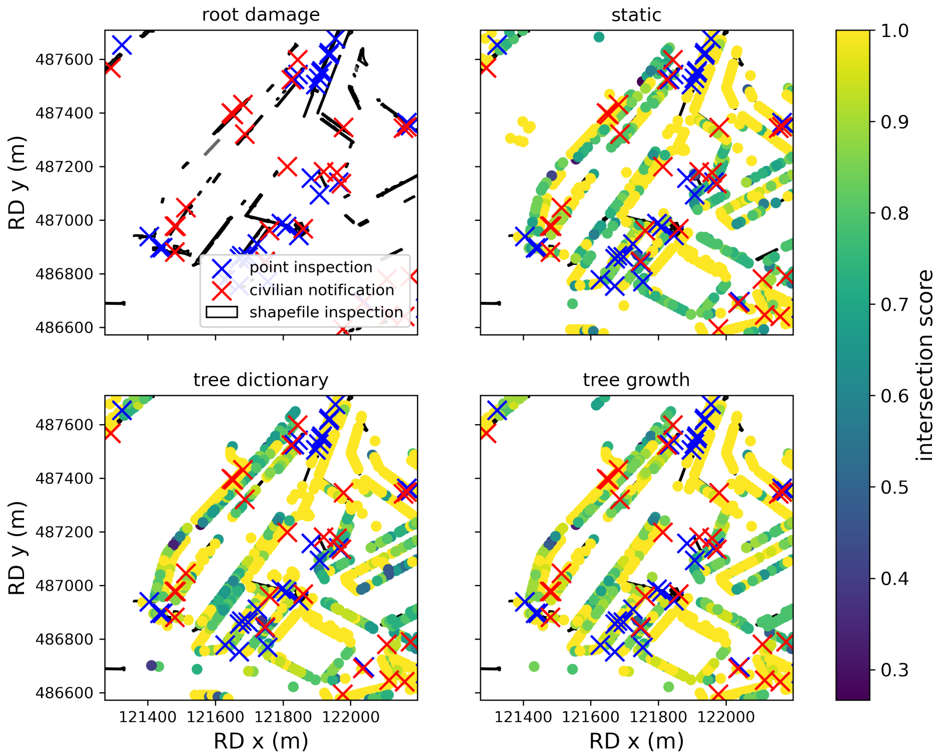


Figure 4.15: The locations of the root damage reports and a comparison with the three methods for subregion *het Wallengebied*. For each method, the circles indicate the tree locations and are colored by the value of the intersection score of their estimated root volume by the corresponding method. The red crosses indicate the locations of the civilian notifications. The point data of the road inspection records are visualized with blue crosses, and the shapefiles are included in black to grey, where black represents the most severe damage and grey moderate damage.

To get a clearer view of the relation between the damage reports and the intersection score, we zoomed in on the upper part of *het Wallengebied*, which can be seen in Figure 4.16. This figure shows that the locations of the shapefile damage reports are closely corresponding to rows of trees. The blue crosses for the point inspection also seem to correspond to tree locations. Only the red crosses seem to deviate more, but it can also be that they are located close to trees for which no root volume or intersection score could be estimated.

The same figures are also created for subregion *IJburg*, of which the zoomed-in version for the Southern part can be seen in Figure 4.17. The figure for the full subregion of *IJburg* is included in Appendix D. For *IJburg* and *het Wallengebied*, the intersection scores are close to 1 for many trees. Figure 4.18 shows the location of the damage reports and a comparison with the three methods for subregion *Sarphatipark*. The literal park in this subregion can be distinguished by the points with low intersection scores.

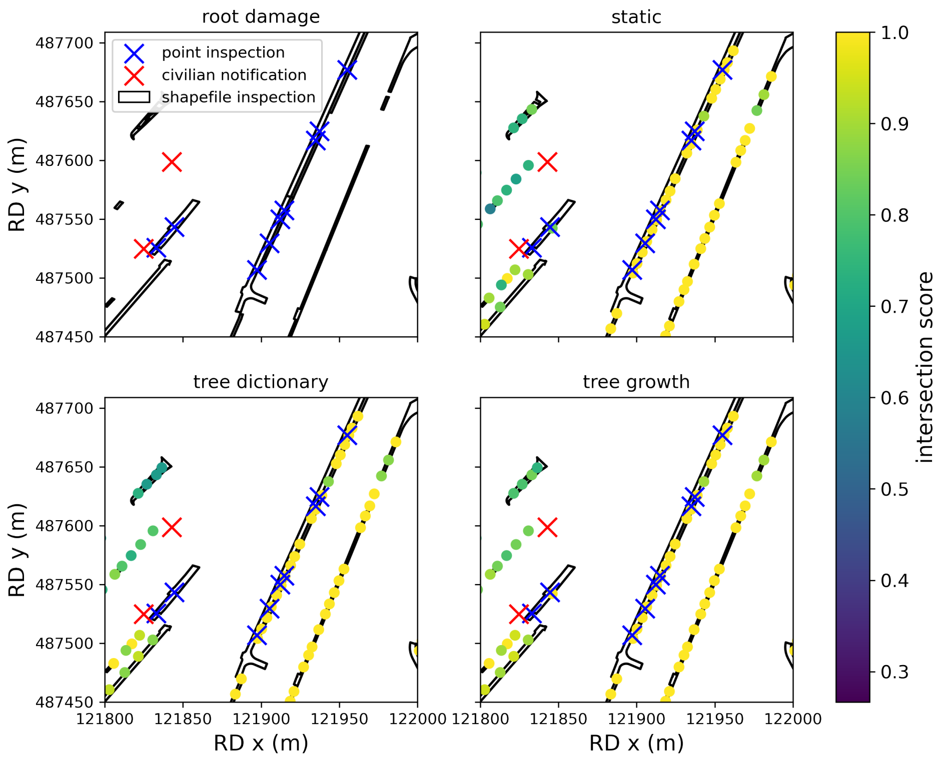


FIGURE 4.16: The locations of the root damage reports and a comparison with the three methods for the Northern part of subregion *het Wallengebied*. This figure is a zoom-in on the upper part of Figure 4.15. For each method, the circles indicate the tree locations and are colored by the value of the intersection score of their estimated root volume by the corresponding method. The red crosses indicate the locations of the civilian notifications. The point data of the road inspection records are visualized with blue crosses, and the shapefiles are included in black to grey, where black represents the most severe damage and grey moderate damage.

The figures show a difference between the three methods. If a circle for a tree is missing in the plot for one method but is present in the others, this one method can not estimate a root volume for this type of tree while the others can. There can also be a difference in color for the intersection score since the three methods can estimate a different root volume for a tree.

The figures also show that the location of the shapefiles and the point inspections often correspond with the location of the circles, so where trees are located for which the root volume could be estimated, and the intersection score is calculated. The civilian notifications seem to deviate more from the tree locations, especially in Figure 4.17, although in reality, there should be trees in the area with the many red crosses in this figure. Crosses and shapefiles that do not seem correlated with tree locations can be due to an offset in their location, or it could be that they correspond to a tree for which

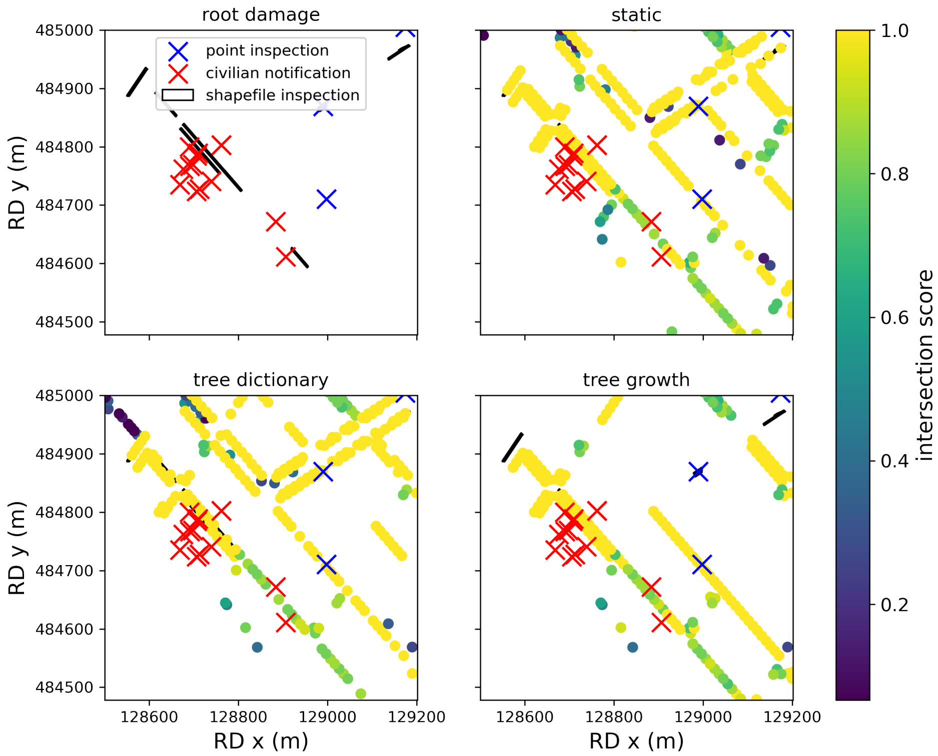


FIGURE 4.17: The locations of the root damage reports and a comparison with the three methods for the Southern part of subregion *IJburg*. For each method, the circles indicate the tree locations and are colored by the value of the intersection score of their estimated root volume by the corresponding method. The red crosses indicate the locations of the civilian notifications. The point data of the road inspection records are visualized with blue crosses, and the shapefiles are included in black to grey, where black represents the most severe damage and grey moderate damage.

the root volume or intersection score could not be calculated. For the population of red crosses in Figure 4.17, it is the case that the intersection score could not be calculated, which is likely because the soil profile type could not be determined.

4.4.5 Frequency of the intersection scores related to root damage

To quantify the relation between the root damage reports and the intersection score, we created histograms of the scores that belong to trees that can be related to the damage. For the point inspections and civilian notifications, we used Python to see whether the estimated root volume cylinders contain an inspection or notification. If so, the intersection score relating to the cylinder or tree is included in the histogram. For the shapefiles, we used the geographic information system (GIS) application QGIS 3.22.1[12]

[12]https://qgis.org/en/site/

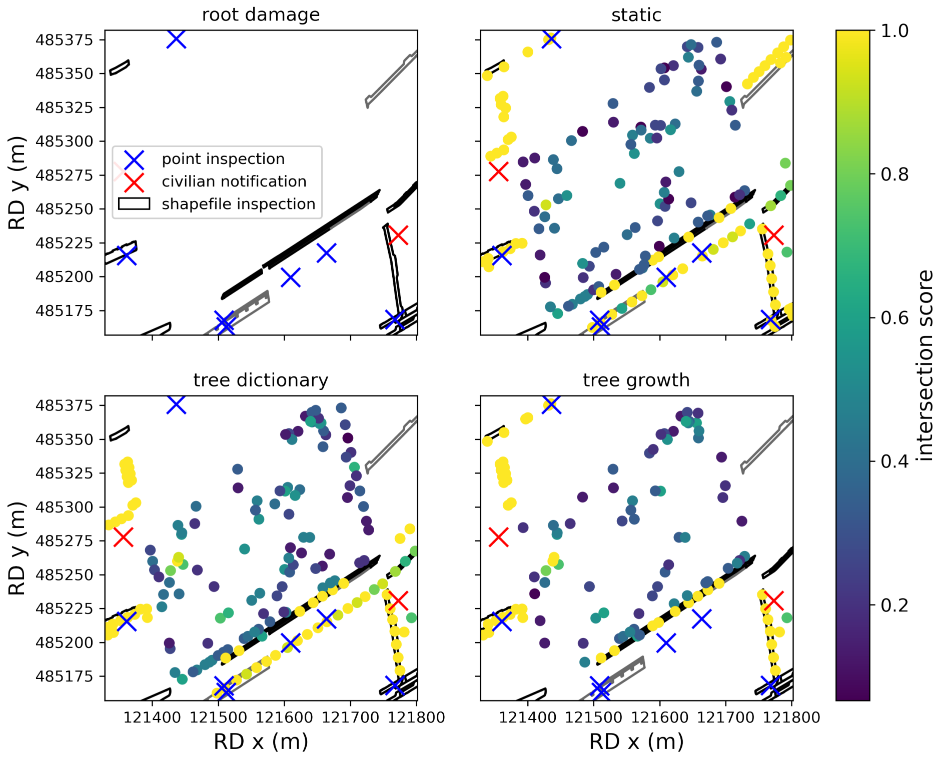


FIGURE 4.18: The locations of the root damage reports and a comparison with the three methods for subregion *Sarphatipark*. For each method, the circles indicate the tree locations and are colored by the value of the intersection score of their estimated root volume by the corresponding method. The red crosses indicate the locations of the civilian notifications. The point data of the road inspection records are visualized with blue crosses, and the shapefiles are included in black to grey, where black represents the most severe damage and grey moderate damage.

with the plugin CityJSON Loader[13] to include the estimated CityJSON root volumes in QGIS. We used the "Select by location" tool to select the cylinders that intersect with the shapefiles and used Python to find the corresponding intersection scores of the selected cylinders. These intersection scores thus correspond to root damage and are used in the histograms.

Figure 4.19 shows the resulting histograms for the shapefiles from the road inspections for subregion *het Wallengebied* for all three methods. The histograms for the point data from the road inspections can be seen in Appendix D. They follow a similar pattern but contain fewer data points. None of the civilian notifications fell within an estimated root volume cylinder, so none of them could be related to a specific tree with an estimated root volume and intersection score. The histograms contain 16 bins corresponding to each possible intersection score from 0 to 1.

[13]https://plugins.qgis.org/plugins/CityJSON-loader/

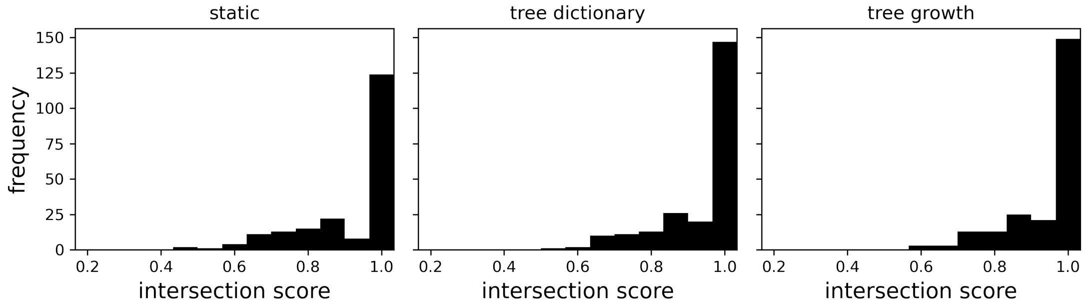


FIGURE 4.19: Histogram of the intersection scores related to the shapefiles of the road inspections for the three methods for subregion *het Wallengebied*.

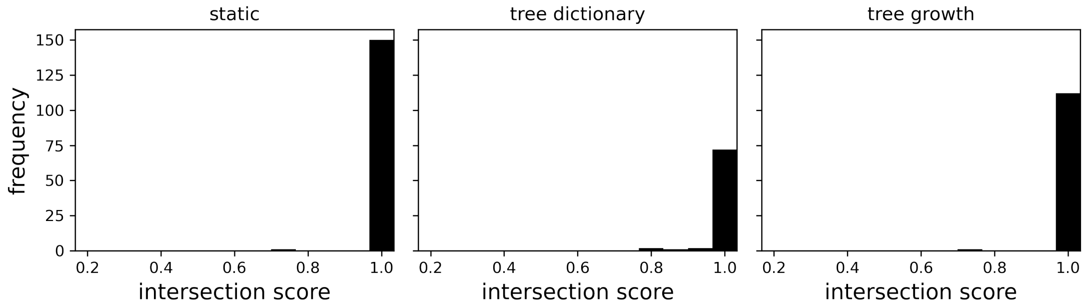


FIGURE 4.20: Histogram of the intersection scores related to the shapefiles of the road inspections for the three methods for subregion *IJburg*.

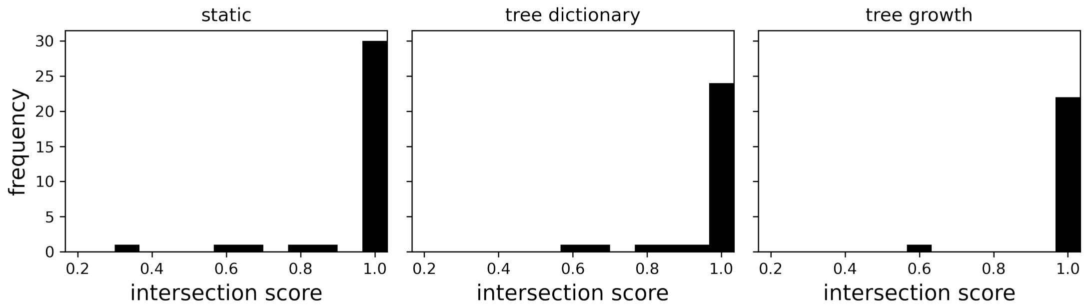


FIGURE 4.21: Histogram of the intersection scores related to the shapefiles of the road inspections for the three methods for subregion *Sarphatipark*.

Figure 4.20 and Figure 4.21 show the resulting histograms for the shapefile data for respectively subregions *IJburg* and *Sarphatipark*. For subregion *IJburg*, no match could be found between the point data from the road inspections and the estimated root volume cylinders. For subregion *Sarphatipark*, a few matches could be found with intersection score 1, and the resulting histograms can be seen in Appendix D. Again, none of the civilian notifications in both these subregions could be related to an estimated root volume and, consequently an intersection score.

The histograms for all three subregions peak in the intersection score 1, implying a total overlap of the cylinder boundary with infrastructure not meant for plant growth. Most of the intersection scores related to root damage are above 0.6, with a few exceptions. This indicates a correlation between the intersection score and damage reports since the estimated cylinders related to damage reports locations mostly have high intersection scores. However, the scatter plots indicated that an intersection score of 1 is the most occurring score in general, which could lead to a bias of the root damage shapefiles relating to cylinders with a score 1 most often. To give a fair comparison, we should normalize the histograms for the occurrence of the intersection scores in the corresponding subregions.

For each subregion and method, we normalize each possible intersection score that is related to shapefiles by the total occurrence of that intersection score. The results can be seen in Figure 4.22 for *het Wallengebied*, in Figure 4.23 for *IJburg*, and in Figure 4.24 for *Sarphatipark*. A normalized frequency of 1 indicates that all cylinders with that intersection score could be related to the road inspection shapefiles. These histograms, in general, still show an increasing normalized frequency as the intersection score is higher. An exception is the static method for subregion *het Wallengebied*, where the highest intersection score of 1 has a decrease in normalized frequency. Also, for subregion *Sarphatipark*, the static and tree dictionary methods show a lower normalized frequency for the intersection score 1. However, this subregion does not contain many data points, making it hard to draw conclusions.

The histograms show a correlation between the intersection score and the damage reports since the estimated root volumes that fall within the road damage shapefiles mostly have high intersection scores. Thus, root lifting is more likely to happen when estimated cylinders intersect primarily with infrastructure not meant for plant growth. This implies that the model could help determine areas prone to root lifting in the future. However, the figures also show that the normalized frequency is around 0.5 at the highest, which means that the other half of the cylinders could not be related to the shapefile road damage, while they do have a high intersection score. There can be multiple explanations for this. Firstly, it could be that the road was inspected and no root damage was found. This can be for example because the tree is not tended to cause root lifting in the roads, but had a high intersection score due to a possibly inaccurate root volume estimation, or it is tended to cause root lifting but measures like tree root bunkers or aeration systems have been taken to prevent it. Secondly, it could be that the tree actually caused root lifting, but no road inspections were done. To find out which explanation is the most likely, one should inspect the tree *in situ*.

The figures show that the three methods produce similar histograms of intersection scores. What differs the most between the figures is the frequency, which can be explained by some methods being capable of estimating the root volume for more trees in

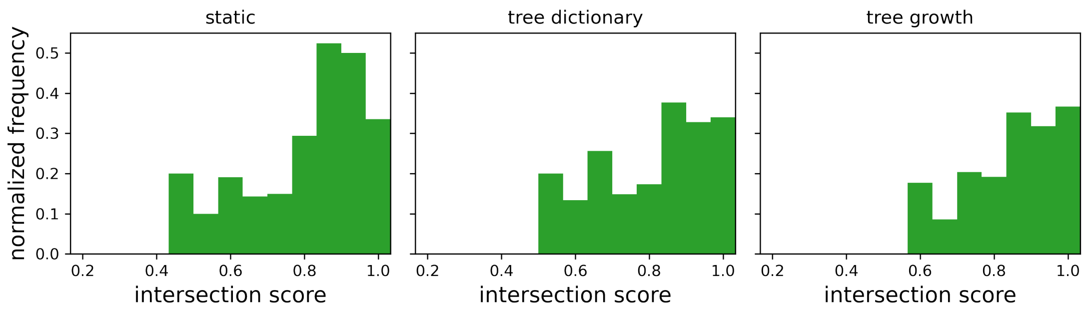


FIGURE 4.22: The normalized frequency of the intersection score for the three methods for subregion *het Wallengebied* related to the shapefiles of the road inspections.

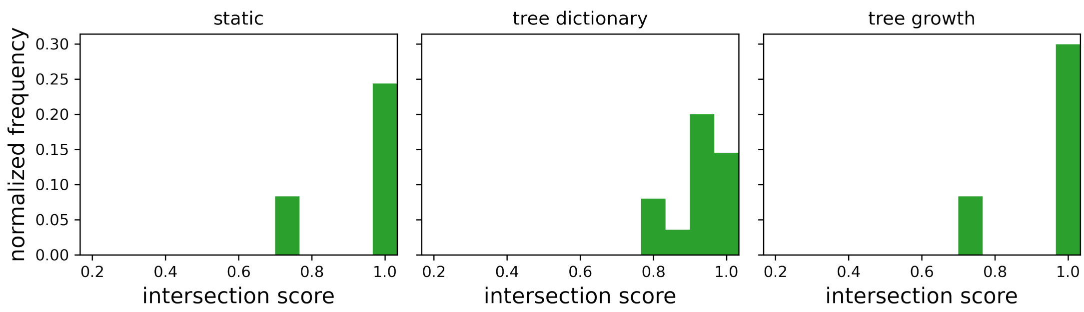


FIGURE 4.23: The normalized frequency of the intersection score for the three methods for subregion *IJburg* related to the shapefiles of the road inspections.

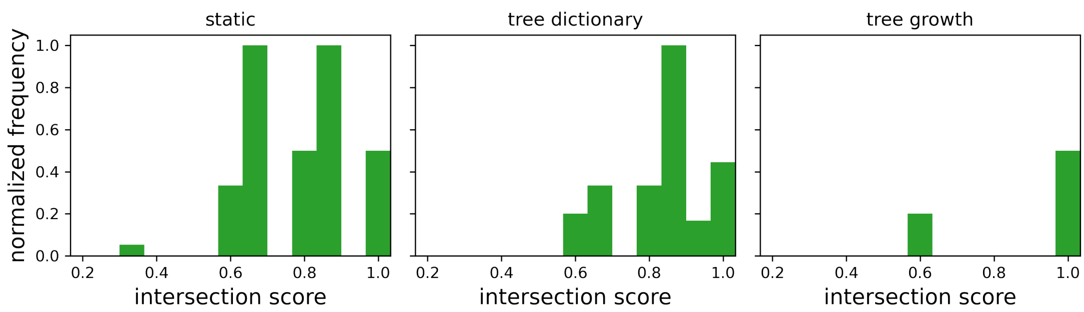


FIGURE 4.24: The normalized frequency of the intersection score for the three methods for subregion *Sarphatipark* related to the shapefiles of the road inspections.

specific subregions. There are slightly more low intersection scores related to the root damage for the static method, which could imply that this method underestimates some root volumes which should otherwise have higher intersection scores, but the difference is not significant.

4.5 Results for Amsterdam

Based on the three evaluation approaches, the three methods seemed to perform similarly. All the evaluations, however, were done with data from around 2020. Since the tree growth method tends to overestimate the tree and root volume size and the static method uses the data from 2020, which can lead to underestimations in the future, we chose to use the tree dictionary method to create the output for all the trees in the datasets from the municipality of Amsterdam.

Running the code for the tree datasets of the whole city was not as straightforward as for the subregions. First, the CVSs containing the groundwater measurements from Waternet could be downloaded by hand for the small subregions. Still, since the area of Amsterdam includes over 2500 monitoring wells, we had to do this differently to obtain a GHG mesh for the whole city. We used the Python library Beautiful Soup[14] for pulling the data out of the HTML files for each monitoring well in Amsterdam and finding the download link for the CSV. We then used the Python library Requests[15] to download the CSV from the link.[16]

Secondly, the mesh of the GHG values that was created for the whole city contained holes. Luckily, Paraview could be used to fill these holes. This was done by selecting and extracting the cells surrounding a hole and then applying Delaunay triangulation on the extraction with the "Delaunay2D" filter from Paraview. This fills the hole, which can then be merged with the original mesh.[17]

We run the code for the more than 260000 trees in Amsterdam for 2010, 2015, 2020, 2025, 2030, 2035, 2040, 2045, 2050, 2055, and 2060. These years were chosen in consideration of memory usage and the fact that the average circulation of trees in the city is around 40 years [58]. We first save the data for the cylinder measures in NumPy arrays, and later we convert them to CityJSON format. The resulting files are around 1GB per year, containing three ambition levels for all the trees for which the model could estimate a root volume. We first tried to run the model for intervals of a year instead of five years, but this would cost too much memory, and the root volume cylinders change very little on the timescale of a year.

[14] https://beautiful-soup-4.readthedocs.io/en/latest/

[15] https://pypi.org/project/requests/

[16] Due to their size and the fact that these files are frequently updated and corrected for mistakes, they are not contained in the GitHub project. The CSV files for the subregions are present on GitHub, they are from around March 2022.

[17] The mesh with holes and the filled mesh are created in May 2022 and are available in the GitHub project. However, the groundwater data is frequently updated, so it is advised to create a new mesh at some point.

Running the code for the full datasets took around four days. To run the code quicker when doing another run, we temporarily saved the data from the URL requests since this showed to be the slowest step in the model. This made the assumption that the data from the URL requests would not have changed when rerunning the code with this saved information. This assumption concerns data about the BGT and AHN, which are not expected to change on such a short timescale, but when rerunning the model after a few months, it is advised to update these values again.

We also improved the code that stores the data as CityJSON. We first tried to store the data for a specific year and ambition level at the same time for all the trees. This uses a lot of computer memory, so therefore we changed the code to write the CityJSON file per tree and thus appends the new data without loading the old data. Besides, we changed the coordinate storage from floats to integers, which reduced the size of the files.

Because of the memory of the output files for the whole city, they are not included in the GitHub page of the project. They are available for municipality employees in the group drive at G:\ALG\Data\B_Data\Boomkluiten 3D. This folder contains both the output CityJSON files and binary tiles.

4.6 Visualization in 3D Amsterdam

The root cylinder output that was generated for subregion *het Wallengebied* with the tree dictionary method can be seen here[18]. This is a subpage of 3D Amsterdam[19] containing the UI and functionalities as described in Section 3.4. The subpage was created since the principle of 3D Amsterdam is that what they show should be for the whole city, and we only generated the cylinders for the subregions in the beginning. In the coming period, the 3D Amsterdam team will include the Unity code and the model output created in this project on the main 3D Amsterdam page, which means the subpage might be deleted in the future.

Figure 4.25 shows a screenshot of the subpage containing the root volumes. The timeline and the sliders to adjust the transparency are also visible. The three ambition levels can be seen, of which the optimal one is made partly transparent. The cylinders are partly underground and partially sticking through the quay walls. On the subpage, it is possible to navigate underground and view the full cylinders. The main 3D Amsterdam page has more functionalities to view underground; a user can turn off the entire ground level or they can use a ‘dome’ to look below the surface.

[18] https://3d.amsterdam.nl/?project=boomwortels
[19] https://3d.amsterdam.nl/

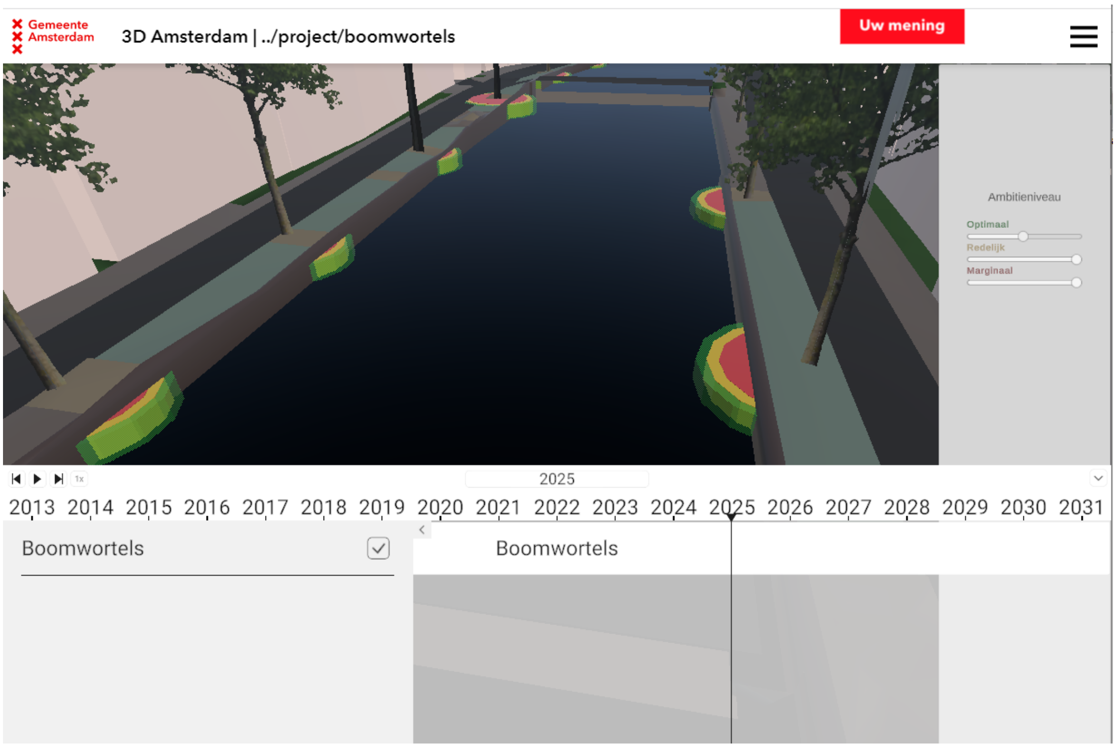


FIGURE 4.25: A screenshot of the subpage of 3D Amsterdam containing the estimated root volumes. The UI objects like the timeline and the sliders to control the transparency of the layers corresponding to the three ambition levels can also be seen.

Chapter 5

Conclusions

The central question of this report is *Can a simulation of tree root growth in a 3D model of a city provide accurate and valuable insight into the location and impact of the roots?* The answer to this question is that yes, the model can provide valuable insight into the location and impact of the roots, but there are improvements to make the model more accurate. We found that the model is capable of giving a general indication of the space that the roots require. However, in some cases, it is necessary to reshape the cylinders to provide a more accurate indication of the location of the roots. We also found that the model can give insight into which areas are prone to root lifting in the future. Yet, to make these predictions more accurate, additional factors like root lifting measures should be taken into account. The following paragraphs elaborate on these conclusions and other findings.

We created a model that estimates how much volume the trees need for their roots now and in the future. The 3D Amsterdam model is used to visualize the root growth, which can be controlled with an appropriate UI. We evaluated the output and impact of the root model for different subregions in Amsterdam: *het Wallengebied*, *IJburg*, and *Sarphatipark*. Three different methods were created for estimating the root volume: the static, tree dictionary, and tree growth methods. The static method was able to estimate the most root volumes, which is because this method is not dependent on species. In contrast, the tree dictionary and tree growth method need species-specific information that is not available for every species.

We used three different approaches to evaluate the accuracy and impact of the root model. The first approach is only applicable to the tree growth method. We evaluated how accurately this method can predict the height and crown size of a tree based on its age. It was found that the model often overestimates the height and crown size in all three subregions, especially for older trees. This could be explained because the prediction equations are based on younger trees. Besides, we used the equations for the US climate region that is most comparable to the Netherlands, while some critical factors might not be taken into account in this comparison. When the height and crown class of a tree are overestimated, the tree growth method also overestimates the root volume. Furthermore, it was found that trees of the same species can be very variable in height and crown size. The soil profile type could not explain this difference, but an explanation might be crown damage from stressors.

The second approach to evaluate the accuracy of the root model makes use of ground radar scans. These were available for 22 trees around the project area *Stationsplein*, of which 19 could be used. The ground radar images showed that the root growth is not always symmetric around the tree. Therefore, the cylindrical shapes will not always accurately indicate the location of the roots, which is also the case for the cylinders that are sticking through the quay walls in 3D Amsterdam. To improve this, we advise reshaping the cylinders when necessary. Chapter 6 elaborates on this. We also compared the output of the root model with the density images by creating a volume rendering of the images and counting the pixels corresponding to a high root density. The number of pixels was normalized for the area in meters and pixels, and was compared to the estimated root volume of the 19 trees. A slight increasing pattern could be observed for each method, implying that the model can give a general indication of how much space the roots require. However, there were also many outliers. This was also the case when comparing the raw data counts to the estimated root volumes. Still, the raw data points and density images only go to a depth of 1 meter. It is uncertain how many roots are located below this depth. Therefore, we cannot conclude whether the outliers are due to wrong estimations of the root model or if they result from missed root detections.

The third approach to evaluate the model accuracy compares the estimated root volume cylinders with root damage reports from citizens and the municipality. We did this by defining an intersection score for each cylinder, representing what fraction of the cylinder vertices fall outside plant growth areas. The location of none of the civilian notifications was accurate enough to match with a tree. The road inspection reports from the municipality contained shape- and point files, of which the shapefiles were most helpful in locating which trees and cylinders were involved with root lifting. The evaluation showed that mostly cylinders with high intersection scores could be related to road damage reports, which is expected since they correspond to root volumes overlapping the most with infrastructure not designated to trees. This means that the model can be used to evaluate where the estimated root volume cylinders for a large part overlap with infrastructural elements and to predict which areas are prone to root lifting in the future. However, some additional factors should be considered to make these predictions more accurate, like where the municipality took measures to prevent root lifting. We elaborate on this in the Future Work chapter (Chapter 6).

The three methods seemed to perform similarly based on the evaluations. Still, we cannot validate if this is also the case for the future since all three evaluation approaches are based on data from around 2020. We did see that the tree growth method tends to overestimate the height and crown size of trees, which can lead to an overestimation of the future root volumes. The validation for this method also showed that trees of the same species could be very variable in height and crown size, even when planted in the same year. This could indicate that the static model would be the most reliable for estimating the current root volumes since it includes the actual tree data for the height and crown size instead of only the theoretically predicted values like the tree dictionary and tree growth methods do. However, we expect that the static model is not helpful in estimating the future root volumes since it uses the 2020 data, which would likely cause an underestimation of the future root volumes. In conclusion, we recommend the tree dictionary method for estimating the subsurface space that should be preserved for the tree roots due to the expected under- and overestimations of respectively the static and tree growth methods. Therefore, we used the tree dictionary method to estimate the root volumes for the whole city of Amsterdam.

Chapter 6

Future Work

We already discussed some of the shortcomings of the model and the available data used as input or validation. This section proposes improvements to those and other shortcomings and interesting additions.

6.1 Improving the input

Growth equations for the Netherlands We found that the tree growth method often overestimates the height and crown size, especially for older trees. In addition, it was found that the actual height and crown size can be very variable for trees of the same species planted in the same year. Therefore, we propose to create allometric growth equations based on datasets of trees in the Netherlands and to use them instead of the equations from the Urban Tree Database. These datasets should also include older trees and preferably factors such as soil profile type and stressors. A good start for Amsterdam would be to do this for the 15 most common genera. This addition would not only improve the estimated root volumes but also provides more accurate insight into the future size of a tree. There are guidelines that indicate the required spacing between, for example, tree crowns and tram cables, so predicting the crown growth over time is helpful for checking if this requirement holds in the future [11]. Furthermore, tools like i-Tree can use the tree information to quantify the benefits of trees and even express this in monetary value [27].

Extending the tree dictionary The dictionary we created for the tree dictionary method currently only contains the crown and height information about the 15 most occurring genera in Amsterdam. These are trees that also occur often in other Dutch cities like Utrecht [59], but to use this method on all trees, they need to be included in this dictionary as well. For this thesis, we added the data manually to the dictionary. Still, some methods might be available to automatically extract the necessary crown and height data from the tree information websites.

Tree crown size inquiry The static method could only be used for the three subregions in Amsterdam since the crown data was only available for these regions. To use the static model for the whole city, the municipality should obtain the crown data for the entire city. There are many data and Geographic Information System experts within the municipality, so the municipality could consider extracting it from areal data themselves with this expertise. Otherwise, they could consider purchasing it from external companies like Cobra Groeninzicht, which provided the crown data for this thesis. The tree crown data would not only be helpful in estimating root volumes but it can be used in combination with tools like i-Tree to quantify tree benefits and their monetary value [27].

Tree data availability The tree data from the municipality is currently available in four static datasets that get updated every three years [9]. This means that the used datasets contain trees that are already cut down and are missing newly planted trees. It would be good to have an Application Programming Interface (API) for the trees, such that new information about the trees can be requested more frequently, and the estimated root volumes can be adjusted, deleted, or added when a tree disappears or is planted.

Groundwater data availability It was a hassle to obtain the groundwater measure files for the whole city of Amsterdam. For a subregion, it was doable to download all the CSV files for the corresponding monitoring wells. However, it is not feasible to do this for the whole city of Amsterdam since it contains over 2500 wells. An API exists for the properties of the monitoring wells to retrieve, for example, the coordinates or the filter heights of the well, but the actual measurements are missing in this API. To get the measurements for the whole city, we had to dive into the source code, find the CSV files' download link, and use a script to execute this download for all the monitoring wells. It would be better if the groundwater measurements files could be downloaded more straightforwardly and even better if the API would contain the measurements so that the groundwater information can be updated automatically and retrieved more easily.

6.2 Improving the methods

Groundwater interpolation We did the interpolation of the groundwater measurements (GHG) with Delaunay triangulation. This method does not consider obstacles, like canals or underground parking. These obstacles can, however, influence the groundwater levels, so it would be interesting and likely more accurate to include them in the interpolation. The location of obstacles like the canals is included in the BGT, so files like these can help give boundaries to the interpolation.

Faster URL requests Currently, the URL requests to the AHN and BGT servers are the slowest step in the model. There might be methods that can improve this, for example, to request part of the BGT map for a bunch of trees simultaneously instead of for each tree. To do this, the trees should be grouped in, for example, tiles, and the model should be adjusted to run and request the URL information per tile. Another option is to download the complete files before running the model. However, the files are very large and updated every few months or years.

Reshaping the cylinders We assumed a cylindrical shape for the estimated root volumes. A consequence of this is that they sometimes intersect with, for example, quay walls in the 3D model, which is not a realistic situation. Furthermore, the ground radar scans showed that the root growth is not always symmetric around a tree. In those situations, the current model does not accurately indicate the tree roots' location. Therefore, it is advised to establish in what direction roots grow when encountering an obstacle: will they grow mostly sideways to the obstacle or just as much in the direction perpendicular to the obstacle? The cylinders can then be reshaped based on this information. To do this, it should also be established which infrastructural elements can be an obstacle to trees. Quay walls or underground parking are straightforward examples since roots do not stick through them. Pavements and roads are a more complex example since roots can grow underneath them, but it is unsure to what extent these elements hinder root growth.

Not only can infrastructure influence the cylinder shape, but also root volume cylinders of other trees. For subregions *het Wallengebied* and *IJburg*, we found that the cylinders rarely overlap. This is because most trees in these subregions are located in streets, where usually enough space is preserved between trees. In *Sarphatipark*, more cylinders overlapped. We did not focus on reforming the cylinders here since the parks are a relatively small part of the city and are less important in root lifting and designing subsurface infrastructure problems. However, if overlapping cylinders turn out to be more occurring in the city parts other than the subregions studied in this report, it might be valuable to reshape them.

Reshaping the cylinders needs a lot of computing power since one needs to check for every root volume if it intersects with obstacles for every year for which a root volume is estimated. When the root volume geometry is constant in the vertical direction, and the obstacle information is 2D, the intersection calculation can be simplified to 2D. After this step, the root geometry can be converted to 3D again, which is expected to save a lot of computing power.

Alternative geometries The literature review discussed different LODs and corresponding geometrical shapes to represent tree roots. We chose to use LOD 1, which uses cylindrical shapes. This shape applies to Amsterdam since the groundwater levels are very high, so most roots grow sideways. For areas where the groundwater level is not as high, it could be interesting also to use other geometrical shapes like truncated cones or ellipsoids. They could represent different types of roots like tap and heart roots. A complication with this is that these shapes have more unknown parameters like the cones' angles and the ellipsoids' eccentricity.

6.3 Improving the validation

Documenting tree measures Comparing the root damage reports with the intersection score of the cylinders showed that some cylinders have high intersection scores but cannot be linked to damage reports. We explained that one of the reasons for this could be that measures were taken to prevent root lifting. An example of these measures is a tree root bunker, which includes a pressure spreading construction to ensure that the soil does not become too dense. Another example is aeration systems, which provide oxygen for tree roots [11]. To verify if these measures influence root lifting, the municipality should document which measures are taken for which trees. Documenting this is important for another reason since, for measures like the root bunkers, tree soil can be used instead of tree sand or granulate. This influences the estimated root volume, so documenting these measures improves the model input.

Comparison with quay wall damage Since the estimated root volumes intersect with infrastructure like quay walls, it is interesting to investigate if the degree of intersection could be an indicator of quay wall damage. Quay wall damage is an important problem in cities like Amsterdam. The bridges and quay wall program researches, monitors, and renovates the quay walls. They created a map[1] of the locations where they are working or plan to work on quay walls. It could be interesting to document which of the damage could be related to trees or to see if the damage is happening more or less often when the estimated root volumes intersect with the quay walls. If a relation can be found, the model can be used to predict potential future locations with an increased risk of quay wall damage.

Comparison with tree damage Another interesting comparison would be with trees that are or will be cut down because of, for example, storm damage or sickness. The municipality documents this information in this map[2]. It would be interesting to see whether a relationship can be found between the model output and the information on the map. It could, for example, be investigated if storm damage occurs more for trees with shallow estimated root volume cylinders if there is sufficient data about which trees are blown over. Furthermore, it would be interesting to see if trees with estimated root volume cylinders that intersect largely with infrastructure like roads are more likely to be sick.[3]

Ground radar scans We only had access to ground radar scans of 22 trees. It would be interesting to compare the root volume cylinders with ground radar scans in locations other than the project area *Stationsplein*. It would be nice if ground radar scans could be done for various tree species and infrastructural surroundings to see how these parameters influence the root growth. It would also be valuable to compare the root volume cylinders with ground radar scan results that go deeper than 1 meter and possibly on an area larger than the tree crown to determine whether this area contains roots.

6.4 Other future work

Other cities Mapping tree roots is not only important in Amsterdam but also in other cities. Many cities are in trouble with their subsurface space filling up, but since the importance of trees is getting clearer, municipalities aim to plant many of them and give them a proper growing place [60]. It would be nice to distribute the code to other

[1] https://www.amsterdam.nl/projecten/kademuren/

[2] https://maps.amsterdam.nl/vervangen_bomen/?LANG=nl

[3] Currently, a group that is following an education at NieuwlandGeo are investigating if they can find a relation between tree damage and our model output. The results of their project can be valuable for this thesis. However, they will be too late to include in this report.

cities with sufficient tree data, so root volumes can also be estimated for those cities. The 3D Amsterdam team also made their project reproducible for other cities. Their GitHub page[4] includes manuals for setting up your own 3D city model. This way, other cities can create 3D models, in which the estimated root volumes can be included.

Adding metadata Another essential addition to the model is to include metadata in the output CityJSON files. For example, height and crown size could be included since the tree growth model estimates them. Tools like i-Tree can quantify the tree benefits like CO_2 uptake and their monetary value, which are also interesting to include as metadata. The Unity code can be adjusted so that the root volume cylinders can be clicked to view this information.

When data relevant to trees exist in CSV format, this can be loaded using the CSV import tool from 3D Amsterdam. An excellent example of relevant data is the municipality dataset containing monumental trees, which is available here[5]. Combining this dataset with the estimated root volumes shows when one should be extra careful in planning for example new infrastructure, and in deciding to aim for which ambition level for the tree. In addition, the CSV datasets containing the tree information that was used as input can also be added, such that, for example, the height and species of the trees can be seen.

[4]https://github.com/Amsterdam/Netherlands3D
[5]https://maps.amsterdam.nl/open_geodata/

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Appendix A

Soil profile type classification

This appendix lists what properties from the registration of large-scale topographies (BGT, Basisregistratie Grootschalige Topografie) are classified as which soil profile type (open ground, light load, moderate load, heavy load, or unclassified). These classifications are based on the classes mentioned in Handboek Bomen 2018 [8]. The properties are first checked for the key "functie" (function), second for "fysiek_voorkomen" (appearance) and third for "type" and "plus_type" (type). The tables list the terminology as how they appear in the official BGT file, with the English translation between brackets.

A.1 Open ground

function	appearance	type
"berm" (roadside)	"groenvoorziening" (green space)	
"berm" (roadside)	"onverhard" (unpaved)	
	"groenvoorziening" (green space)	
	"loofbos" (deciduous forest)	
	"onverhard" (unpaved)	

A.2 Light load

function	appearance	type
"voetpad" (sidewalk)		
"voetgangersgebied" (pedestrian - zone)		
"fietspad" (bike path)		
"berm" (roadside)	"open verharding" (open pavement)	
		"bordes" (platform)

A.3 Moderate load

function	appearance	type
"parkeervlak" (parking space)		
"inrit" (driveway)		

A.4 Heavy load

function	appearance	type
"rijbaan lokale weg" (road lane)		

A.5 Unclassified

- Buildings: BGT returns "bag_pand" as key.
- Quay walls: BGT returns "kademuur" as type.
- Watercourses: BGT returns "waterloop" as type.
- Any other option that is not mentioned in the previous sections.

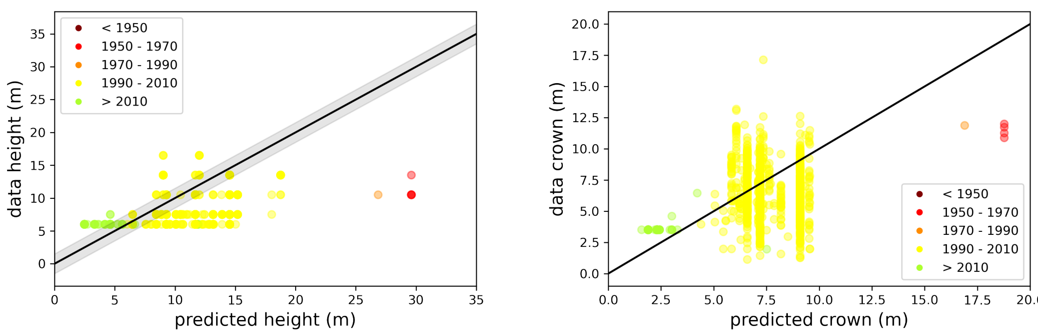
Appendix B

Prediction of height and crown size

This appendix contains the figures corresponding to the predictions of the tree height and crown size by the tree growth method that are not included in the main text.

B.1 Influence of tree age

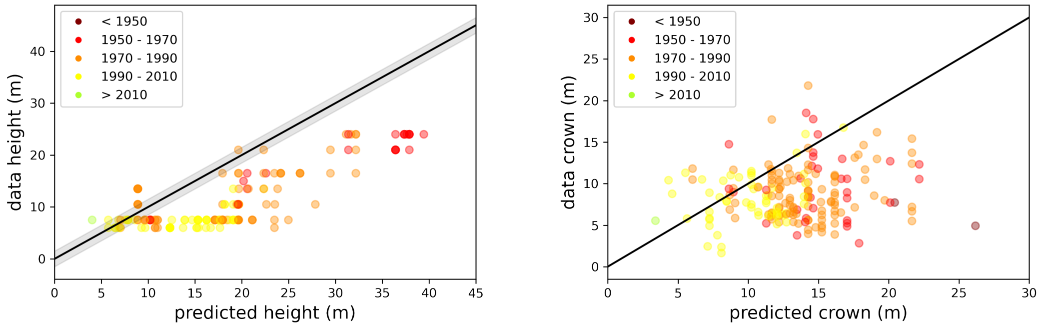
Figure B.1 shows the actual height and crown size as a function of respectively the predicted height and crown size by the tree growth method for *IJburg*, colored by plantation year. Figure B.2 shows the same for *Sarphatipark*. *IJburg* contains many young trees since it is a new building area, which makes the age influence unclear. For *Sarphatipark*



(A) Tree height.

(B) Tree crown size.

FIGURE B.1: Measured height and crown size as function of the predicted height and crown size by the tree growth method for subregion *IJburg*, colored by plantation year. The black line shows where they are equal and contains a shaded area of 3m for the height representing the height range measure of the municipality.



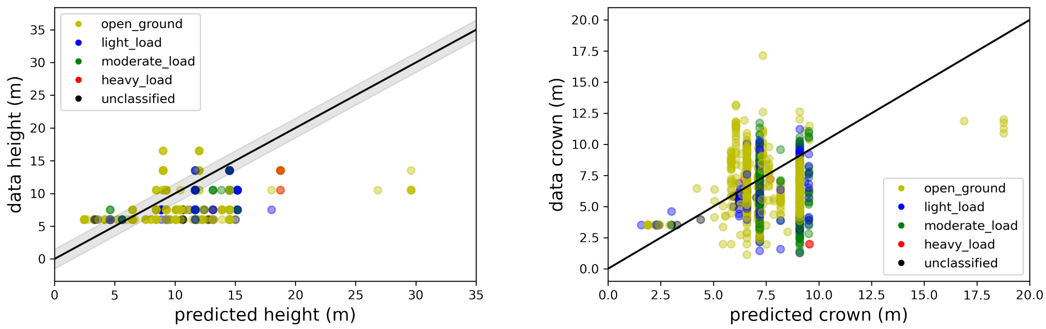
(A) Tree height. (B) Tree crown size.

FIGURE B.2: Measured height and crown size as function of the predicted height and crown size by the tree growth method for subregion *Sarphatipark*, colored by plantation year. The black line shows where they are equal and contains a shaded area of 3m for the height representing the height range measure of the municipality.

the height and crown offset seem to increase with age, but the effect is less clear than for *het Wallengebied*, for which the figures are included in the main text.

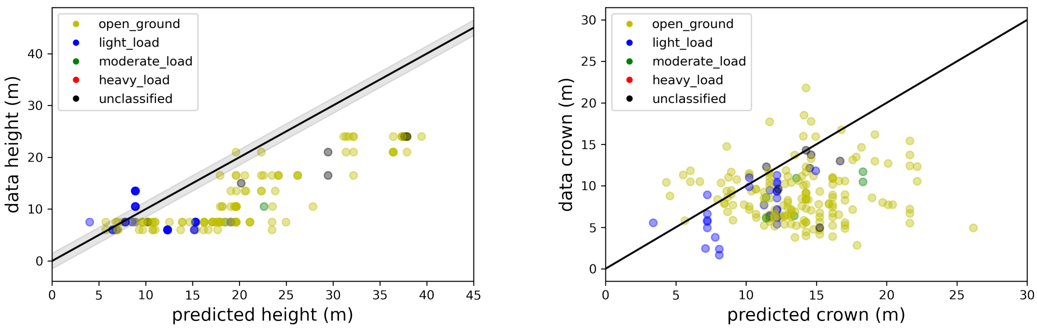
B.2 Influence of soil profile type

Figure B.3 shows the actual height and crown size as a function of respectively the predicted height and crown size for *IJburg*, colored by the soil profile type. Figure B.4 shows the same for *Sarphatipark*. It is hard to see a pattern in these figures. The main text includes tables with the percentage of correct, under-, and overestimated height classes for each soil type. Figure B.4 shows that most trees in *Sarphatipark* are located in the open ground.



(A) Tree height. (B) Tree crown size.

FIGURE B.3: Measured height and crown size as function of the predicted height and crown size by the tree growth method for subregion *IJburg*, colored by soil profile type. The black line shows where they are equal and contains a shaded area of 3m for the height representing the height range measure of the municipality.



(A) Tree height.

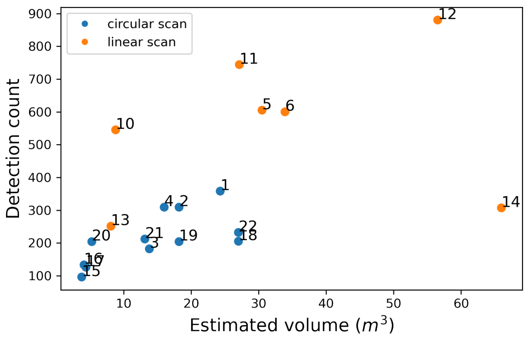
(B) Tree crown size.

FIGURE B.4: Measured height and crown size as function of the predicted height and crown size by the tree growth method for subregion *Sarphatipark*, colored by soil profile type. The black line shows where they are equal and contains a shaded area of 3m for the height representing the height range measure of the municipality.

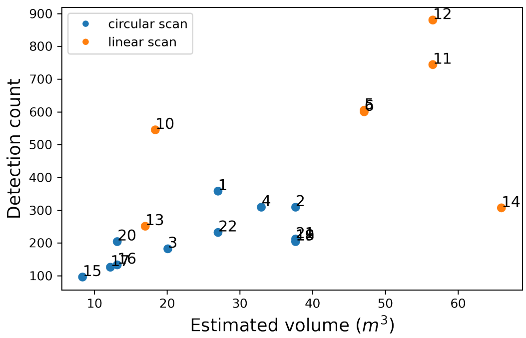
Appendix C

Ground radar detection count

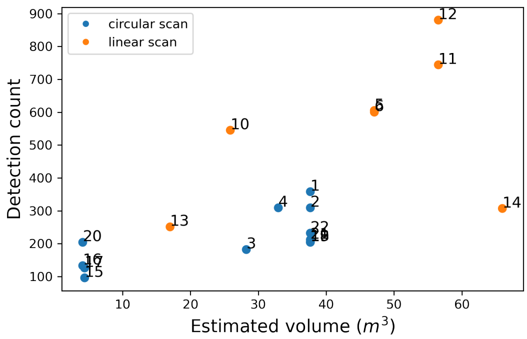
From the raw data from Terra Nostra [7], we extracted the root detection count for each tree. This root detection count is plotted as a function of estimated root volume, for which the optimal estimated root volume was used. The results can be seen in Figure C.1.



(A) Static method.



(B) Tree dictionary method.



(C) Tree growth method.

FIGURE C.1: The root detection count as function of the estimated root volume by the static, tree dictionary, and tree growth methods. The annotations represent the report number of the trees. The blue colors represent the trees for which the scan lines were circular, the orange colors represent the trees for which the scan lines were linear.

Appendix D

Comparison with root damage reports

This appendix contains the figures corresponding to the model comparison with root damage reports that are not included in the main text.

D.1 Additional scatter plots

Figure D.1 shows the location of the damage reports and a comparison with the three methods for subregion *IJburg*. For each method, the circles indicate the tree locations and are colored by the value of the intersection score of their estimated root volume by the corresponding method. The red crosses indicate the locations of the civilian notifications. The point data of the road inspection records are visualized with blue crosses, and the shapefiles are included in black to grey, where black represents the most severe damage and grey less severe damage.

D.2 Additional histograms

Figure D.2 shows the resulting histograms for the point data from the road inspections for subregion *het Wallengebied* for all three methods. The histograms contain 16 bins, corresponding to each of the possible intersection scores from 0 to 1. Figure D.3 shows the same for subregion *Sarphatipark*. For subregion *IJburg*, no estimated root volume cylinder could be matched to the point data from the road inspections.

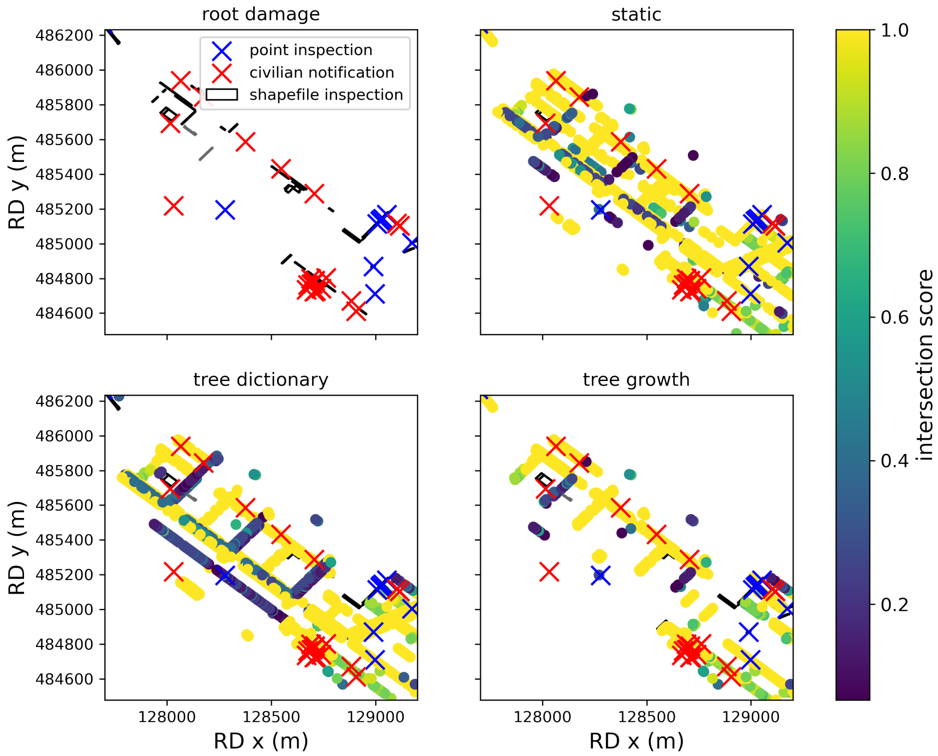


FIGURE D.1: The locations of the root damage reports and a comparison with the three methods for subregion *IJburg*. For each method, the circles indicate the tree locations and are colored by the value of the intersection score of their estimated root volume by the corresponding method. The red crosses indicate the locations of the civilian notifications. The point data of the road inspection records is visualized with blue crosses and the shapefiles are included in black to grey, where black represents the most severe damage and grey moderate damage.

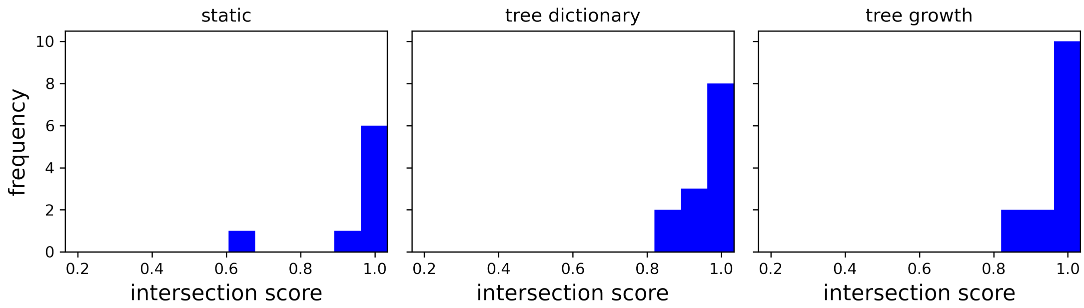


FIGURE D.2: Histogram of the intersection scores related to the point data of the road inspections for the three methods for subregion *het Wallengebied*.

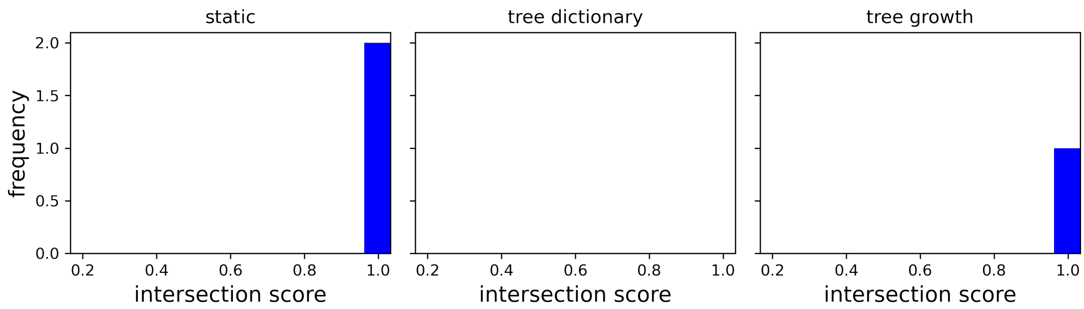


FIGURE D.3: Histogram of the intersection scores related to the point data of the road inspections for the three methods for subregion *Sarphatipark*.