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Document Version
Final published version

Citation (APA)
van der Velde, J. R. T., Price, R. A., Maiullari, D., van Esch, M. M. E., Hartmeyer, L. J., Pouderoijen, M. T., Batenburg, W., Schoon, P., Aktürk Hauser, G., & Keizer, S. K. (2025). *I-Tree 2.0 NL: Next-generation metrics and methodologies for urban forestry and climate resilience in Dutch cities*. Urban Forestry.

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i-Tree

Next-generation metrics and methodologies for urban forestry and climate resilience in Dutch cities

Technical report

2.0 NL

i-Tree 2.0 NL
Next-generation metrics and methodologies for urban forestry and climate resilience in Dutch cities

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CLICK.NL

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i-Tree 2.0 NL

Next-generation metrics and methodologies for urban forestry and climate resilience in Dutch cities

Technical report

TU Delft

CLICK NL

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MVRDV
New Urban Standard

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Boot & Dart
Ebben
Udenhout
M. van den Oever & Zonen

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AMS Institute
Davey Institute

Introduction

Problem definition

Cities must adapt to deal with impacts of climate change such as higher temperatures and longer periods of heat stress, which come on top of existing problems caused by the Urban Heat Island phenomenon. Changes are needed in the physical realm, transitions need to be made in policy and governance, and the resilience of urban communities to these conditions needs to be improved. Greenspace, and the urban forest in particular, is one of the most effective means of climate adaptation through the ability of trees to ameliorate extremes in urban thermal cycles. Beyond this, the urban forest (understood as the entire mosaic of trees in urban public open spaces) offers added benefits to urban water management, air quality, biodiversity, health & wellbeing, and overall urban liveability. The ubiquity of trees and greenspace in cities also positions them as effective agents for building climate resilience in urban communities. Despite these potentials however, and the long tradition of establishing and maintaining urban trees in Dutch cities, the role of the urban forest in addressing these new challenges remains limited. Barriers occur in three areas: the lack of data and relative infancy of scientific tools to model tree performances in relation to urban thermal cycles, the lack of (scientifically developed) methodologies for stakeholders to incorporate urban tree benefits into public infrastructure, and the absence of correlated strategies to effectively empower green infrastructure in resilience-building of cities and urban communities.

<u>Performance metrics & tools</u>
Urban planners, spatial designers and greenspace professionals require precise data and instruments to monitor and model the benefits of urban trees in relation to thermal cycles and urban microclimates. This applies to both the base-line performances of different species, and to performances across the lifespan of the tree. With these performances quantified, the urban forest can be better managed to develop and maintain these benefits, and to form a more integral part of plans for ‘cool’ neighbourhoods and

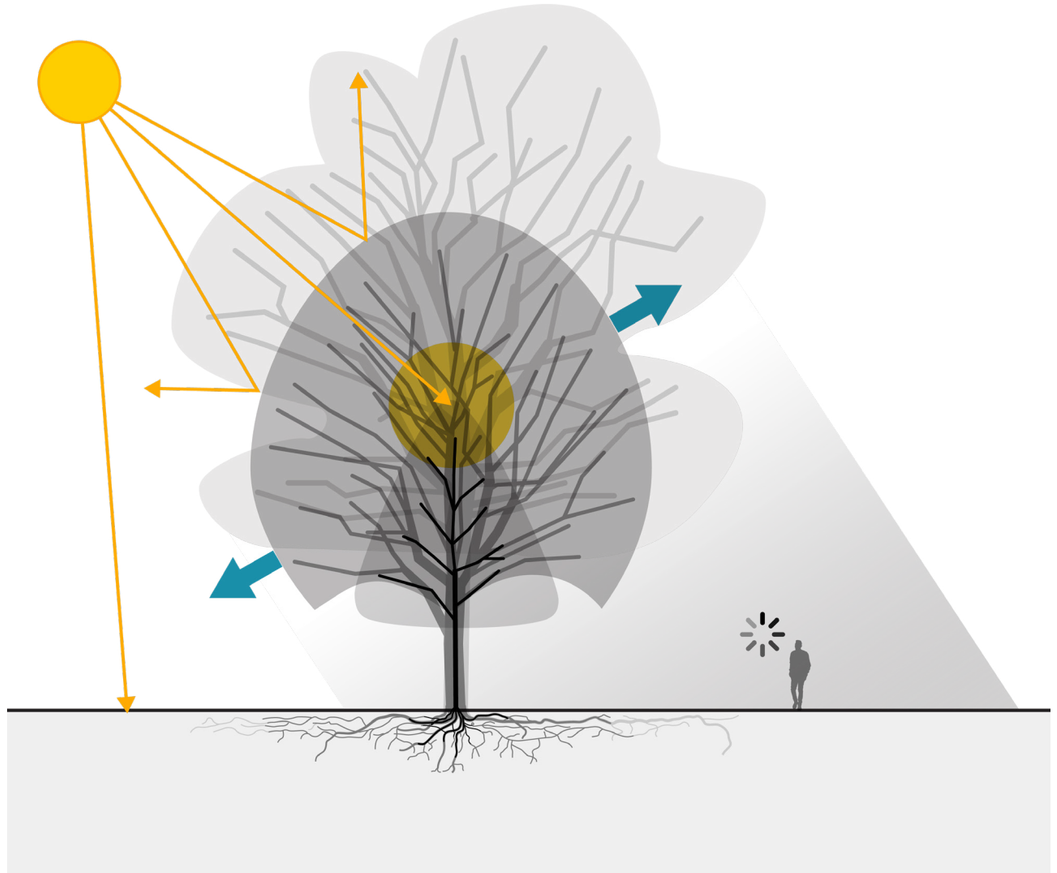


Figure 1. Illustration of the interrelation between tree cooling mechanism, tree growth stages and subsurface conditions under the tree

new urban developments. A central concept in the understanding of these performances is a tree's architecture, a knowledge domain in the Urban Forestry Group at the Faculty of Architecture, TU Delft. Physical traits of a tree such as crown morphology, wood anatomy and foliage characteristics determine how and to what extent a tree cools its environment down, and how this aids thermal comfort. This data can be augmented with metrics on transpiration rates of different tree species, which adds to a tree's cooling capacity through evaporative cooling. If these performances are then calculated over the growth stages of the tree, we can for the first time gain a complete and accurate picture of the thermal benefits of the urban forest. (fig. 1)

The translation of these insights into datasets and an implementation platform is a necessary related step. In recent years i-Tree, a peer-reviewed software suite developed by the USDA Forest Service that provides urban forestry analysis and benefits assessment has been released as international public domain software. Applications within this suite such as i-Tree Eco combines data on single trees or stands in a study area with local data such as meteorological conditions to quantify urban forest structure and ecosystem services to communities. Results of the tool in sample municipalities and key stakeholders in the Netherlands have been positive, but its effectiveness in modelling the performances of trees for heat stress and across the life cycle of the tree was concluded to need further development. (Platform i-Tree Nederland, 2019) Drawbacks lie in the lack of metrics on trees specific to bio-geographical (Atlantic) and climatological (Cfb) zones where Dutch cities are located, and in the absence of baseline data on cooling performances in relation to tree growth curves. The platform does however offer a scientifically sound basis for elaboration and development internationally.

Adoption methodologies
Developing accurate and climate zone-specific datasets within the i-Tree model tool will equip planners, designers and greenspace professionals to more effectively realise urban greenspace for climate adaptation. The adoption and success of tools such as i-Tree Eco however, cannot be assumed on performance benefits alone. New technologies do bring new forms of value, yet their novelty also presents a paradoxical challenge for adoption. For this reason new frameworks are required for planners, designers and greenspace professionals to benefit from the value created by a tool such as i-Tree. In technology development, it is crucial to generate use cases or scenarios where the technology creates value for stakeholders by solving problems. To do so, we must deeply understand the potential of the technology. However, superficial use cases that map assumed user needs are not enough and can lead to the ill-fated 'technology push'. The pushed technology will end up obsolete, as the problems faced by users and stakeholders are not addressed by the comprised solution. To avoid this we must comprehend the needs and desires of the users and various stakeholders to guide how technology is applied in a synchronous way to life. The latter requires an academically developed design approach that is human-centred, iterative and integrated in order to go back and forth between technological potential and human necessity. As such, synchronising - through the use of for instance co-design techniques - the technical potential of urban trees to stakeholder needs and interests via a next generation i-Tree platform is a central challenge here.

Transition strategies
The development of an uptake methodology around the i-Tree tool will prepare city ecosystems for its early adoption, leading to improvements in climate adaption of cities. Despite physical improvements to the urban tissue, urban communities can still remain vulnerable to the effects of climate change. Developing strategies to enable climate resilience among urban communities with and through the urban forest offers the potential for durable outcomes in areas such as sensing, sharing and solving. The need for improvements in urban liveability and particularly in areas of air quality, ecology, health and wellbeing form part of this problematique. The i-Tree tool presents itself as a promising (technical) basis to alter service and social paradigms. The potential of greenspace to form part of strategies enabling this transition lies for example in citizen input to GIS databases on urban heat, the identification of greenspace 'cool-spots and cool routes', the sharing of data, and greenspace implementation, adoption and maintenance (Price et al., 2020).

Goals and outcomes

A. Develop metrics on urban tree cooling performances and urban tree growth curves to:
- quantify the contribution of urban trees to ameliorate extremes in thermal cycles in cities;
- inform physical transformations of greenspace and the urban fabric using trees;
- contribute to the development of i-Tree as a benchmark scientific toolset to quantify and qualify urban trees and forests;

B. Realise effective adoption of i-Tree by:
- working with urban planners, designers and greenspace professionals to guide how the tool is applied in a synchronous way;
- effectuating optimum adoption, change and impact among public space development and management stakeholders around i-Tree;

C. Effectuate transitions in climate resilience and urban liveability by:

- working with urban planners, designers and greenspace professionals to guide how the tool is applied in a synchronous way.

Specific Outcomes

i. Development of a descriptive framework for tree architecture, relevant to urban thermal microclimate amelioration;
ii. An innovative methodology to categorize the most relevant characteristics of urban trees for thermal microclimate amelioration;
iii. Scientific data on tree cooling performances, which quantify the contribution of different tree species to cooling in Cfb climate zone cities, and these performances under varying subsurface conditions;
iv. Metrics on species-specific growth curves that allow for the assessment of existing urban forest assets and the modelling of performances over the life-span of urban trees;
v. Context mappings of values, experiences and needs of stakeholders in relation to urban (thermal) climate resilience;
vi. Speculative elaborations for resilient urban forests, city landscapes and communities;
vii. Implementation prototypes from these visions;
viii. A roadmap for implementation and development;
ix. Dissemination around tree architecture, urban microclimate amelioration, urban tree growth curves, adoption strategies, modelling tools, and citizen resilience.
x. Web-based platform on the research project, with results and links to related projects and initiatives.
xi. Consortium meetings and around key milestones and outcomes of the various work packages.
xii. Interaction between other projects, with expected iterative development of i-Tree 2.0-NL and business development spin-offs.
xiii. Demonstrations and ‘trialing days’ with key government, industry, research and societal partners to test research results and tools.

Setting the Scene

Project structure

Work packages
Three research work packages were set up to develop the various outcomes. WP1 focused on a descriptive framework for tree architecture to categorize the relevant characteristics of urban trees for thermal microclimate amelioration, and on sensing data of tree cooling performances in Cfb climate zone cities. WP2 developed metrics on species-specific growth curves for common urban trees in Cfb climate zone cities. As such WP1 and WP2 contribute to Goal A – the development of methodologies and metrics on urban tree cooling performances and urban tree growth curves. To contribute to the effective adaption of the i-Tree tool and to effectuate transitions in climate resilience and urban livability (Goal B and C), WP3 establishes tools, methods and transition strategies to guide the adoption of metrics and tools developed in work packages 1 and 2. (fig. 2)

Research and additional activities
The core research team consisted of an interdisciplinary team of researchers from the faculty of Architecture and the Built Environment (A+BE) and the faculty of Industrial Design Engineering (IDE) at the TU Delft. The majority of research activities in WP 1, 2 and 3 was carried out by researchers from the faculties of A+BE and IDE. Certain designated research activities and peer reviewing were carried out by researchers from the WUR. Designated research activities from work package 2 were carried out by partners (Cobra Groeninzicht) in the form of contract research. (fig. 3)

WP1
Researchers from the sections of Landscape Architecture and Environmental Technology and Design at the Architecture faculty were responsible for carrying out research within WP1. To carry out the research on the cooling capacity of young urban trees, the research group worked together with the Architecture faculty itself to carry out the measurements within the Urban Climate

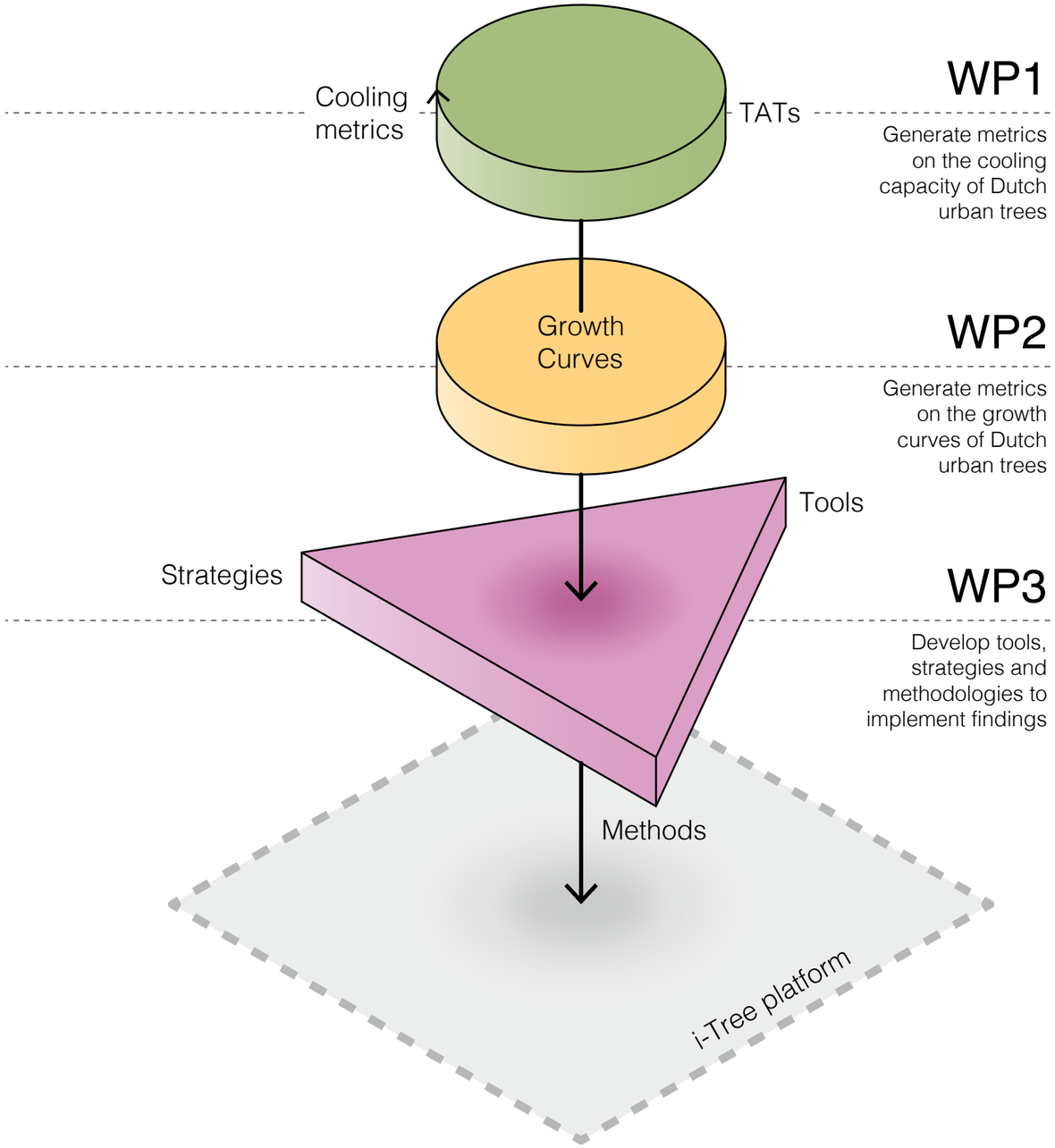


Figure 2. Overview of the interrelation between the three work packages and the i-Tree platform.

Page 18-19, Figure 3. Overview of the division of work among the research team, industry researchers and other partners per work-package including coordination and dissemination.

	Research team			Industry Researchers/ Contributors		Other partners	
Coordination			TU Delft Stadswerk AMS				
WP1	TU Delft	A+BE	Wageningen University	Davey Institute USDA Forest Services	Plantkundig Tree Ground Solutions	Amsterdam Den Haag Dijk en Waard (Heerhugowaard) Dordrecht Groningen Hendrik-Ido-Ambacht Rotterdam Utrecht	A+BE Green Village
WP2					Terra Nostra Cobra Groengezicht		
WP3		IDE		Arcadis MVRDV Komovo			Van den Berk Boot & Dart Ebben Udenhout M. van den Oever & Zonen Pius Floris Idverde Bomenwacht Nederland Plantkundig Tree Ground Solutions
Dissemination			TU Delft Stadswerk AMS MVRDV			Amsterdam Rotterdam Utrecht Den Haag Groningen Dordrecht	

Arboretum. Together with the municipalities of Amsterdam, Den Haag, Dijk en Waard (Herhugowaard), Dordrecht, Groningen, Rotterdam and Utrecht measurements on mature urban trees were conducted. For the transpiration research a collaboration was set up with the Green Village at TU Delft.

WP2
Research within the second work package was mostly carried out by industry researchers from Terra Nostra and Cobra Groeninzicht. Together with researchers from TU Delft, Terra Nostra was responsible for setting up and preparing the research agenda for WP2. The above-mentioned municipalities, as well as the municipality of Hendrik-Ido-Ambacht provided data.

WP3
Researchers from the Department of Design, Organisation and Strategy at the faculty of IDE spearheaded work package 3. The activities aimed to develop a dashboard, methodology and policy draft together with the relevant stakeholders to strengthen the planning, design, and management of urban green spaces. WP3 uses a set of data collection from interviews, co-design sessions, fieldwork, and a workshop to offer innovative interventions that harness WP1 and 2 results through systemic design, speculative design, and participatory design. To generate insights on the needs and wishes of various stakeholders in the green industry, the research team worked together with municipalities (see above), tree nurseries Van den Berk, Boot & Dart, Ebben, Udenhout, M. van den Oever & Zonen, architecture and engineering offices Arcadis and MVRDV, tree consultancies Pius Floris, idverde, Bomenwacht Nederland and Plantkundig. MVRDV furthermore helped create the 8-step methodology, while design offices Komovo together with researchers from Industrial Design Engineering designed and constructed the dashboard.

Coordination
A steering committee consisting of partners from TU Delft, Stadswerk and AMS coordinated the research team, as well as oversaw dissemination activities.

Dissemination
Researchers from TU Delft together with MVRDV and several municipalities furthermore prepared an exhibition as part of the dissemination.

Consortium partners
The full list of consortium partners includes University partners (TU Delft, WUR); local government partners (Gemeente Amsterdam, Gemeente Den Haag, Gemeente Rotterdam, Gemeente Utrecht, Gemeente Groningen, Gemeente Dordrecht, Gemeente Heerhugowaard, en Gemeente Hendrik-Ido-Ambacht);

Industry partners (Aboricutural consultants Terra Nostra, Pius Floris, Idverde, Bomenwacht Nederland, Cobra Groeninzicht, New Urban Standard and Plantkundig, architecture and engineering consultants MVRDV and Arcadis Nederland, Tree Nurseries M. van den Oever, Boot & Dart, Jan de Vries, Gebr. Van den Berk and Ebben, and AMS Institute, Davey Institute, and Vereniging Stadswerk Nederland.

Research activites

Timeline
The project was carried out between the fourth quarter of 2021 and the fourth quarter of 2024. (A supplementary second-stage of the project will take place in quarter one and quarter two of 2025. This report covers the work up to and including the fourth quarter of 2024). (fig. 4)

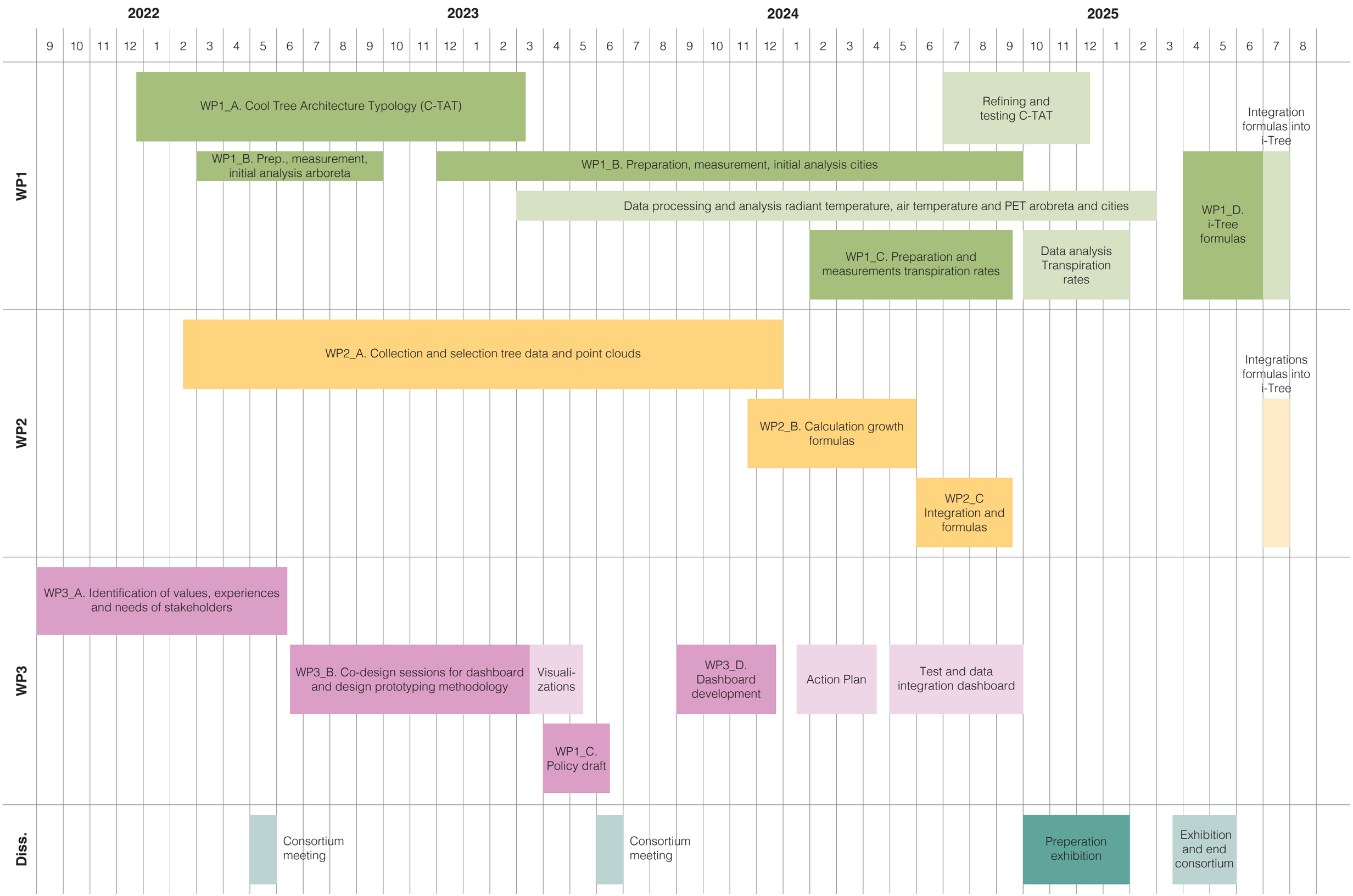
In WP1 2022 was used to develop the tree architecture typology in relation to current performance metrics of trees. In the summer a measurement campaign was carried out in the Urban Climate Arboretum in Delft. In the summers of 2023 and 2024 measurement campaigns were carried out in various cities, as well as in the Green Village in the summer of 2024. The time between summer measurements was used to organize the data and conduct initial analysis, as well as prepare for subsequent measurement. (During the first half of 2025 final calculations are to be carried out and the data integrated into i-Tree).

For WP2 2022 and 2023 were used to set up the research, select and collect the data on municipal trees. The growth curves themselves were calculated in 2024 and integrated into the dashboard, which is part of WP3 in the same year. (The growth curves are to be integrated into i-Tree in the first half of 2025).

The last quarter of 2021 and the first two quarters of 2022 was used for preparatory work for WP3 to identify values, experiences and needs of stakeholders around working with performance metrics of urban trees. Throughout 2022 and 2023 co-designing sessions took place to translate initial findings into strategies, methods and tools. The dashboard, 8-step methodology, and procurement were further elaborated throughout 2023 and 2024. This was supplemented by a policy draft elaborated in 2023.

Dissemination took place at various moments between autumn 2021 and autumn 2024, with individual members of the research team contributing to scientific and conference papers, other written publications, interviews, podcasts, lectures, conferences,

Page 22-23, Figure 4. Gannt chart detailing the research activities per work package throughout the duration of the research.


2022
2023
2024
2025
9 10 11 12 1 2 3 4 5 6 7 8 9 10 11 12 1 2 3 4 5 6 7 8 9 10 11 12 1 2 3 4 5 6 7 8 9 10 11 12 1 2 3 4 5 6 7 8
WP1
WP1_A. Cool Tree Architecture Typology (C-TAT)
Refining and testing C-TAT
Integration formulas into i-Tree
WP1_B. Prep., measurement, initial analysis arboreta
WP1_B. Preparation, measurement, initial analysis cities
Data processing and analysis radiant temperature, air temperature and PET arobreta and cities
WP1_D. i-Tree formulas
WP1_C. Preparation and measurements transpiration rates
Data analysis Transpiration rates
WP2
WP2_A. Collection and selection tree data and point clouds
Integrations formulas into i-Tree
WP2_B. Calculation growth formulas
WP2_C Integration and formulas
WP3
WP3_A. Identification of values, experiences and needs of stakeholders
WP3_B. Co-design sessions for dashboard and design prototyping methodology
Visuali-zations
WP3_D. Dashboard development
Action Plan
Test and data integration dashboard
WP1_C. Policy draft
Diss.
Consortium meeting
Consortium meeting
Preperation exhibition
Exhibition and end consortium

congresses and exhibitions. Collective dissemination moments were organized in the form of consortium meetings. (A concluding workshop, presentation of results and exhibition will beheld in the first half of 2025).

Detailed description of activities per work package

Work Package 1: Tree Architecture & Cooling Metrics
Coordination: TUD_Architecture & Built Environment (TUD-ABE)
Implementation: postdoc-TUD (PD1), project leader1-TUD (PL1), technician1-TUD (T1), technician2-TUD (T2), researcher1-WUR (R1), municipal tree officers (MTO), arboriculture technician1 (A1)

WP1_A. Cool Tree Architecture Typology (C-TAT)
i. Literature review on tree architecture focussing on species-specific traits influencing micro-climatic conditions. Development of a descriptive framework for tree architecture relevant to urban thermal microclimate amelioration including data analysis, desk study of descriptions and illustrations from recognized tree catalogues, tree architecture documentation/ descriptions, preparation of illustrations and tables and writing up of results for scientific publication.
ii. Elaboration and refinement of a Cool Tree Architecture Typology (C-TAT) through observations and documentation of specimens in the urban climate arboretum TU Delft. Development of definitive sub-traits and analysis of material including ranking, clustering and hierarchy models.

WP1_B. Preparations, measurements and data analysis of trees in arboretum & selected cities
i. Field measurements to establish shade cooling values, transpiration cooling values & Human thermal comfort values) of juvenile trees in UCA field laboratories.
ii. Field measurements to establish shade cooling values, transpiration cooling values & Human thermal comfort values) of 3 species of mature trees in 6 selected cities.
iii. Data processing and analysis radiant temperature, air temperature and PET arboreta and cities.

WP1_C. Preparation and measurements transpiration rates
i. Literature review to collate relevant findings on transpiration, water use and drought tolerance of trees, in relation to cooling performances as a result of transpiration cooling, in the Cfb climate zone.
ii. Validation of transpiration rates by monitoring trees and their water consumption in containers.
iii. Data analysis of transpiration rates.

WP1_D. i-Tree formulas
i. Development of formulas translating cooling metrics for integration as source code into the i-Tree tool.

Work package 2: Tree Growth Curves
Coordination: TUD_Architecture & Built Environment (TUD-ABE) + Terra Nostra
Implementation: project leader1-TUD (PL1), technician1-TN (T1), municipal tree officers (MTO), arboriculture technician (A1), remote sensing technician (LT)

WP2_A. Collection and selection tree data and point clouds
i. Tree data, containing tree species, condition, planting year, growth site and location, was collected from participating municipalities. Solitary trees were selected and divided in age classes per tree species. Point clouds were extracted from 3 collection years to calculate growth curves. Growth curves for tree height and crown width in relation to age were created.

WP2_B Calculation growth formulas
i. Growth curves were then calculated for 60 species.

WP2_C Integration and formulas
i. Results were implemented in the Dashboard created in work package 3.

Work package 3: Resilience mapping, Vision-building & Prototyping
Coordination: TUD_Industrial Design Engineering
Execution: postdoc2-TUD (PD2), project leader2-TUD (PL2), municipal tree officers (MTO), landscape architect/urban designer1-MVRDV (LAU1) arboriculture technician1 (A1), landscape architect/urban designer2-Arcadis (LAU2)

WP3_A. Identification of values, experiences and needs of stakeholders
i. Interviews focusing on the values, experiences and needs of stakeholders, to map stakeholder journeys in urban green space.

WP3_B. Co-design sessions for dashboard and design prototyping methodology
i. Co-design sessions to prototype dashboard and design methodologies. Policy needs and shortcomings are also identified in workshops.
ii. Development of further iterations of the dashboard design, including visualizations.

WP3_C. Policy draft
i. Policy needs and shortcomings identified in workshops are developed into a policy draft and and Procurement Draft with practical recommendations for strengthening the position of

urban green spaces.

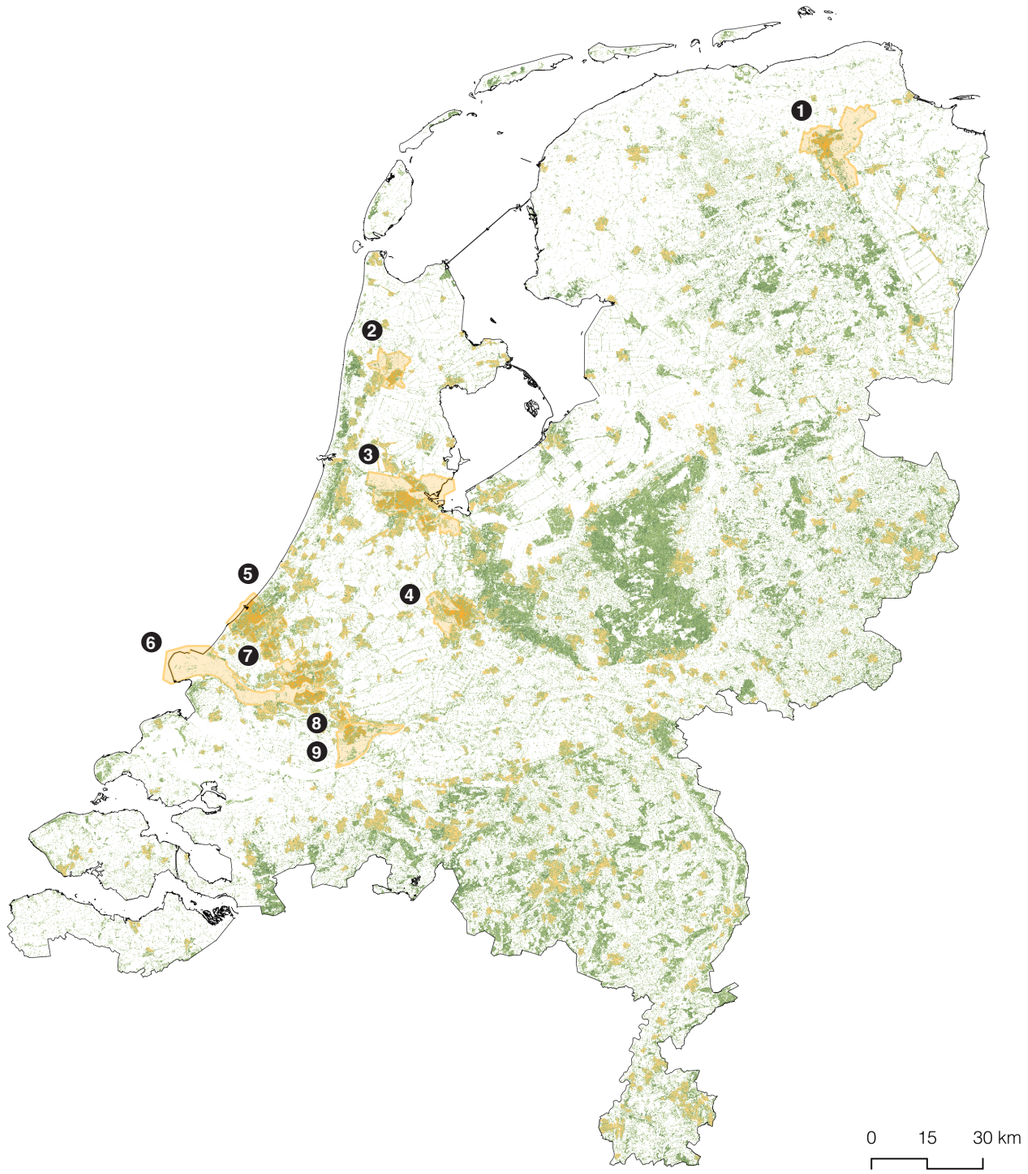
WP3_D. Dashboard development
i. Action plan test.
ii. Data integration in dashboard.

Study area
This research was conducted in nine municipalities in The This research was conducted in nine municipalities in the Netherlands (see Figure 5 and Table 1). According to the Köppen-Geiger climate classification, the Netherlands has a temperate maritime climate (type Cfb). Throughout the country, the winters are mild with mean temperatures around 10C. Coastal regions have more hours of sunshine than inland regions and a relatively small annual and diurnal temperature range. The growing season starts around the 1st of April and lasts until the end of September.

Data collection and measurements for work packages 1 and 2 were primarily carried out in the partner municipalities Amsterdam, Den Haag, Dijk en Waard (Herhugowaard), Dordrecht, Hendrik-Ido-Ambacht, Groningen, Rotterdam and Utrecht. GIS and AHN data of urban trees was collected for use in both work packages. This was complimented by on-site measurements for WP1 - both long-term to evaluate the transpiration cooling capacity of urban trees, as well as one-day measurements campaigns in the summer to collect data

Cities	GIS + AHN Data	Transpiration Cooling measurements	Shade Cooling Measurements
Amsterdam	x	x	x
Den Haag	x	x	x
Dijk en Waard	x	x	
Dordrecht	x	x	
Hendrik-Ido-Ambacht	x		
Groningen	x	x	x
Rotterdam	x	x	x
Utrecht	x	x	x
UCA, TU Delft		x	x
Green Village, TU Delft		x (also transpiration)	

Table 1. Overview of data collection and measurement activities that took place within each of the partner municipalities, as well as on the TU Delft campus for work packages 1 and 2



1. Groningen | 2. Dijk en Waard | 3. Amsterdam | 4. Utrecht | 5. Den Haag | 6. Rotterdam | 7. Delft | 8. Hendrik-Ido-Ambacht | 9. Dordrecht

Figure 5. Map of all cities and towns that make up the study area of the project

on shade cooling. Additionally, both cooling and transpiration data was collected on the TU Delft campus, in the Urban Climate Arboretum (UCA) in the forecourt of the Architecture faculty (cooling research) and at the Green Village (transpiration research) respectively.

Work package 3 utilizes different case study areas to build up tools, methods and transition strategies that can be applied in the Netherlands at large. To build the alpha version working prototype of the dashboard the Oranjeloper (Amsterdam), Selwerd (Groningen) and the Handelsplein (Rotterdam) were used as test cases, while the Marineterrein in Amsterdam serves as a case study area to establish an 8-step methodology for a spatial design process, that incorporates trees and green more holistically. Findings from this case study were furthermore used to work out a draft for a new public procurement procedure.

Summary
WP1 aims to quantify the cooling effects of various tree species in the Netherlands, focusing on how physiognomic characteristics of trees – or tree architecture—affect their cooling capacity. Five key traits of trees were established that impact reflection, absorption and transmission of radiation including Foliage Translumineschense, Foliage Porosity, Crown Density, Wood Zoning and Wood Grain. The categorization of trees into “Cool Tree Architecture Types” (C-TAT) based on cluster analysis resulted in 51 types (from a total of 69 species and cultivars). A further typology consisting of nine types was derived from a cluster analysis of the two most complementary traits Foliage Translumineschense and Crown Density.

Field measurements taken from 69 trees during the summer of 2022, monitored the variables air temperature, relative humidity, wind speed, and globe temperature. These data were used to calculate Mean Radiant Temperature (MRT) and Physiological Equivalent Temperature (PET), which determine human thermal comfort. Results indicated that trees significantly lower air temperature, reduce wind speed, and increase humidity under their canopies, with MRT showing the most pronounced cooling effect. However, tree cooling performance varied with weather conditions, and factors like wind speed and tree spacing affected the results.

Comparison of measurement data and C-TAT types (both the large set of 59 and the smaller set of 9) revealed few significant correlations.

Despite limitations such as sample size and environmental constraints, the study provides valuable insights for urban planners seeking to optimize tree species selection for climate mitigation in cities.

WP1 I **Cooling and Tree Architecture**

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1.1 Extended problem definition

Urban environments are increasingly facing challenges related to rising temperatures and the urban heat island effect, which exacerbates discomfort and health risks for residents. Trees serve as a natural solution to mitigate these effects, primarily through evapotranspiration and shade provision. However, despite the acknowledged cooling benefits of urban forestry, there is a notable gap in empirical data regarding the specific cooling capacities of various tree species. Key physiognomic traits such as crown morphology, wood anatomy, and foliage characteristics are hypothesized to influence a tree's cooling performance, yet studies exploring these relationships are scarce. This presents a pressing need to systematically assess the cooling capacities of different tree species, along with the respective contributions of their physiological characteristics.

WP1 aims to quantify the cooling effect of selected tree species under similar environmental conditions, utilizing field measurements and standardized assessment protocols. Furthermore, it explores how traits such as crown shape, leaf size and density, and wood structure correlate with the cooling effects observed in the selected species. To this end a tree architecture typology (TAT) is developed, accommodating the range of urban tree species relevant to the climatic zone of The Netherlands.

By providing these empirical data and insights, the research will assist urban planners, policy-makers, and conservationists in making informed decisions when selecting tree species for urban greening initiatives. This can lead to improved urban thermal comfort, reduced energy consumption for cooling, and enhanced overall quality of life in urban areas.

1.2 A Cool Tree architecture Typology (C-TAT)

Introduction C-TAT

Next to establishing baseline cooling metrics for different tree species, a parallel aim of WP1 was to elaborate the architectural traits of trees impacting thermal conditions, and the correlation between these and measured cooling performances (as a form of validation). Literature shows that a considerable bandwidth in values exists for indicators on tree properties such as gap fraction and leaf area index (LAI). These variations can be linked to differences in radiation reflection, absorption, and transmission by different species, which greatly impact values such as mean radiant temperature (MRT) beneath the crown. A structured and validated overview of various traits impacting metrics such as gap fraction and LAI has to date received little attention. Insights into these traits, and the categorization of trees into various tree architecture types is also expected to overcome the challenges of individually quantifying the large number of tree species and cultivars planted in Cfb climate zone cities. To this end, a “Cool Tree Architecture Typology” (C-TAT) was developed, involving a structured overview of physical characteristics that impact the cooling performance of trees, hypothesizing that trees with a similar C-TAT profile have a comparable cooling performance. The C-TAT framework builds on the concept of “tree architecture”, a field of plant study that understands trees in terms of their physiognomy, morphology, and morphogenesis.

Description C-TAT trait categorisation

The literature on tree architecture was reviewed focussing on species-specific traits influencing micro-climatic conditions. A descriptive framework for tree architecture relevant to urban thermal microclimate amelioration was developed, including data analysis, desk study of descriptions and illustrations from recognized tree catalogues, tree architecture documentation/ descriptions, preparation of illustrations and tables and writing up of results for scientific publication into a detailed descriptive methodology to describe architectural traits of trees impacting radiation (Van der Velde et al., 2023).

Building on the traits crown, wood and foliage from the literature, sub-traits expected to impact reflection, absorption and transmission of radiation were identified, including: Crown Proportion, Wood Grain and Density, Wood Zoning, Foliage Texture, and Foliage Luminance. In the following step this trait set was tested by field validation activities consisting of photographic documentation of various traits and subsequent visual analysis. A first conclusion from the fieldwork was that crown proportions relate to whole tree cooling performances and not intrinsic performances such as foliage characteristics, which remain constant regardless of tree size. For this reason crown proportions as a trait was removed from the trait list. A further development was that the measurement of crown density was best done by analysing the gap fraction of the crown, as a measure of crown porosity. The definitive tree traits taken further into the validation step included Foliage trans-luminescense, Foliage porosity, Crown density, Wood zoning and Wood grain.

During the research period, photographs were taken at structured moments of 69 tree species/cultivars located in the forecourt of the urban climate arboretum at the faculty of Architecture at the TU Delft. The trees were photographed in elevation at two separate moments: in full leaf at the end of summer and leafless in the middle of winter. These images were used to analyse the traits of wood zoning and wood grain. Fish-eye lens photos were taken beneath the crown with the lens pointing vertically upwards in summer situations. (The comparatively large number of trees relative to the limited research location surrounded by buildings meant that the trees could not always be photographed in situ against the sky or an even background and that the camera positions sometimes had to be moved). These images were used to analyse the trait Crown density. Branchlets and leaves were also photographed, while growing on the tree and detached from it. Detached foliage photos were taken on a flat, evenly grey surface equipped with a measuring rod. These images were used to analyse the traits Foliage trans-luminescense and Foliage porosity.

The photos of the five tree traits (Foliage Trans-luminescense, Foliage Porosity, Crown Density, Wood Zoning and Wood Grain) were printed in full color on A4 format and visually assessed and ranked from ‘least’ to ‘most’ for each trait in an interactive workshop with three experts. Although a tree could sometimes move up or down one or two places, in general little discussion was needed to arrive at a definitive ranking. Based on this ranking, thresholds within each trait were visually identified resulting in the establishment of three categories per trait (see Appendix 1). Due to the number of tree architecture variables and the explorative nature of this study, it was decided to rank the 69 trees relative to each other for a selection of defined properties to investigate correlations with temperature values. In a following step this ranking was used to establish categories - three per “tree architecture” trait - to be able to more easily compare trees as a whole.

The ranking principle of the five traits are based on the following considerations:

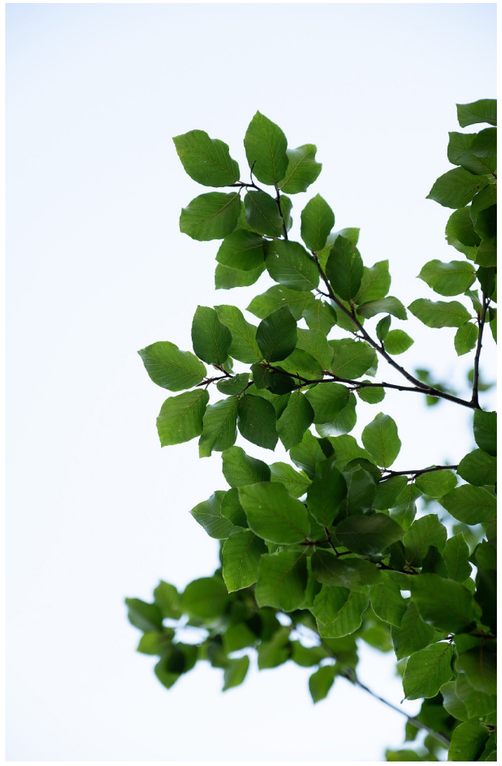
- Foliage Trans-luminescense (most to least) was derived from a series of detailed photographs of leaves. It is defined as the amount of light passing through the individual leaf, from most to least trans-luminescent. The assumption is that leaves with a low trans-luminescense lead to a positive contribution to cooling performance.

- Foliage Porosity (most to least) was derived from the series of photographs of a typical branchlet with summer leaves. It is defined as the amount of open space between the leaves relative to the leaf surface within a fictive contour around the outer leaves on the branchlet. The assumption is that a low foliage porosity results in a positive contribution to cooling performance.

- Crown Density was visually assessed from the fisheye lens photographs. Although gap fraction, on which the trait crown density is based, can be calculated, different methods show quite different results, hence why the same methodology of relative ranking was chosen here. The ratio between the sky covered by leaves and branches relative to the visible sky determines the ranking from most to least visible sky. The assumption is that a larger portion of covered sky will positively influence cooling performance.

- Wood Zoning (even to uneven) is defined as the evenness of the distribution of branches in the crown, from unevenly arranged to evenly arranged. An uneven arrangement leads







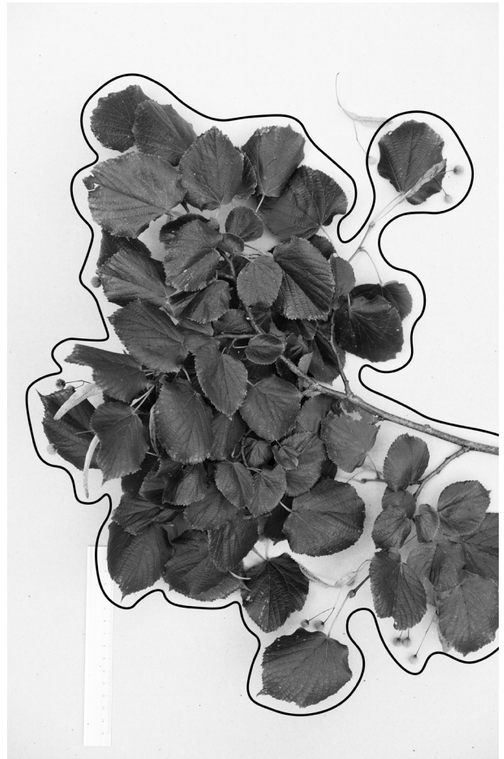
Pages 34-39, Figures 6-20. Images illustrating the differences in Foliage Trans-luminescense, Foliage Porosity, Crown Density, Wood Zoning and Wood Grain of different tree species in the Urban Climate Arboretum.

Foliage Trans-luminescense

From left to right:
Celtis occidentalis: High luminosity (category 1)
Fagus sylvatica: Medium luminosity (category 2)
Quercus ilex: Low luminosity (categroy 3)













Foliage Porosity

From left to right:
Prunus cerasifera “Nigra”: High porosity (category 1)
Ulmus “Clusius”: Medium porosity (category 2)
Tilia platyphyllos “Delft”: Low porosity (categroy 3)

Crown Density

From left to right:
Populus x canescens “De Moffart”: High gap fraction (category 1)
Prunus cerasis: Medium gap fraction (category 2)
Ulmus “Clusius”: Low gap fraction (categroy 3)







Wood Zoning

From left to right:
Cedrus libani: Low degree of eveness (category 1)
Magnolia kobus: Medium degree of eveness (category 2)
Thuja plicata: High degree of eveness (categroy 3)







Wood Grain

From left to right:
Gymnocladus dioica: Coarse branch structure (category 1)
Pyrus calleryana “Chanitcleer”: Medium fine branch structure (category 2)
Fagus sylvatica: Fine branch structure (categroy 3)

to more and larger spaces between groups of branches and concentrated ‘clumps’ of leaves, while an even arrangement ensures evenly distributed small spaces between the leaves. It is assumed that with a more even distribution less radiation is transmitted into and through the crown, which positively influences cooling performance.

- Wood Grain is defined as the density (‘grain’) of branching, from coarse (less) to fine (more) branching. This trait could be derived from winter photos. It is assumed that dense branching leads to a denser crown, which reflects more sunlight and thus positively contributes to cooling performance.

C-TAT type

In order to compare tree species not only on the basis of a single trait but holistically, a C-TAT type was identified for each tree species. The type is expressed as a five-digit number, which lists the category (1-3) under which each tree species falls per trait. Based on correlation calculations (see section 1.3.2.4) the order of the digits is as follows: Crown Density, Wood Zoning, Foliage Porosity, Foliage Trans-luminescense and Wood Grain. Based on this order of traits a first overall hypothetical ranking of the trees was established with Thuja Plicata scoring the highest with a “33333”, while Morus Alba and Koelreuteria Paniculata scoring the lowest with a “11111”. With this method the 69 species were reduced to a total of 51 architectural types. (table 2)
An abbreviated type was furthermore trialled, taking into account Crown Density and Foliage Trans-luminescense only, as trans-luminescense is the only trait that is not at least partially expressed through the evaluation of crown density. In other words these two traits have the least crossover in terms of characteristics. This clustering resulted in nine architectural types.

Species	Foliage		Crown	Wood		C-TAT	
	Trans-luminescense	*Porosity*	*Density*	*Zoning*	*Grain*	*Type*	*Abbreviated type*
Acer campestere	29	31	42	43	50	22222	22
Acer cappdadocium “Rubrum”	54	33	60	35	29	32232	33
Acer platanoides “Emerlad Queen”	57	49	65	25	8	32231	33
Acer pseudoplatanus	3	56	32	7	10	21311	21
Acer saccharinum	5	22	33	18	9	21211	21
Alnus x spaethii “Spaeth”	49	47	30	36	37	22222	22
Amelanchier lamarckii	17	25	24	42	44	22212	21
Betula nigra “BNTF” Dura Heat	4	15	15	24	65	12113	11
Betula pendula	20	24	20	19	56	21213	21
Betula pubescens	32	7	4	22	58	12123	12
Betula utilis “Jacquemontii”	19	4	8	31	59	12113	11
Carpinus betulus	13	61	61	34	54	32313	31
Castanea sativa	9	59	49	52	24	33311	31
Catalpa bignonioides	11	53	25	8	2	21311	21
Cedrus libani	68	62	11	1	11	11331	13
Celtis occdientalis	1	63	52	5	39	31312	31
Chamaecyparis lawsoniana cv.	34	54	64	66	66	33323	32
Cornus mas	63	48	68	64	42	33232	33
Corylus colurna	14	67	44	27	19	22311	21
Crataegus monogyna	42	5	5	38	57	12123	12
Fagus sylvatica	27	19	57	30	64	32113	31
Gingko biloba	43	51	28	2	6	21221	22
Gledistia triacanthos “Inermis”	7	43	13	3	26	11212	11
Gymnocladus dioica	6	44	36	10	1	21211	21
Juglans regia	39	28	35	17	3	21221	22
Koelreuteria paniculata	16	14	9	4	18	11111	11
Liquidambar styraciflua	22	52	54	50	4	33311	31
Liriodendron tulipifera	18	35	53	46	12	32211	31
Magnolia grandiflora	45	42	26	65	41	23222	22
Magnolia kobus	48	29	18	48	49	22222	22
Metasequoia glyptostroboides	33	27	59	59	53	33223	32
Morus alba	2	20	2	20	20	11111	11
Nyssa sylvatica	25	68	47	49	47	33312	31
Parrotica persica “Vanessa”	56	10	63	41	35	32132	33
Picea abies	65	11	67	39	67	32133	33
Pinus strobus	62	26	19	44	55	22233	23
Pinus sylvestris	61	30	29	16	61	21233	23
Populus alba	51	2	10	47	46	12122	12
Populus nigra “Italica”	24	13	62	29	14	32111	31
Populus x canadensis	31	3	6	33	45	12122	12
Populus x canescens “De Moffart”	52	6	1	37	13	12121	12
Prunus avium	40	50	14	6	16	11221	12
Prunus cerasifera “Nigra”	60	1	27	23	48	22132	23
Prunus cerasus	53	34	40	68	27	23232	23
Prunus maackii	30	64	7	45	17	12321	12
Prunus padus	47	45	12	12	23	21221	22
Prunus sargentii	59	58	51	53	25	33231	33
Prunus x yedonis	55	60	17	51	21	23331	23
Pyrus calleryana “Chanitcleer”	36	41	37	60	43	23222	22
Quercus cerris “Marvellous”	64	38	31	9	33	21232	23
Quercus ilex	66	17	43	63	51	23132	23
Quercus petraea	37	40	34	11	40	21222	22
Quercus robur	38	57	58	62	60	33323	32
Robinia pseudoacacia “Nyirségí”	21	37	16	14	5	21211	21
Sorbus aucuparia “Edulis”	26	23	45	28	28	32212	31
Sorbus intermedia	44	9	3	13	36	11122	12
Styphnolobium japonicum	10	16	23	15	15	21111	21
Taxodium distichum	35	18	41	40	63	22123	22
Taxus baccata	67	46	56	57	68	33233	33
Thuja plicata	69	55	66	69	69	33333	33
Tilia americana “Moltkei”	41	12	48	56	22	33121	32
Tilia cordata	46	66	46	58	32	33322	32
Tilia platyphyllos “Delft”	28	69	55	61	31	33322	32
Tilia tomentosa “Szeleste”	12	39	38	21	7	21211	21
Tilia x europaea “Pallida”	8	65	50	54	30	33312	31
Ulmus “Clusius”	50	36	69	67	38	33222	32
Ulmus “Rebona”	58	32	39	55	52	23233	23
Ulmus x hollandica	23	8	22	26	34	22112	21
Zelkova serrata	15	21	21	32	62	22213	21

Page 42-43 Table 2. Ranking and categorization of tree species based on different traits within the TAT.

1.3 Cooling capacity of urban trees |
1.3.1 Materials and methods

1.3.1.1 Measured and calculated values

Trees have several cooling mechanisms that contribute to reducing temperatures in their surroundings. These are:

- Shade: A tree provides shade through reflection, absorption and reduced transmission of solar radiation through the tree canopy. This leads to a significant reduction in radiant energy reaching humans, objects and surfaces beneath it, lowering their temperatures.

- Transpiration: Trees release water vapor from their leaves into the atmosphere through their stomata during photosynthesis. This evaporative process requires energy, which is extracted from the environment as heat, cooling the air.

- Altered wind patterns: Trees change the direction and speed of wind flow. Their presence can redirect winds around people, structures or other obstacles, affecting how air circulates in an area, which can have a positive but also a negative effect on thermal comfort, as convective heat transfer is limited in areas with low wind speeds.

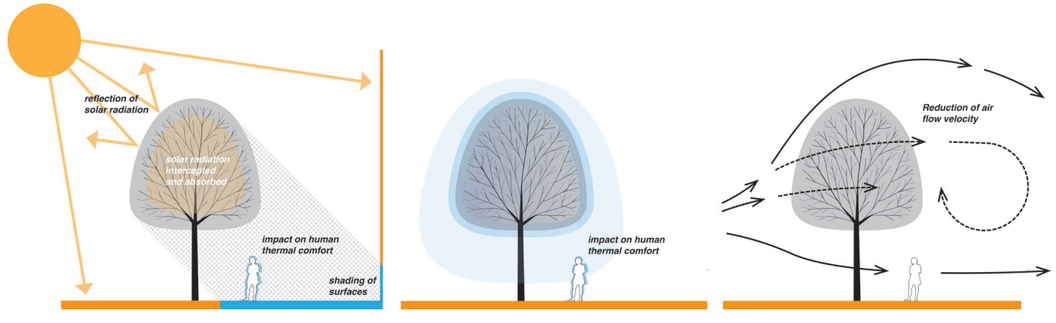


Figure 21. Cooling mechanisms of trees: shading and radiation, evaporative cooling, and influencing air flows.

To quantify these cooling mechanisms and their impact on human thermal comfort, we performed measurements within the tree canopies and in the tree shades. Measured values were air *temperature (AT), relative humidity (RH), wind speed (U) and Globe Temperature (T_g)*, the latter two in the tree shade only (see fig 22).

Based on these measurements, two more values were calculated:

- Mean Radiant Temperature (MRT): Derived from globe temperature, air temperature, and relative humidity, MRT represents the average temperature of surfaces – including sky and sun - surrounding a point.

- Physiological Equivalent Temperature (PET): A thermal comfort index that combines air temperature, humidity, wind speed, and MRT to estimate perceived temperature, reflecting the human body's thermal response.

1.3.1.2 Measurement campaigns

Equipment and Protocols for Measurements
The following equipment was used for measurements:

- HOBO Onset MX2301A Temperature/RH data logger, encased by a TFA Dostmann 98.1114 radiation shield (canopy);
- Kestrel 5400 WGBT Heat Stress Tracker (shade and reference at person height);
- Davis Vantage Pro2 (reference at crown height);

HOBO loggers were installed on the widest part of the crown of each tree, facing north to minimize incident solar radiation entering the casing. The loggers were set to a 1-minute measurement frequency. Data was stored locally in the logger. The loggers have a capacity of approximately 30 days, after which the loggers are read out.

Measurements in the trees' shades were performed on warm cloudless days with an (expected) daily maximum air temperature of at least 22 degrees Celsius, between 12.00 and 16.00 hrs, in the period from June 21st until September 21st. The kestrels were positioned atop tripods at a height of 1.5 meters above ground level, to correspond to human exposure. The instruments were placed in the middle of the canopy shade and repositioned every 10 minutes following the movement of the sun. One kestrel was placed in the sun as a reference. (Up to) 12 trees were measured simultaneously during a campaign day.

Measurement campaigns

A total of 69 trees made up of various species and cultivars were monitored during the summer 2022 (see Appendix 2 for the measurement campaign day protocal). The trees had been growing since 2020 in a specially designed above-ground planter consisting of airpot on a pallet encased in a protective triplex casing. (fig. 23, 24 & 25) Trees in air-pots were positioned in the forecourt of the Faculty of Architecture and the Built Environment in Delft. In order to reduce the building's interference with the measurements, groups of trees were moved to the left side of the square during the measurement days. The six sets of trees were organised based on height and monitored during six warm (>20 ^{o}C) cloudless days.

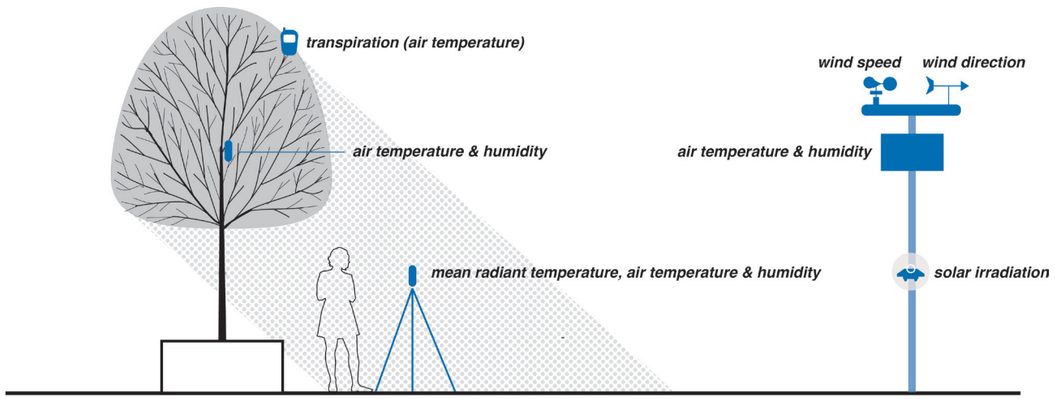


Figure 22.Types of measurements and their locations in measurement campaigns.







Figure 23, 24 & 25. Overview of the Arboretum in Delft.

17/06/2022	**22/06/2022**	**18/07/2022**	**19/07/2022**	**09/08/2022**	**10/08/2022**
High height	*High height*	*Medium height*	*Medium height*	*Low height*	*Low height*
Acer campestre	*Acer platanoides* 'Emerald Queen'	*Acer pseudoplatanus*	*Betula pendula*	*Catalpa bignonioides*	*Amelanchier lamarckii*
Acer cappadocicum 'Rubrum'	*Acer saccharinum*	*Alnus x spaethii* 'Spaeth'	*Betula utilis var. jacquemontii*	*Chamaecyparis lawsoniana cv.*	*Castanea sativa*
Betula nigra 'BNTF' Dura heat	*Carpinus betulus*	*Crataegus monogyna*	*Cedrus libani*	*Corylus colurna*	*Koelreuteria paniculata*
Betula pubescens	*Gleditsia triacanthos f. inermis*	*Juglans regia*	*Celtis occidentalis*	*Gymnocladus dioica*	*Parrotica persica* 'Vanessa'
Gingko biloba	*Liquidambar styraciflua*	*Morus alba*	*Cornus mas*	*Magnolia grandiflora*	*Picea abies*
Magnolia kobus	*Liriodendron tulipifera*	*Pinus strobus*	*Fagus sylvatica*	*Prunus cerasifera* 'Nigra'	*Pinus sylvestris*
Metasequoia glyptostroboides	*Populus alba*	*Prunus x yedoensis*	*Nyssa sylvatica*	*Prunus cerasus*	*Prunus padus*
Populus x canadensis	*Populus x canescens* 'De Moffart'	*Sorbus intermedia*	*Populus nigra* 'Italica'	*Prunus maackii*	*Prunus sargentii*
Prunus avium	*Pyrus calleryana* 'Chanticleer'	*Styphnolobium japonicum*	*Robinia pseudoacacia* 'Nyirségi'	*Thuja plicata*	*Quercus ilex*
Quercus cerris 'Marvellous'	*Taxodium distichum*	*Tilia x europaea* 'Pallida'	*Sorbus aucuparia* 'Edulis'	*Tilia americana* 'Moltkei'	*Taxus baccata*
Quercus petraea	*Ulmus* 'Clusius'	*Zelkova serrata*	*Tilia cordata*	*Tilia tomentosa* 'Szeleste'	
Quercus robur	*Ulmus x hollandica*		*Tilia platyphyllos* 'Delft'	*Ulmus* 'Rebona'	

Table 3. Measurement days and respective sets of trees.

1.3.1.3 Methods for Data Processing

In order to analyse the results, the data collected during the campaigns were retrieved from local data storage, preprocessed, and corrected. In a second phase Mean Radiant Temperature and Physiological Equivalent Temperature were calculated. Finally statistical analyses and data plotting were carried out for the entire dataset.

Alignment time intervals

During the campaigns, data from Hobos and Kestrels were stored locally with different time intervals (1minute - Hobos, 3 seconds -Kestrels). Thus, aggregation techniques were used to average the values at 10-minute intervals. R-environment was used for the purpose.

Error calculation

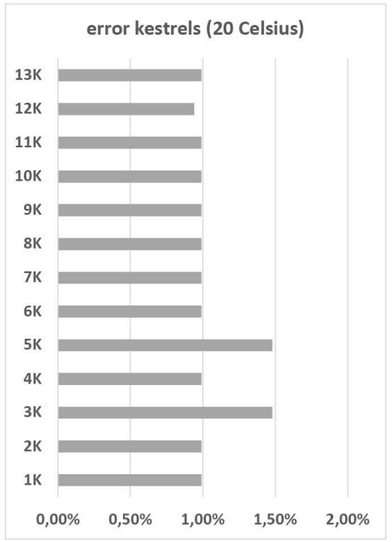
After the measurements, the air temperature and relative humidity errors of each instrument were calculated in a controlled environment. All sensors were placed in a controlled climate chamber for three days at AT:20 ^{o}C – RH:90%, AT:40 ^{o}C – RH:30%, AT:30 ^{o}C – RH:60%. Based on the variance of air temperature and relative humidity between the chamber and the measured values, an error for each sensor was calculated and used to correct the campaigns' values. As shown in figure 26 and 27, the error of Kestrel and Hobos instruments was found to be dynamic, meaning that the accuracy of the sensors changed according to the temperature and humidity to which the sensor is exposed.

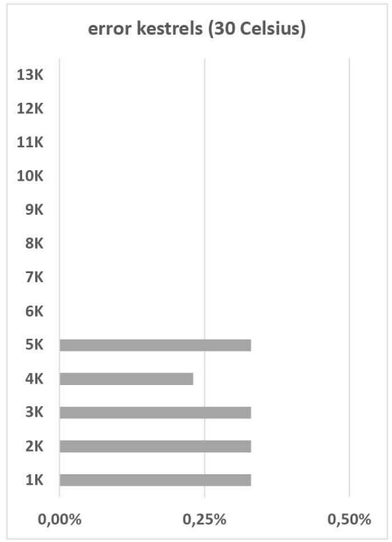
Kestrels and Hobos generally overestimate AT at 20 ^{o}C and RH at 30%, and underestimate AT at 40 ^{o}C and RH at 90%. While the Kestrel error is below 1.5% for air temperature, this can reach 11% in relative humidity measurements. Hobo loggers follow the same pattern, reaching up to 18% error in relative humidity.

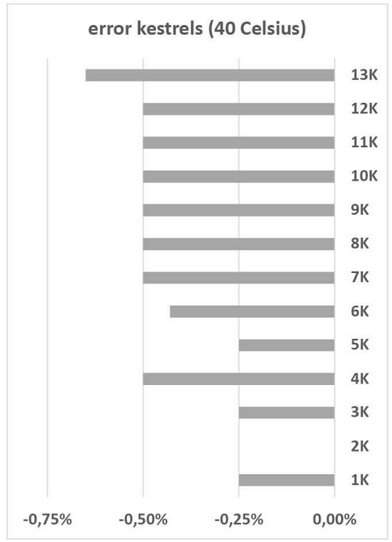
Due to the dynamic error observed, the correction of campaign values was performed by calculating the error function for each instrument from the three measurements in chambers, as shown in the examples in figure 28. The function was used to model the linear error variation based on air temperature and relative humidity values. Finally the correction is applied to the original values measured during the campaigns.

Calculation Error (Kestrels)
Summary of errors in chamber

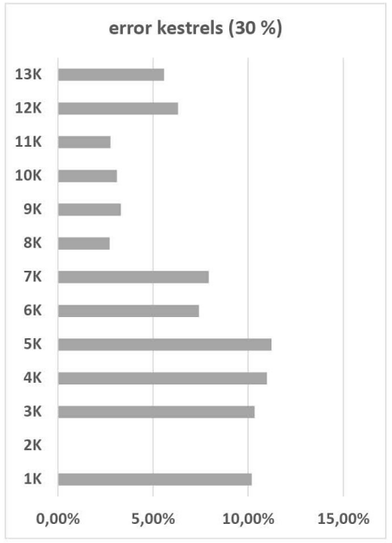
Air temperature

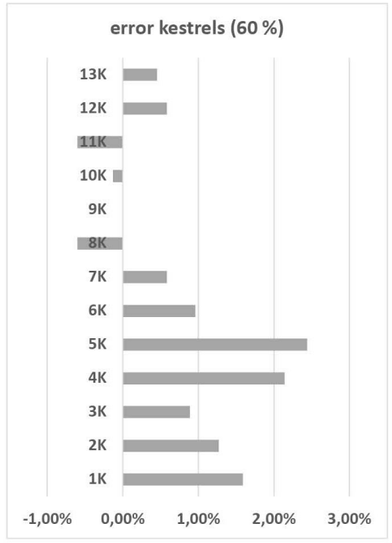






Relative humidity





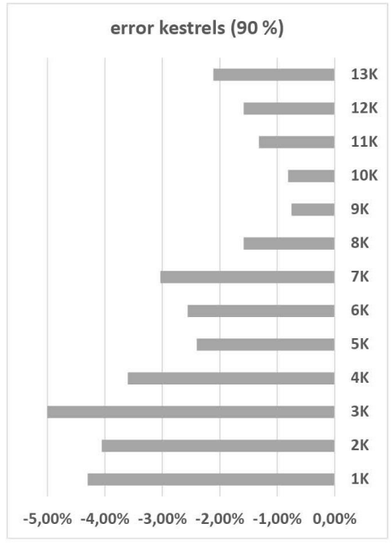
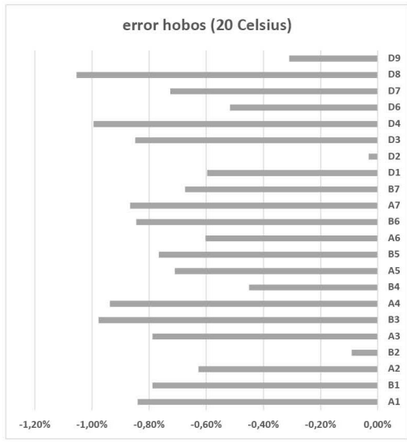


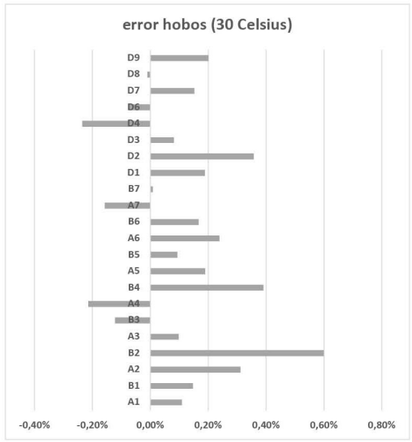
Figure 26. Summary of error calculations for Kestrel instruments in the climate chamber.

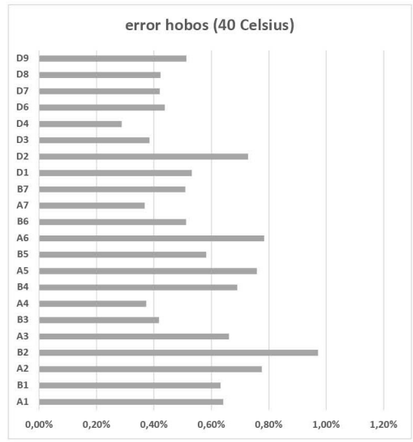
Calculation Error (HOBOs)

Summary of errors in chamber

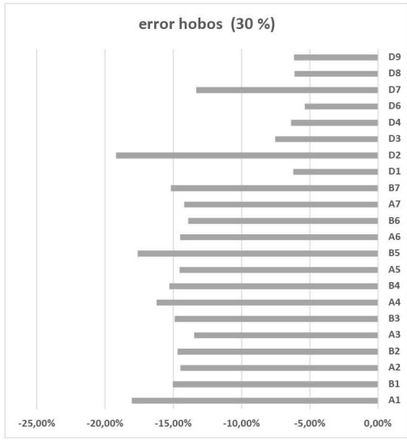
Air temperature

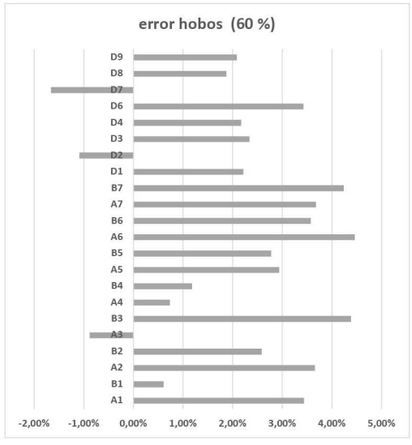






Relative humidity





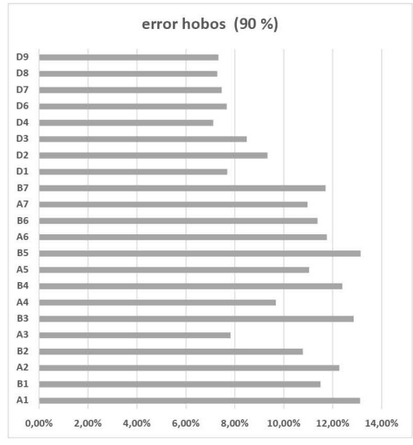


Figure 27. Summary of error calculations for Hobo logger instruments in the climate chamber.

MRT and PET calculation

In a second phase Mean Radiant Temperature and Physiological Equivalent Temperature were calculated. The Mean Radiant Temperature (MRT) was calculated using the formula below, which considers the globe temperature (T_g), air velocity (V_a), emissivity (ε), and globe diameter (D). The formula used was:

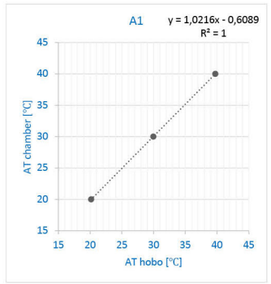
$$\mathrm{Tmrt} = \left[(\mathrm{Tg} + 273.15)^4 + \frac{1.1 \times 10^8 \, Va^{0.6}}{\varepsilon \, D^{0.4}}\right]^{1/4} - 273.15$$

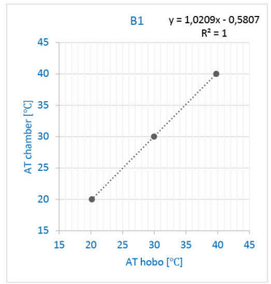
In this equation, Tg is the globe temperature in Celsius, converted to Kelvin by adding 273.15. The air velocity (V_a) was measured at the height of 1.5 meters to represent the typical human body level. Emissivity (ε), was set according to the globe material's characteristics, and the diameter (D) of the globe was taken as 0.15 meters. This equation allowed us to approximate the mean radiant temperature by accounting for the convective and radiative heat exchanges between the globe and its surroundings.

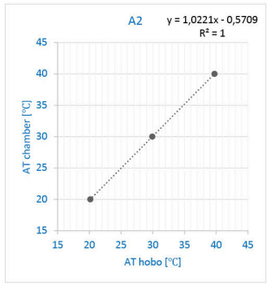
The Physiological Equivalent Temperature (PET) was calculated using the RayMan model, a specialized software for assessing human thermal comfort in outdoor and urban environments. The RayMan model integrates various environmental parameters, including air temperature, relative humidity, and MRT, to estimate PET values. Inputs were based on measured kestrel data. The output PET provides a standardized temperature index that represents human thermal perception, offering a basis for comparing thermal comfort across different environments.

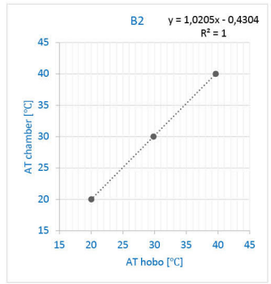
Calculation Error (HOBOs)

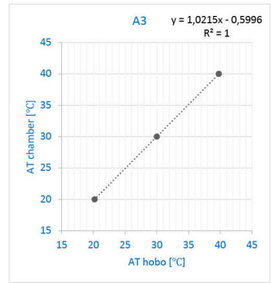
Air temperature

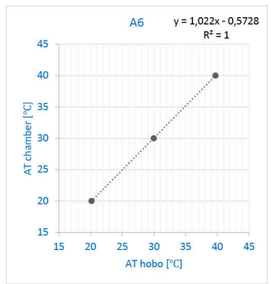


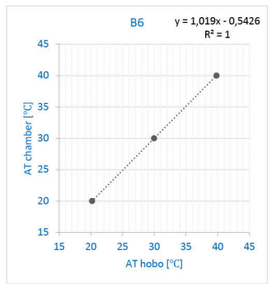


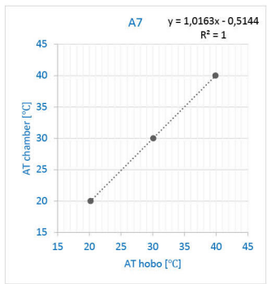


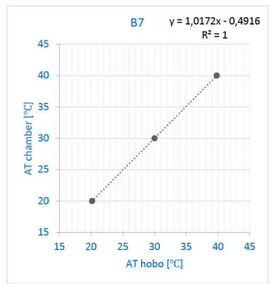


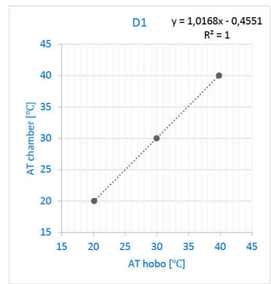


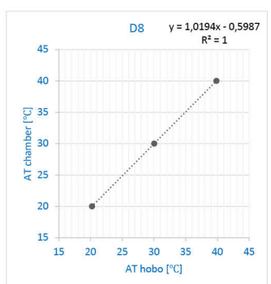












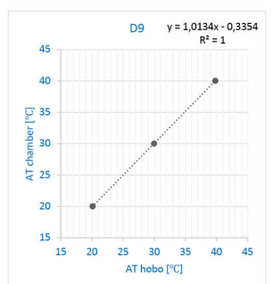


Figure 28. Functions for error corrections.

1.3.2 Results

1.3.2.1 Tree cooling performance in the shade below trees' crown

The climate performance of trees was observed through measured and calculated variables: AT, WS, RH, MRT and PET. Figures 29, 30, 31 and 32 report the 25-75 daily percentile of variation between values measured at a reference point in the sun, and values measured in the shade of each tree crown. Values are grouped per campaign, indicating that comparisons between measured values should be interpreted in light of the overall weather conditions during the measurement day.

AT (Figure 29)
The difference in air temperature between a reference point in direct sunlight and the shaded point beneath the tree canopies varied across the six measurement campaigns. Generally, the temperature delta ranged from -2.6°C to 0.7°C. Values below zero indicate that the air temperature in the shade of tree is lower than the reference point, and thus the cooling potential of the tree during the day. Trees do not always contribute to reducing air temperature, as shown in the results of campaign 1. A possible explanation is that high wind speed combined with high temperature diminish the beneficial effects of evapotranspiration.

WS & RH (Figure 30 & 31)
Wind speed deltas also varied across the six days of measurements, with values generally ranging between -1.7 m/s and 0.6 m/s. The relative humidity difference between shaded and sunlit areas ranged from -2.8% to 4.8%. Generally trees contribute to reduce wind speed because of their roughness and increased the moisture level in the air through evapotranspiration. However, in high temperature and high wind speed conditions, relative humidity in the shade tends to be lower than the reference point value.

MRT (Figure 32)
The Mean Radiant Temperature values demonstrated the strongest cooling effect of tree canopies, with values ranging from -34.5°C to -21.5°C. The substantial reduction in MRT under the tree canopy underscores the significant impact of trees in mitigating radiant heat, thereby enhancing thermal comfort in shaded areas compared to sun-exposed locations.

PET (Figure 33)
The research findings on Physiological Equivalent Temperature (PET) revealed high variability and the benefit of tree shade on human thermal comfort. The PET under the 69 trees analysed, ranged between 31°C and 45°C, demonstrating substantial differences in thermal comfort depending on the tree. Delta values, calculated between the PET at a reference point in the sun and PET calculated under the shade of each tree canopy, showed that the trees under analysis reduced PET by 14.8°C to 23.7°C. Furthermore, during the critical midday to afternoon period (12:00–17:00), the PET reduction varied significantly across tree specimens, exhibiting a range of elasticity from 4.4°C to 1°C.

More information on the measurements of the cooling effects of a selection of mature trees and the results of the data analysis can be found in Appendix 3.

Page 60, Figure 29. Air Temperature Delta.

Page 61, Figure 30. Wind Speed Delta

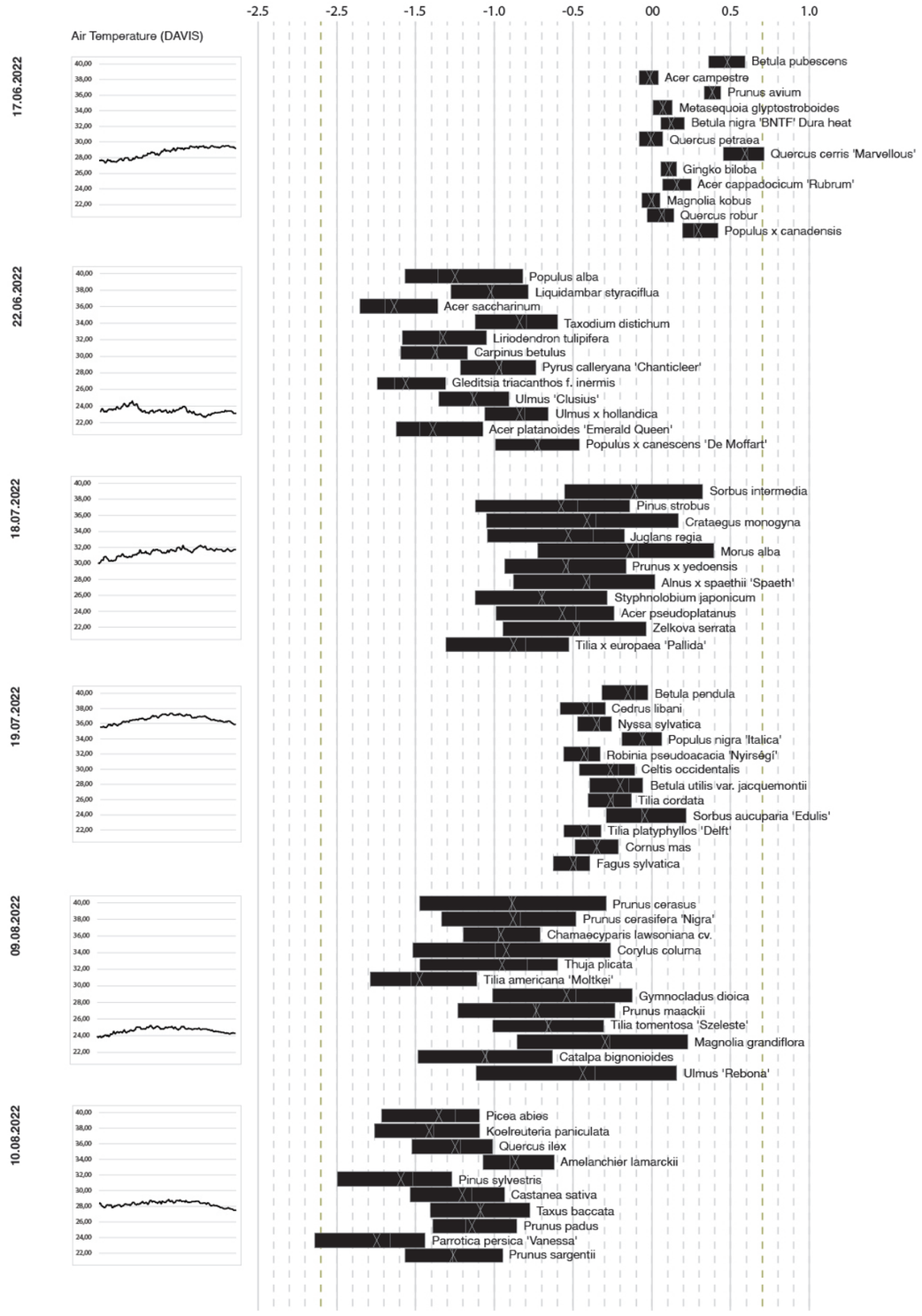
Page 62, Figure 31. Relative Humidity Delta.

Page 63, Figure 32. Mean Radiant Temperature Delta.

Page 64. Figure 33. Physiological Equivalent Temperature Delta.

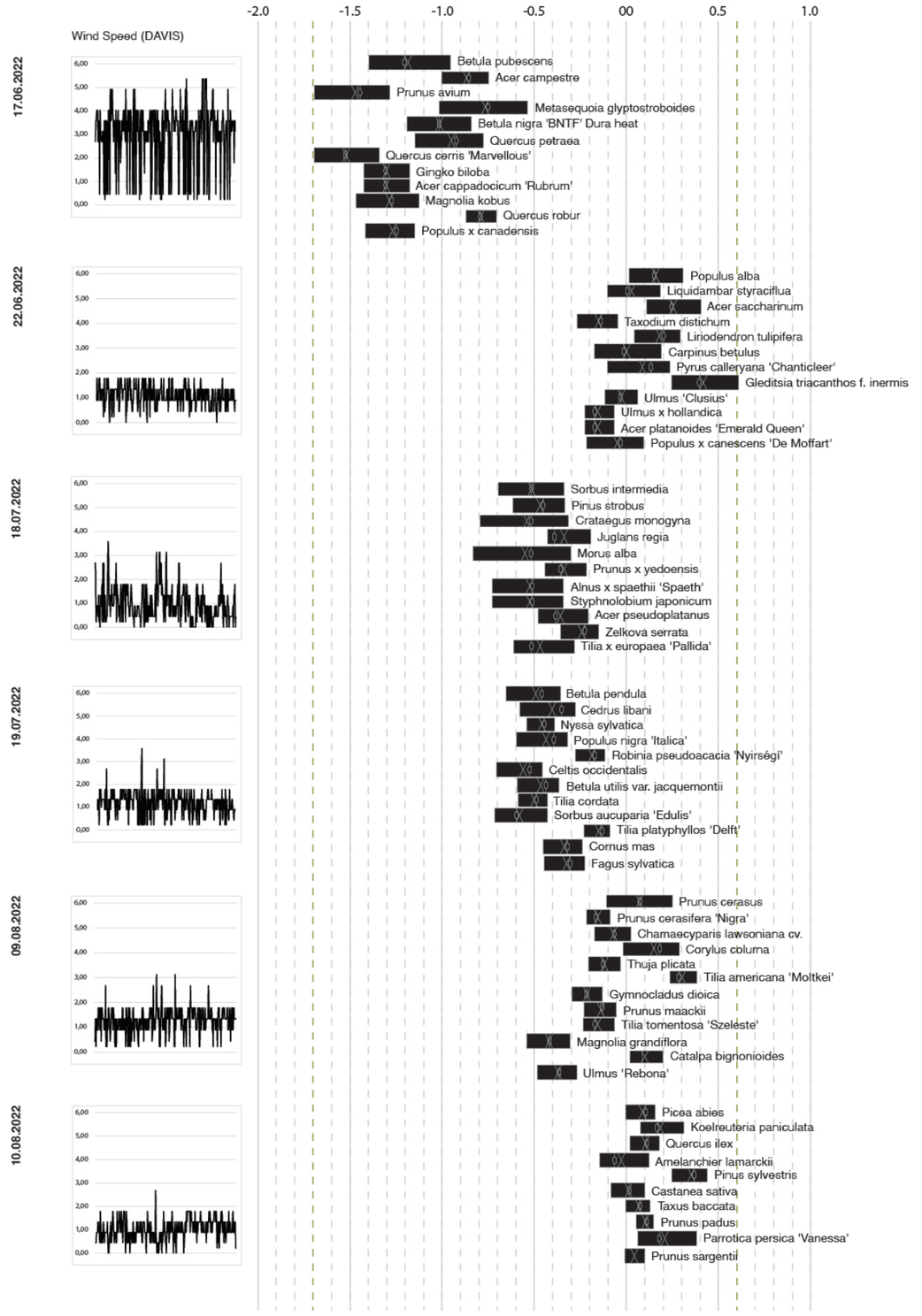
Air Temperature Delta

Difference between values collected by Kestrel 5400 at a reference point (sun) and below tree crown (shadow)



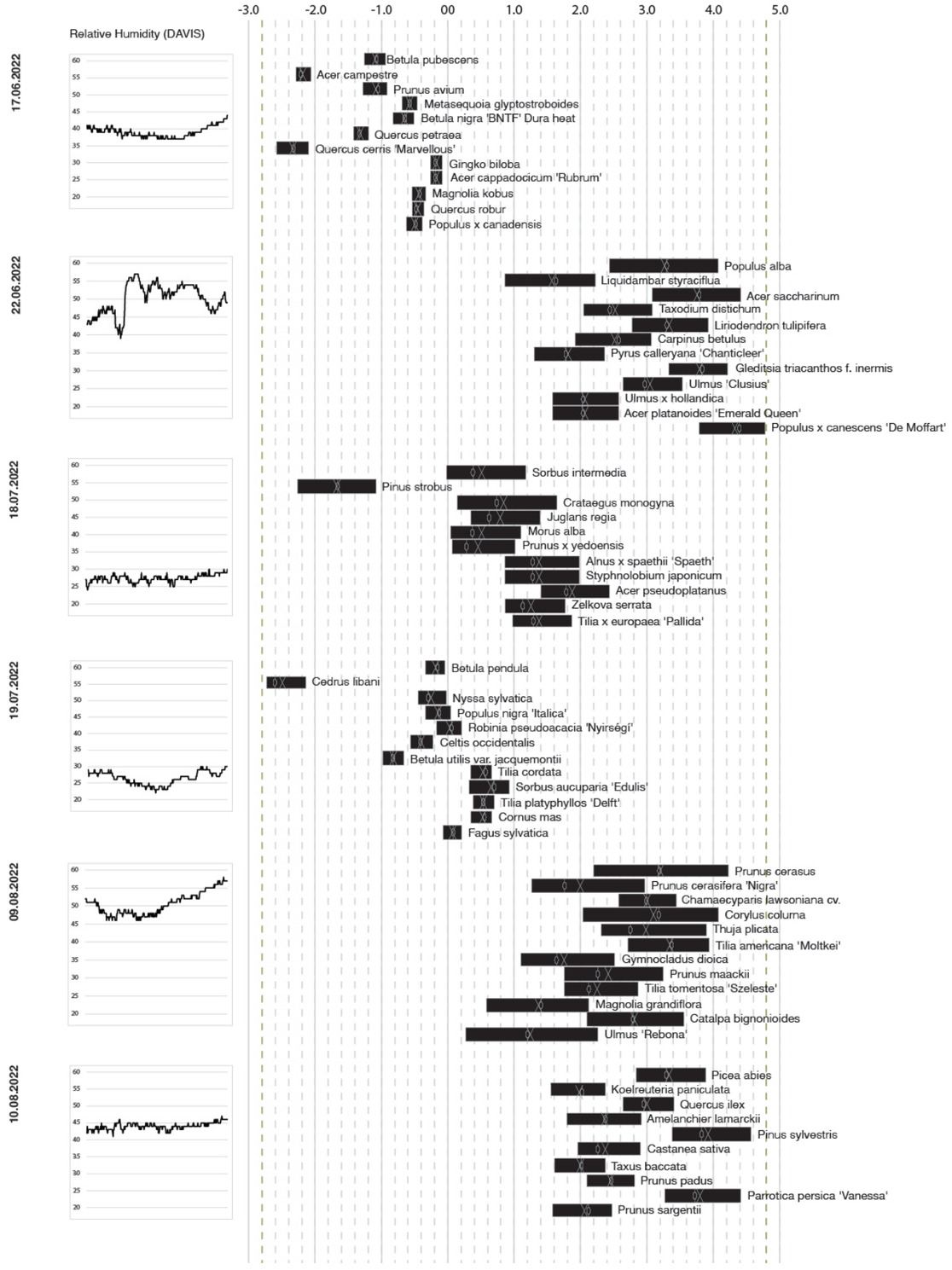
Wind Speed Delta

Difference between values collected by Kestrel 5400 at a reference point (sun) and below tree crown (shadow)



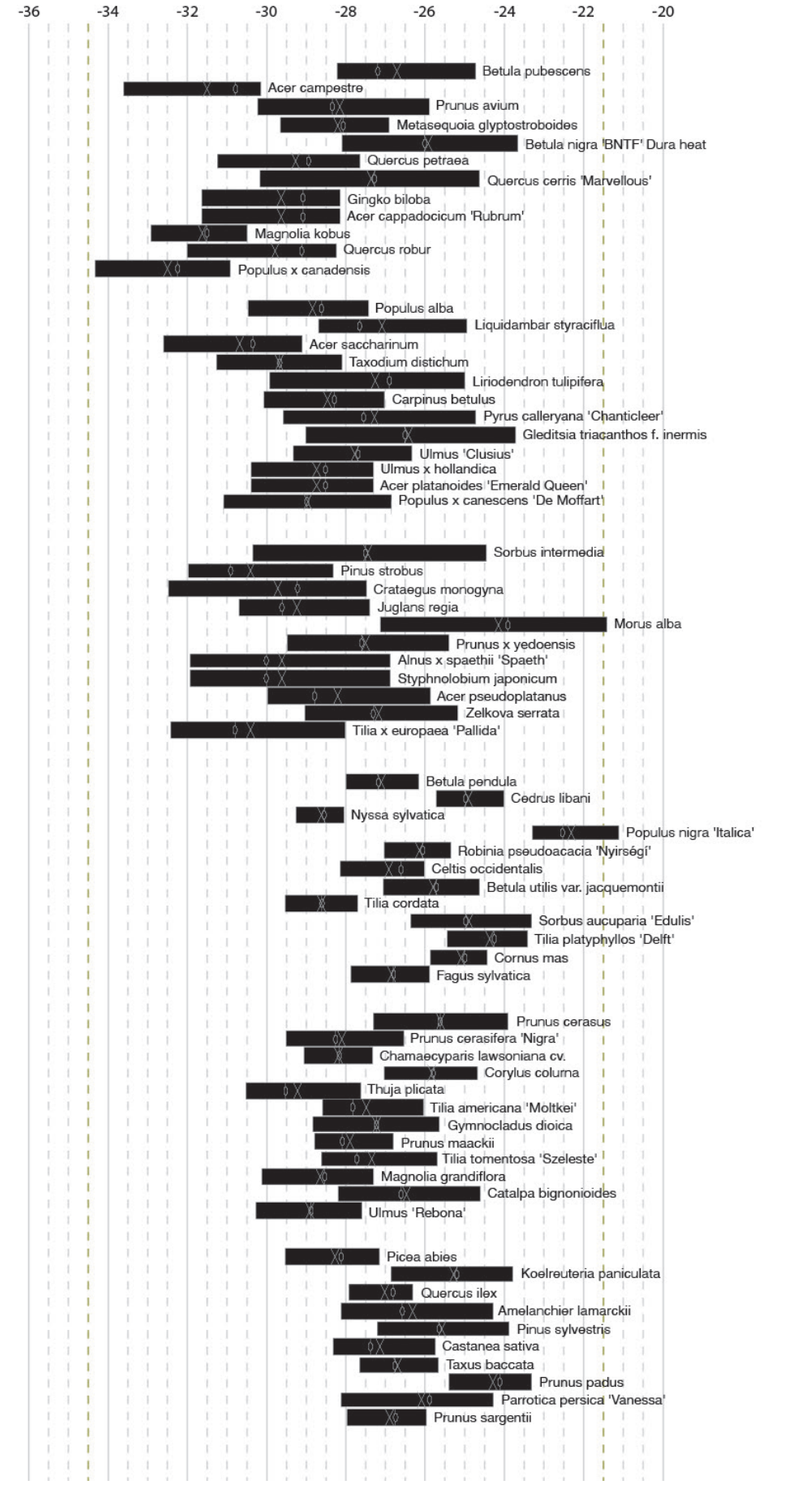
Relative Humidity Delta

Difference between values collected by Kestrel 5400 at a reference point (sun) and below tree crown (shadow)



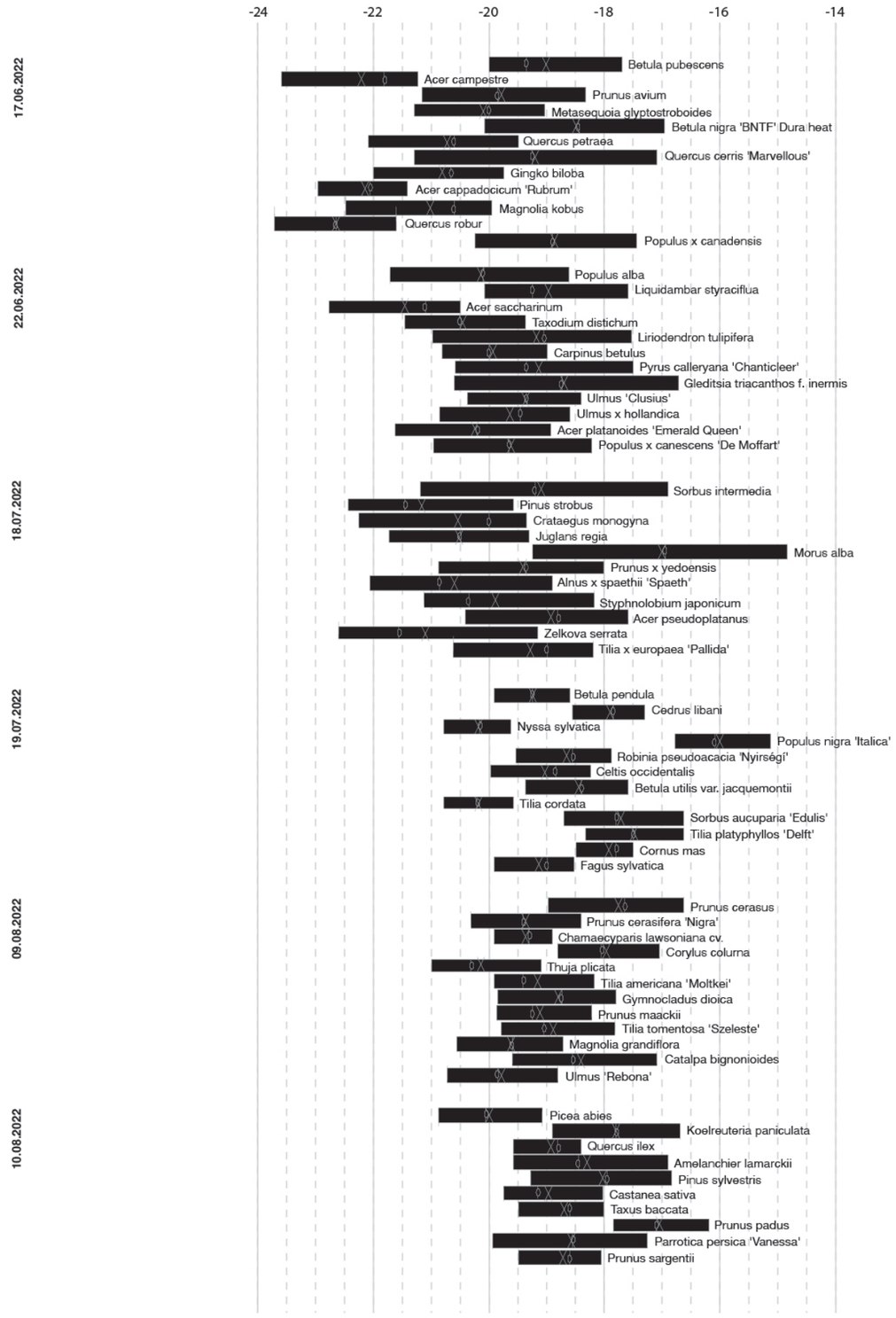
Mean Radiant Temperature Delta

Difference between values collected by Kestrel 5400 at a reference point (sun) and below tree crown (shadow)



Physiological Equivalent Temperature Delta

Difference in PET between values calculated at a reference point (sun) and below tree crown (shadow)



1.3.2.2 Elasticity of tree cooling performance

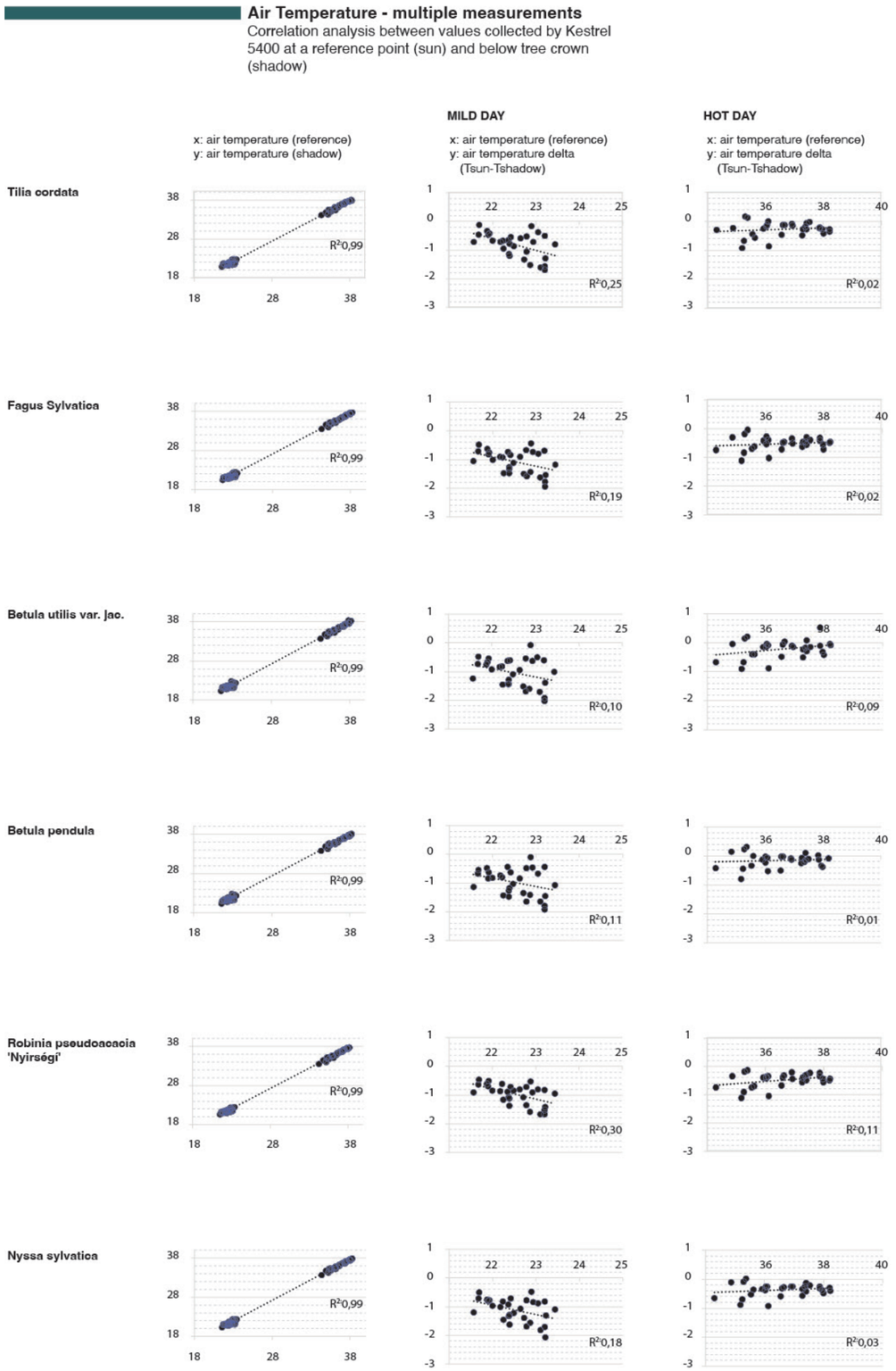
During the campaigns, temperature values were collected through Kestrel instruments positioned beneath the tree canopy at 1,5m from the ground, and through Hobo loggers positioned in the tree crowns. Based on the values collected during campaign days, elasticity is summarised in Figure 34. Elasticity is defined as the variation between the 25th and 75th percentile of values measured during the specified time period (12h-17h). The ranges, measuring the extent of air temperature variation within the observed period, show that temperature variations are generally greater in tree crowns than beneath the tree canopy, except for 8 trees. Beneath the tree canopy the maximum elasticity reached 2.5°C, indicating relatively limited temperature variation. By contrast, elasticity in the tree crowns was higher, with a maximum of 3.5°C. This higher temperature fluctuation can be attributed to the crowns' direct exposure to environmental factors such as sunlight and wind, leading to greater thermal variability. In contrast, shaded areas beneath the canopy experience more stable temperatures due to reduced direct solar radiation and wind exposure.



Page 67, Figure 34. Daily 25-75 percentile of air temperature values in canopy (Hobos) and tree shade (Kestrels).

1.3.2.3 Cooling performance under different temperature conditions

Differences in mesoscale climate conditions during the campaigns affect the comparison among tree cooling performances. With multiple measurement days for trees, a pattern, however, can be observed. An example is reported in Figure 35, where six trees were monitored with kestrel instruments during a mild day and a warm day. The cooling performance can be seen as a function of air temperature with a high correlation during mild days and low correlation during hot days. During the mild day under analysis temperature reaches 23.5 oC and cooling potential increases with the increase of temperature, explaining up to 30% of the variation. However, during hot days reaching 38 oC, the correlation between temperature and cooling potential of trees decreases greatly. This consistent pattern among trees was measured multiple times, indicating that the higher the temperature, the lower the cooling performance of trees.



Page 69, Figure 35. Comparison of variations in air temperature reductions on mild and hot days.

1.3.2.4 Comparing the C-TAT types and cooling performance

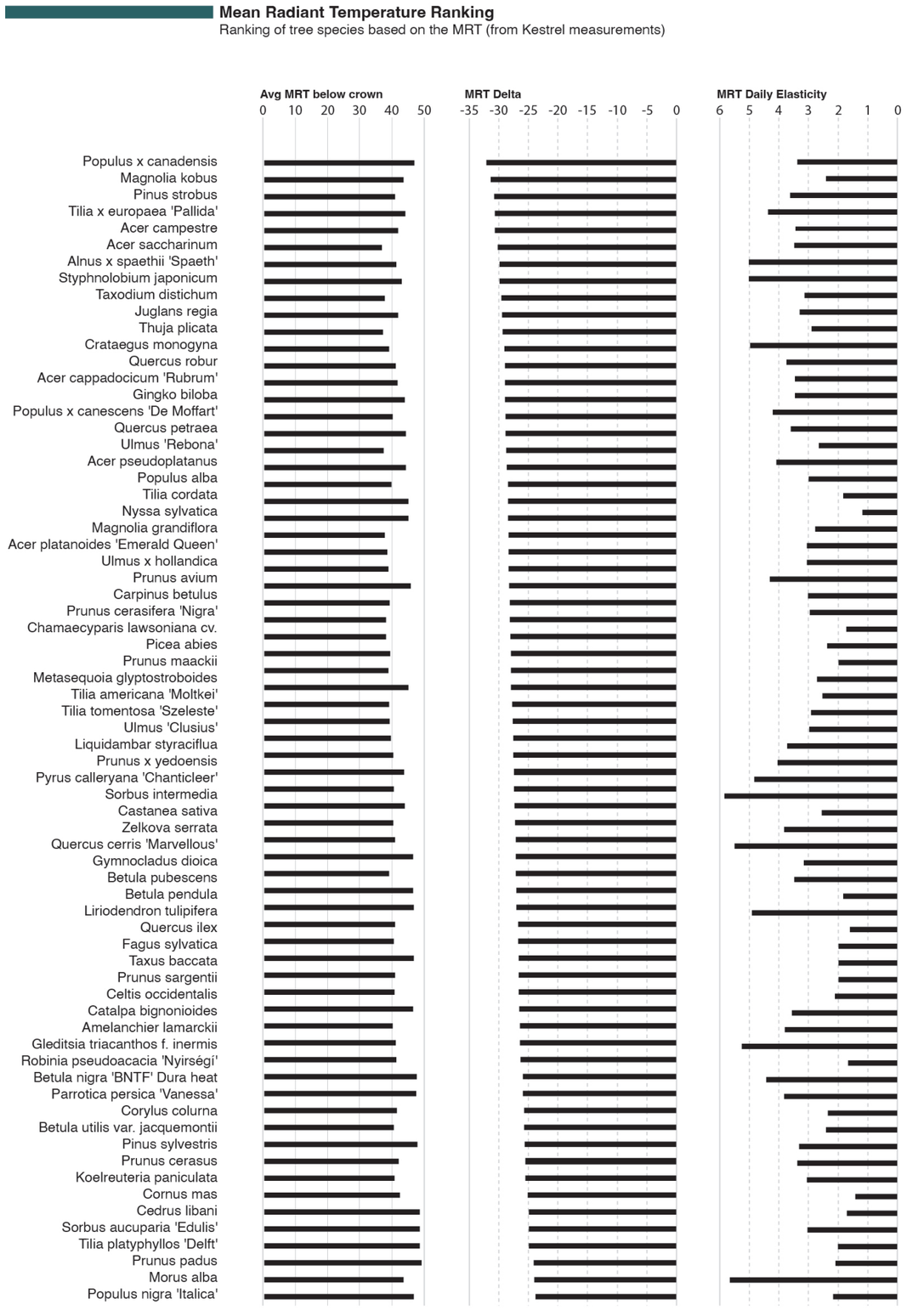
To examine a possible relationship between tree traits and cooling performances, the results of the preliminary C-TAT ranking established in section 2.2 were compared to mean radiant temperature (MRT) values. Of the 69 monitored trees during the campaign period, MRT beneath tree canopies ranged from 36.5°C to 51°C, illustrating the variability in cooling performance across different species and conditions. The median difference in MRT between a reference point in the sun and the shaded area beneath the trees ranged from -32.2°C to -22.5°C, emphasizing the substantial reduction in radiant heat under the tree canopy. Furthermore, even though the delta in MRT during the measurement period had an elasticity of between 6°C and 1°C, indicating that while cooling performance fluctuated over time, trees consistently moderated radiant heat exposure in their surroundings. Column 2 in Figure 36 shows the ranking of the 69 monitored trees from highest reduction in MRT delta to lowest reduction.

In order to evaluate the relationship between the C-TAT types and the measured cooling performances, statistical regression analyses were performed between the individual and overall rankings of tree traits (see table 2) and median elasticity and delta of the Mean Radiant Temperature (see table 4). For the individual traits correlations up to 0,360 occur. Hereby, MRT elasticity values are generally highly correlated to TAT traits compared to MRT delta values. When comparing individual traits, the highest correlation can be found between the Crown density ranking and the MRT elasticity values with a correlation coefficient of 0,360. There is however no correlation between Crown density and Median Delta MRT, scoring 0,042. The highest correlation between Median Delta MRT and an individual trait, namely Grain

		Median Delta MRT	Median Elasticity MRT	Average MRT
Foliage	*Trans-luminescense*	-0,103	0,184	-0,160
	Porosity	0,042	0,242	0,011
Crown	*Density*	0,042	0,360	-0,148
Wood	*Zoning*	-0,158	0,271	-0,294
	Grain	-0,161	0,146	-0,053
C-TAT	*Type*	-0,032	0,385	-0,127
	Abbreviated type	-0,010	0,390	-0,132

Table 4. Ranking of the 69 monitored trees from highest reduction in MRT delta to lowest.

Page 71, Figure 36. Ranking of the 69 monitored trees from highest reduction in MRT delta to lowest.

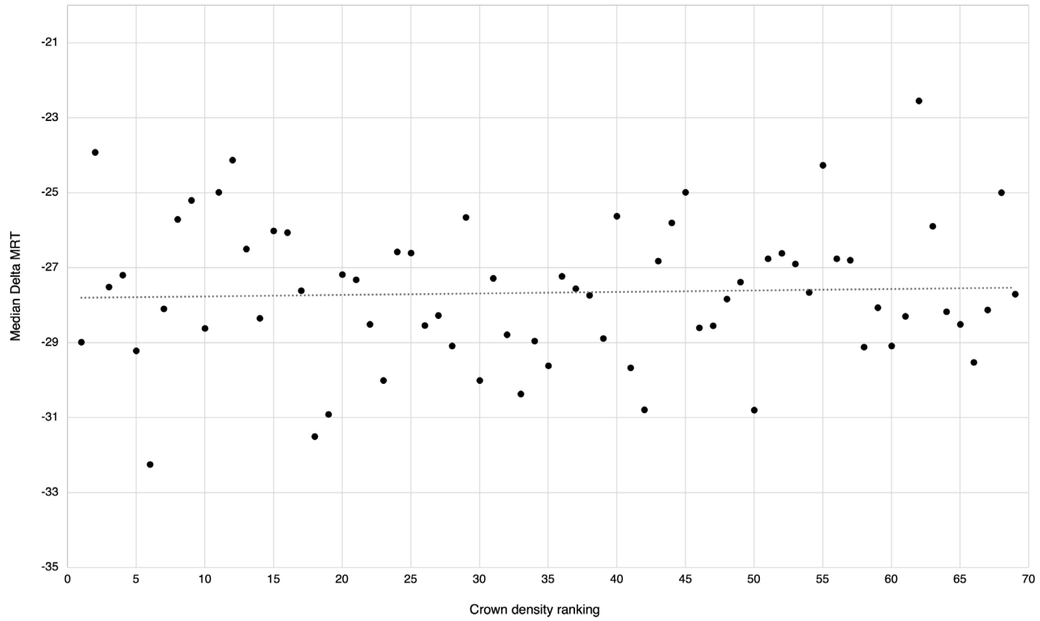


and Density, is -0,161. Grain and Density however scores the lowest correlation related to Median Elasticity with 0,146.

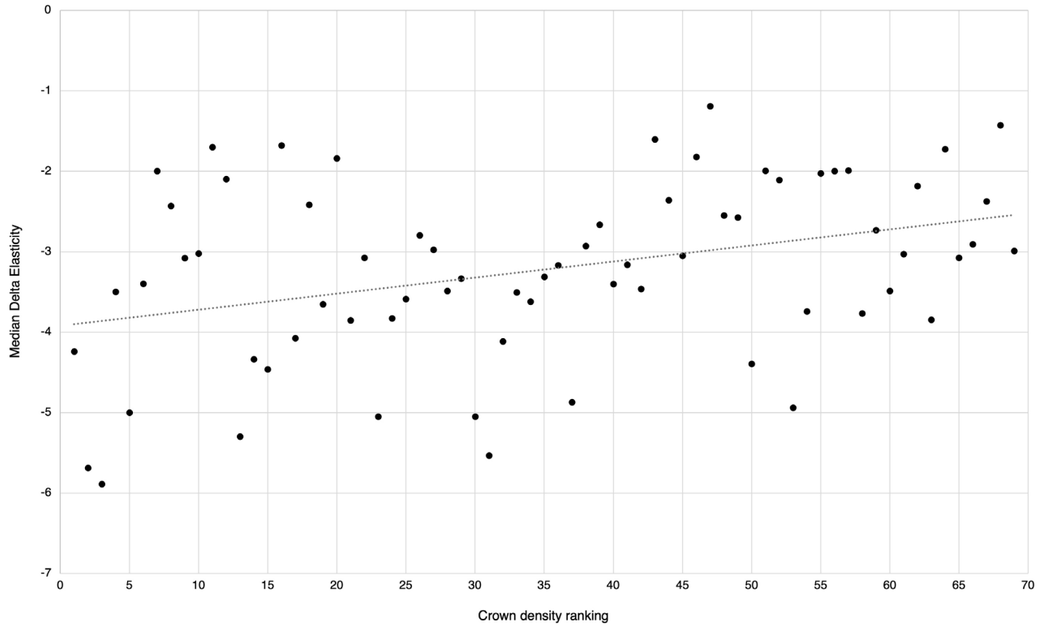
The correlation between MRT Elasticity and the weighted ranking of all TAT traits together, as well as the abbreviated version only containing Crown density and Trans-luminescence, show comparable correlations to the individual assessment of the Crown density, with coefficients of 0,390 and 0,368 respectively. This pattern repeats with the calculations for correlations between the overall rankings and Median Delta MRT, both scoring around 0. These results can be attributed to the high relative weight of the Crown density trait within the overall ranking.

Correlation Crown Density and Cooling performance

Median Delta MRT



Median Elasticity



Figures 37 & 38. Scatter plots visualizing the correlation between the Crown density and Cooling performance of the young trees.

1.3.3 Limitations

Several limitations can be noted for this measurement campaign:

1. Temporal Limitations: The majority of the trees were measured during only one campaign day. Although we aimed for similar weather conditions, there were differences in the weather variables (i.e. air temperature, wind speed and direction, relative humidity and irradiation) between measurement days that lead to different tree cooling potential and presumably performance. This limitation closely relates to the second;

2. Sample Size: Although we had a large number of trees, each species was represented by one specimen only. Therefore, attributing results for the specimen to the species is difficult. The limited sample size both regarding measurement days and specimens combinedly affect the robustness of statistical analyses and the ability to draw strong conclusions.

3. Spatial Setting and Environment: In the spatial setup of the trees, spacing, location and orientation were carefully considered to be able to isolate single-tree effects as much as possible in the space given. However, the possibility of mutual interference between tree effects can not be completely excluded. In addition, external factors such as nearby urban structures (the arboretum was enclosed by the faculty building on three sides and bordered by a road on the other side.) had an influence on the microclimatic conditions, complicating the isolation of tree effects on cooling.

4. Instrumentation Constraints: The instruments used for the measurements do not follow WMO standards, implying a measurement error that is possibly somewhat larger than professional meteorological precision instruments. The measurement error was assessed for all instruments in controlled conditions (a climate chamber) and the results were corrected accordingly.

5. Human Factors: The presence of human activity in the arboretum during data collection could affect measurements, such as localized heat from foot traffic or nearby objects. In addition the repositioning of the instruments every 10 minutes interferes with the measurements.

Acknowledging these limitations is crucial for interpreting the results and understanding the scope of the study's findings.

1.3.4 Outlook

This research underscores the significant role that trees play in microclimate regulation, particularly regarding Mean Radiant Temperature (MRT) and Physiologically Equivalent Temperature (PET). The findings reveal that not all tree species exhibit the same cooling performance, highlighting substantial variations among different tree types. This first exploration with tree types common in Dutch cities can already guide planners and designers in future tree selection.

It proved challenging to attribute the cooling performance to single tree traits as defined in the tree architecture typology (TAT) developed, although crown density shows a (moderate) correlation with the elasticity of the cooling performance. Future studies should incorporate a broader range of specimens from a single species, also taking into account varying ages to capture the developmental aspects that may affect cooling performance. A larger and more diverse sample size might increase the correlation between tree traits and cooling performance. Furthermore, this could provide invaluable insights into how different life stages of trees contribute to microclimate modulation.

In addition, there is a pressing need for comprehensive studies that delve deeper into how weather conditions influence the cooling effects of trees, as this preliminary study indicates that cooling performance decreases with ambient temperature, as well as with wind speed.

Finally, there is an opportunity for the further development of Tree Architecture Typology. By integrating a wider array of traits that influence cooling performance, and possibly including absolute values of these traits, researchers can create a more nuanced framework for evaluating the efficacy of tree species in urban environments. Additional factors such as crown volume and leaf area could be considered and weighted accordingly to enhance our understanding of their contributions to cooling. This will help optimize tree selection and placement in urban settings for maximum climatic benefits.

1.4 Transpiration capacity of urban trees |
1.4.1 Materials and methods

1.4.1 Measurement values and equipment

Measured and calculated values
The aim of this part of the work package is to generate more accurate data on transpiration rates, and by extension the impact of transpiration cooling of trees on air temperatures. To this end four variables were identified for each tree: (1) Transpiration rate, (2) Water loss in relation to soil humidity, (3) Water loss in relation to air temperature and humidity in the crown, and (4) Difference in air temperature and humidity between tree crown and surroundings. To establish these values measurements were taken for each tree including: (5) total weight, (6) air temperature in the crown, (7) humidity in the crown, and (8) moisture content of the soil. These measurements were accompanied by (9) reference measurements of the surroundings as well as (10) calculation of leaf area.

Transpiration

1. Transpiration rate (kg/m^2/d)
   Type: Derived from water loss of tree per day (kg/d) and total leaf area of the tree (m^2)
   Sensor: above-ground Lysimeter
   Moment: Bright warm days

2. Water loss (kg) in relation to soil humidity (%)
   Type: Comparison between water loss per tree per hour and change in soil humidity per tree planter per hour
   Sensor: above-ground lysimeter (scales) and in-ground soil hygrometer
   Moment: Bright warm days

Transpiration Cooling

3. °C difference in air temperature between tree crown and surroundings (Δ°C)
   Type: Comparison between air temperature in the crown and air temperature measured by the weather station
   Sensor: Hobo MX2301A and weather station WSC-11
   Moment: Bright warm days

4. Air temperature in the crown (°C) in relation to water loss (kg)
   Type: Comparison between air temperature in the crown and water loss per tree
   Sensor: Hobo MX2301A and above-ground lysimeter (scales)
   Moment: Bright warm days

Base measurements

5. Tree weight (kg)
   Type: Measurement
   Sensor: above-ground lysimeter (scales)
   Moment: Continuous in 5 min increments

6. Temperature in tree crown (°C)
   Type: Measurement
   Sensor: Hobo MX2301A
   Moment: Continuous in 3 min increments

7. Relative humidity in tree crown (%)
   Type: Measurement
   Sensor: Hobo MX2301A
   Moment: Continuous in 3 min increments

8. Humidity soil (%)
   Type: Measurement
   Sensor: in-ground soil hygrometer
   Moment: Continuous in 20min increments

Reference measurements

9. Weather data
   Type: Measurement

Values: Air temperature (°C), Relative Humidity (%), Wind speed (m/s) and direction, Global radiation (W/m^2)
Sensor: Weather station WSC-11 on nearby rooftop location at +5,2 NAP (6,2m above ground)
Moment: Continuous in 5 min increments

10. LA/Leaf area (m^2) and LAI/ Leaf area index of tree (m^2 /m^2)
Type: Calculation
Sensor: Terrestrial LiDAR scanner Leica P40
Moment: LiDAR scan on specific moment at the end of the growing season (20th of August 2024)

Tree selection
For the transpiration measurements the same tree species are used than for the cooling measurements - Platanus x hispanica, Tilia x europea and Betula pendula. These species are chosen as they are the most popular street trees in the Netherlands. In addition, two poplar cultivars are measured - Populus canadensis “Robusta” and Populus canescens “De Moffart”. The sort is chosen in accordance with research objectives of Eva Stache, who collaborated with the i-Tree 2.0 NL team on the transpiration research. The specific species and cultivars are chosen as they have been previously measured in the Urban Climate Arboretum project, which means further information on their cooling performance is available. All five trees are young trees and have been acquired from a tree nursery in the early spring of 2024. In July of 2024 the trees were between 4,3m and 8,8m tall.

Species	*Platanus hispanica*	*Tilia x europaea* “Pallida”	*Populus canadensis* “Robusta”	*Populus canescens* “De Moffart”	*Betula pendula* “Zwisterse Glorie”
Trunk diameter (DBH1) (cm)	7,8	7,4	9,6	8	9
Total height (m)	6,1	4,3	8,7	6,6	7,7
Height till living top (m)	6,1	4,3	8,7	6,6	7,7
Crown base (m)	2,5	2	2,5	2,5	2
Crown diameter N/S (m)	2,3	1,7	3,5	3,5	2
Crown diameter E/W (m)	2,3	1,7	3,5	3,5	2
Sides sun exposure (0-5)	5	5	5	5	5
% Missing crown	10	5	10	15	5
Condition	good/fair	good/fair	good	good	fair
Soil volume (m^3)	0,86	0,88	0,83	0,82	0,85

Table 6. Size and condition of the five trees that are part of the transpiration research, measurements taken on 1st of August 2024.

1.4.2 Measurement campaigns

Measurement set-up
The trees were placed in wooden planter boxes measuring 1370mm x 1160mm x 906mm. (fig. 39) These planters were clad internally with Air-pot material (Air-Pot® is the registered trademark of the Caledonian Tree Co. Ltd) on the inside for the various advantages this material offers for above-ground propagation. The root ball of the tree was furthermore fixed to the planter with lashing straps to prevent the tree from toppling over as long as it is not properly rooted in the planter. The planter boxes have permeable bases so that excess water can pass through in order to prevent the root area from becoming waterlogged.

Planter and tree are centered on the lysimeter to measure the weight change due to transpiration. To prevent atmospheric evaporation from the open planter box a tarp was wrapped around the planter during measurement campaigns. During a campaign the tarp was fixed to the side of the planter with glue clamps to avoid movement of the tarp. A soil hygrometer was buried into the soil at an equal distance between tree stem and planter edge and in the vertical center of the planter. The hobo logger was installed in the widest part of the crown in order to measure the maximum effect that transpiration can have on air temperature and humidity in the crown.

Measurement protocol
Transpiration measurements were undertaken on days with maximum temperatures of above 20°C in accordance with the KNMI definition of warm days (KNMI, n.d.). Days are furthermore

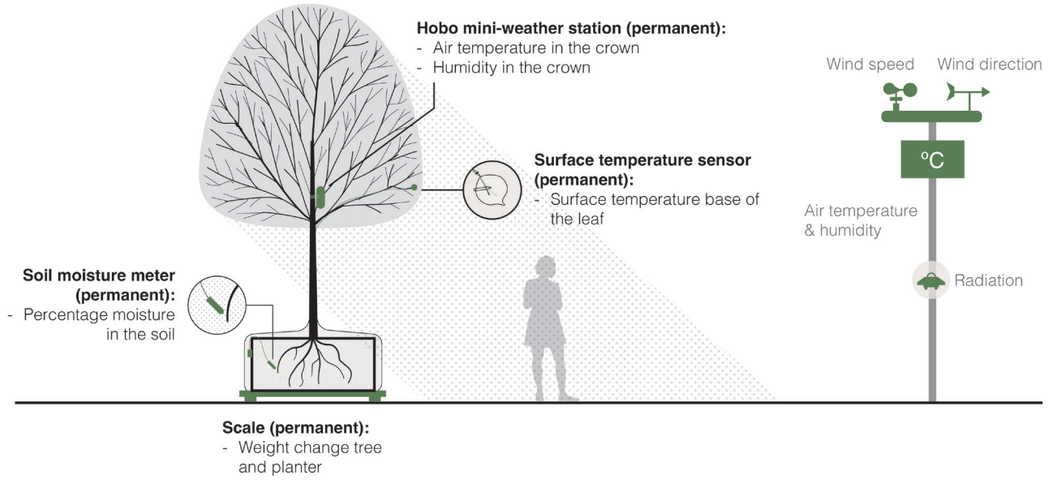


Figure 39. Illustration of the measurement set up for the transpiration research.

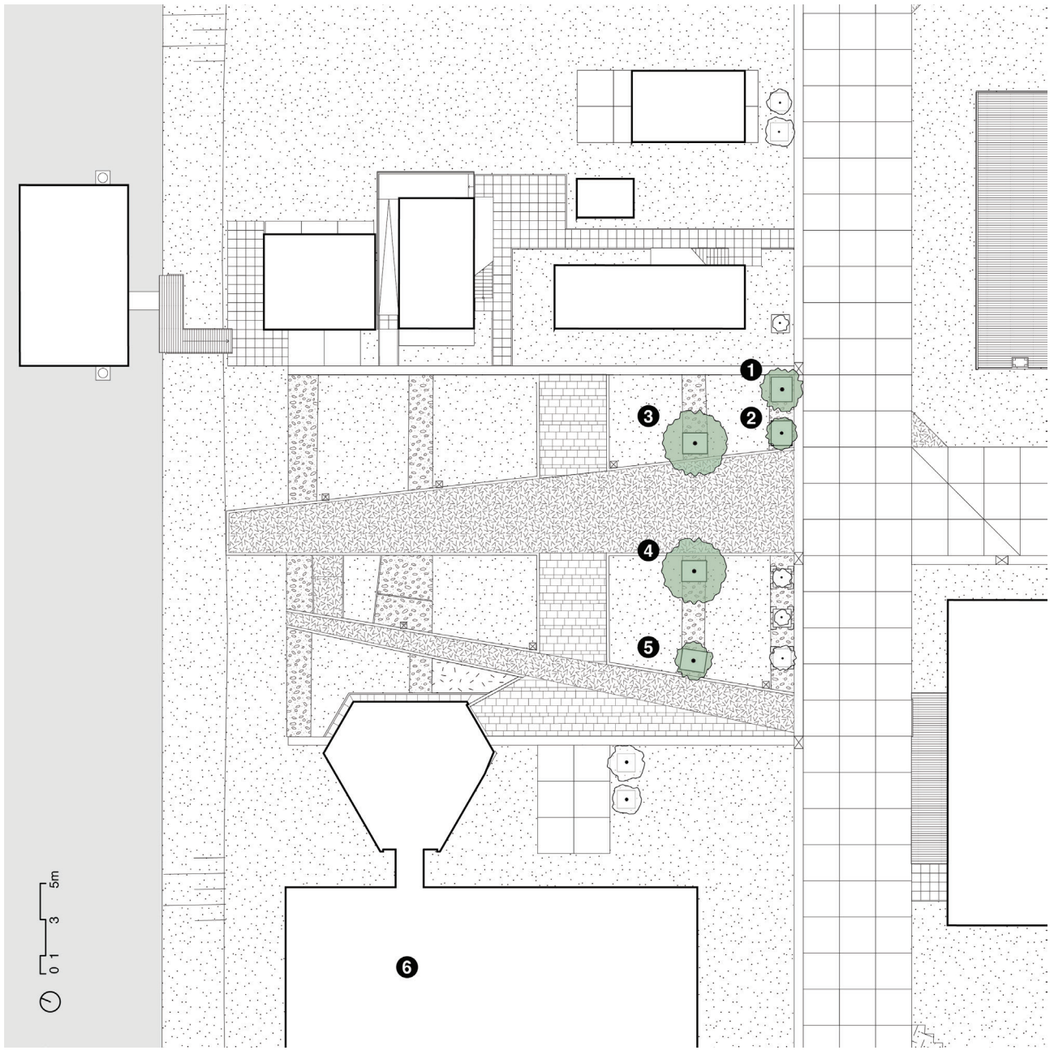
chosen with no precipitation and zero to minimum cloud cover (few high clouds are acceptable). This is done to assess maximum transpiration rates and cooling of each tree species. Measurements are held on three consecutive days that meet these conditions, to investigate how transpirations rate change through time, when warm weather conditions persist, and trees are not watered. A measurement is stopped after 72 hours or when trees stop transpiring water (when no more change in the weight of tree and planter is noted, during daylight hours).

On the day preceding the measurement the trees were watered twice to ensure that the soil was maximally saturated. In the morning the water bags around the tree stem were filled (75l for Tilia x europea, 150 l for Platanus x hispanica, Betula pendula, Populus canadensis “Robusta” and Populus canescens “De Moffart”). Water drips out of the bags during the days slowly permeating the soil. After sundown trees are watered a second time, as transpiration has now mostly stopped or significantly slowed down. Then trees were watered with a hose for three minutes each or until the water started dripping out of the planter. Water was then directly applied to the soil. After the water had mostly stopped dripping out the planter, the tarp was wrapped around the planter and secured with clamps. Small holes at the bottom of the planter allow for excess water to drain from the planter, to prevent the tarp from becoming so heavy that it hangs





Figure 40 & 41. Measurement set-up with tarps fixed around the planters, photo taken August 11, 2024.



1. Platanus hispanica | 2. Tilia x europaea “Pallida” | 3. Populus canadensis “Robusta” | 4. Populus canescens “De Moffart” | 5. Betula pendula “Zwisterse Glorie” | 6. Location weather station

Figure 42. Position of five trees, that are part of the transpiration research, on the heat square of the TU Delft Green Village; situation summer 2024.

on the ground and disturbs the working of the scales.

The next day measurement starts at sunrise. Measurements lasted for 72 hours, during which time trees and planters were not interfered with unless a tree stopped transpiring water. After three days or in the event of a tree stopping transpiring, tarps were removed and trees are watered immediately (see amounts above). Measurements were repeated when weather conditions were suitable again. Outside of the measurement windows trees were watered twice a week with additional water given when temperatures rose above 25°C.

1.4.3 Measurement setting

Location
The five trees, which are part of the transpiration research, are measured in Delft on the Green Village terrain. (fig. 43) The trees are located on the “Hitteplein” or heat square, the central square of the Green Village, where various measurements are undertaken concerning the thermal behavior of urban materials. Trees and tree planters are placed on narrow straps of gravel with street tiles and grass adjacent to the strips of gravel.(fig. 42) The heat square is surrounded by two-storey buildings to the east and west of the square and by a one-story building to the South. To the north of the square a canal is located.



Figure 43. Location of TU Delft with Green Village within it in the city of Delft.

Time frame
The young trees, which came directly from the nursery, were initially planted into pots on the Green Village terrain in March 2024. In the following months measurement equipment and sensors were installed on and around the trees. The transpiration measurements and auxiliary surrounding measurements were carried out in the summer of 2024 between the 18th of July and the 3rd of September. In total seven measurements were done.

Collaborations
The transpiration research is carried out in collaboration with Eva Stache, PhD researcher at the faculty of Civil Engineering and Geosciences. The installation of the trees, their maintenance and the measurement campaign were carried out jointly. All data gathered throughout the measurement campaign was shared among the two parties. Data evaluation is however done separately with differing focal points.

Measurements were carried out on the Green Village terrain located on the TU Delft campus. The Green Village is a field lab for sustainable innovation founded by the university and supported by the European Union and the province of South (The Green Village, n.d.). In the field lab researchers, private businesses, governmental organizations and citizens come together to research and validate projects and products centered around sustainable building, future energy systems and climate adaptive cities. The transpiration research is part of the research

Date	Activity
21.03.2024	Planting trees in pots
25.04.2024	Setting up scales and moving trees onto scales
04.07.2024	Installation hobo’s and placing tarps between scale and planter
29.07.2024	Installation surface temeprature sensors
07.08.2024	Installation soil moisture meters

Date	Measurement	Comments
18-20.07.2024	Test measurement	
27-28.07.2024	First measurement	Stopped due to unexpected rain
30.07-01.08.2024	Second meausurement	
11.08-13.08.2024	Third measurement	
18-20.08.2024	Fourth measurement	
28-30.08.2024	Fifth measurement	
01-03.09.2024	Sixth measurement	

Table 6. Overview installation activities for the transpiration research at the Green Village.

Table 7. Overview dates and duration of transpiration measurement campaigns.

portfolio concerned with research on climate adaptive cities. This meant that the resources and personnel of the Green Village were accessed for the installation and maintenance of the trees. The Green Village team furthermore shares weather data with the i-Tree 2.0 NL team, providing data captured by the weather station on top of the Co-creation center at the Green Village.

Leaf area and Leaf area index (LA/LAI) measurements were carried out by students as part of the TU Delft elective. Here students learn to obtain and work with point cloud data.

Summary
Knowledge of growth curves of urban trees makes it possible to estimate ecosystem services, such as cooling performance, up to their adult stage and for future climate scenario's. The main objective was to develop generic growth curves to cover the range of city tree species in the Netherlands, to allow reverse calculations from optimal cooling performances metrics determined for mature trees in WP1. To be able to calculate growth curves a large amount of tree data was necessary. Tree data, containing tree species, condition, planting year, growth site and location, was collected from the 8 participating municipalities. Only solitary trees were selected and divided in 8 age classes per tree species. The point clouds from the trees were extracted from 3 collection years, spanning from 2009 to 2022 (Actueel hoogtebestand Nederland, AHN2, AHN3 and AHN4) to be able to calculate growth curves. Growth curves for tree height and crown width in relation to age were created. Combining point clouds of trees with municipal tree data resulted in more than 6 million tree observations. Growth curves were successfully calculated for 60 species. The results of this workpackage were implemented in the Dashboard created in workpackage 3.

WP2 I **Tree Growth Curves and their Indicators**

Authors
dr. W (Wendy) Batenburg, dr. P (Petra) Schoon

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2.1 Extended problem definition

Urban planners, spatial designers and greenspace professionals require precise data and instruments to monitor and model the benefits of urban trees in relation to thermal cycles and urban microclimates. With these performances quantified, the urban forest can be managed better to develop and maintain these benefits, and to form a more integral part of plans for ‘cool’ neighborhoods and new urban developments. Knowledge on the growth of the tree is essential to model a timeline for the urban trees. For example, development of future scenario’s for planning purposes, policy goals and insight into progress on thermal regulation in urban areas can be very beneficial to get insight into climate adaptation of the city now and in the future. Tree growth formulas are used in the i-Tree Eco software, but here you are still unable to predict the growth of an individual tree species (UFORE methods; i-Tree, n.d.). I-Tree Eco uses these formulas to predict measurements and ecosystem services such as carbon storage, when incomplete datasets are imported into the software. Forecast is a function within i-Tree Eco, which calculated ecosystem services over time. However, results relate to the whole group of trees and not individual trees or a subset of the trees. In addition, the allometric formulas in i-Tree Eco are related to tree growth in the United States. Correction for a different continent and climate is possible, by adjusting the amount of frost-free days. This is mainly a correction for the number of days a tree is in-leaf and not for the difference in growth rate between different climates. For the Netherlands the growth rate of trees is known for only a few species particularly related to forestry, but not urban trees. Trees in a forest have a different growth rate compared to urban trees. They grow faster in height, due to competition of neighboring trees, they often have access to more fertile soil and are not restricted in their subsoil space for root development. The soil life, like beneficial mycorrhizal fungi, is much more prominent in forest compared to urban soil. All these parameters influence the growth rate of a tree, making allometric formulas from forestry unsuitable to calculate the growth of urban trees. This work package focusses on the development of urban tree growth curves of height and crown diameter with a good spatial variation across the Netherlands. The formulas can be used to develop a timeline for the ecosystem services of urban trees to discover their potential now and in the future. Height, crown diameter were calculated using aerial Lidar point clouds. The growth rate for 60 tree species was calculated using data from 8 municipalities. The growth formulas were implemented in de Dashboard created in work package 3.

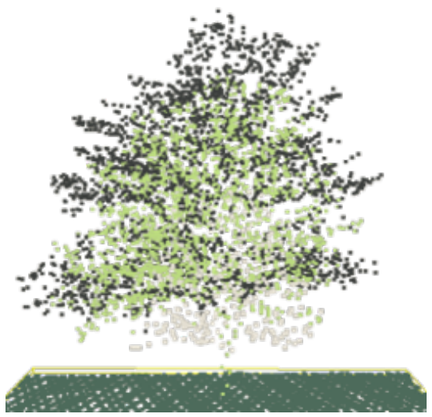
2.2 Materials and Methods

2.2.1 Overview values measured and calculated

Crown width and growth
To determine crown width and growth within the tree crown, a convex hull was fitted around the tree crown projection for every individual tree for each AHN period. The crown shape was then calculated as the convex hull of these points. Through the intersection of the centroid 8 axes were fitted in 4 directions: north-south, east-west, northwest-southeast, northeast-southwest. The width of the crown was measured as the average length over these directions. Crown growth was determined as the predominant change (fig. 44 & 45).

Tree height
The tree height was determined directly from the LiDAR point cloud data as the average of the 5% highest points of the last returns. Both the tree height and the crown width are given in meters.

A



B



Figures 44 & 45. (A) Open source LiDAR point cloud data for each tree was used to extract tree attributes such as tree height, crown width. This was done for each AHN period. (B) Convex hull fitted around a solitary tree. Growth within the tree crown was measured in 4 directions with predominant change.

2.2.2 Data Collection and Processing

Tree data was collected from the municipalities. After tree selection, the data was checked and only trees with complete datasets were used. Trees were selected according to several selection criteria (see next paragraph). Point clouds from LIDAR scans were collected from the freely available AHN-2, AHN-3 and AHN-4 (Actueel Hoogtebestand Nederland). The trees from the Lidar scans were clipped to the selected trees. From these pointclouds the maximum height of the trees was calculated. To calculate the crown width a convex hull was fitted for every tree. A convex hull is a polygonal fit of the crown of a tree. Data was checked and outliers were discarded. To develop growth formulas the planting year was fitted to the tree height and crown width and merged with the AHN capture date. An overview of the entire method is given in the flowchart in figure 46.

Municipal tree data selection
Tree data from 8 municipalities were collected. The participating municipalities are Den Haag, Rotterdam, Dordrecht, Groningen, Dijk en Waard, Amsterdam, Utrecht and Hendrik-Ido-Ambacht. This data consisted of the most recent tree safety inventory, including location of the tree, tree species and planting year. Trees of all ages were selected based on the 75 species in the TAT database. Only free standing trees were selected using analysis of the pointclouds. This means a tree crown should not touch or overlap another tree crown. Trees with a crown in close proximity to a building were also not selected. Data on surface area of the growth site was collected. Trees were subdivided into standing in pervious or impervious surface. Both types of surfaces were included in the study to analyze the effect of surface type on the growth rate. Due to pruning, storm events, diseases or age a tree can lose part of its height or crown. Therefore it is possible for a tree to show a decrease in growth rate. A limit to this decrease was set at -10% to prevent circumstances such as described from influencing the growth formulas.

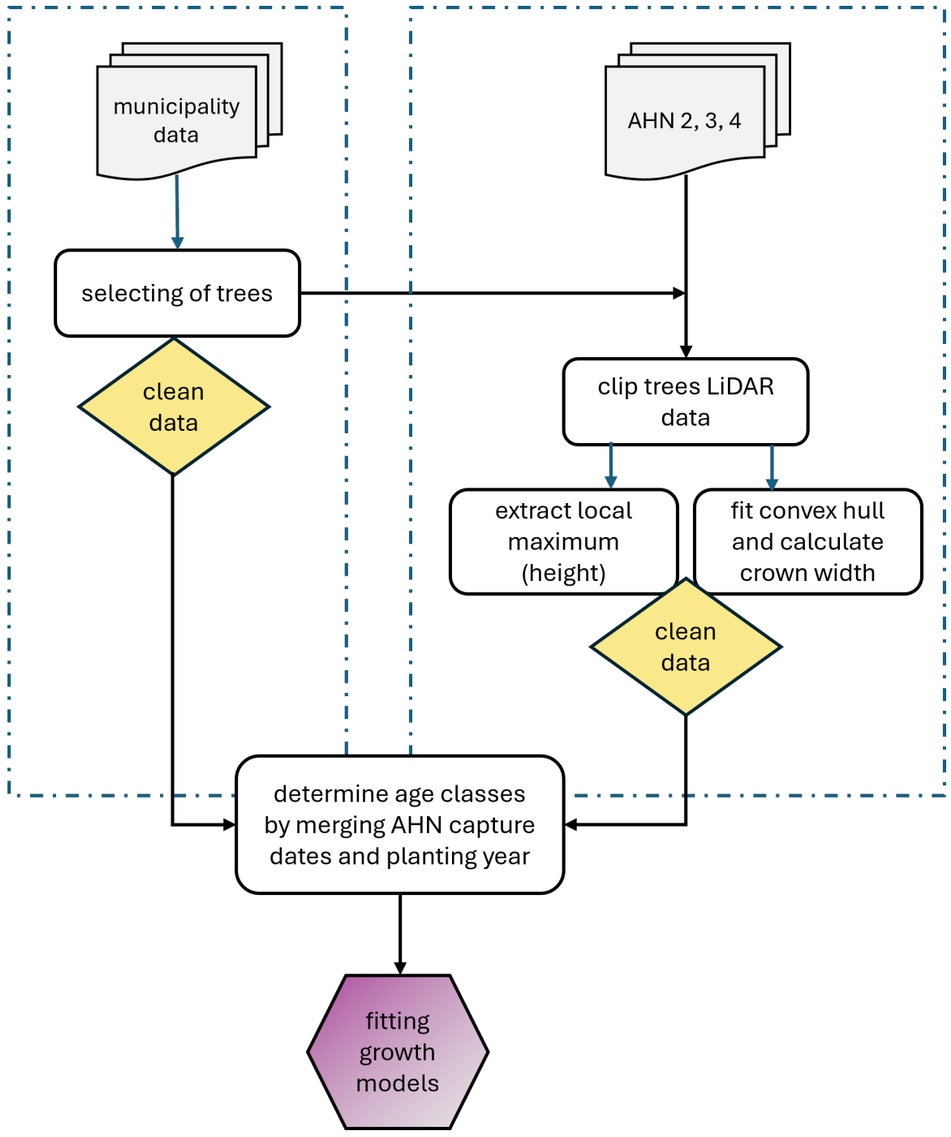


Figure 46. Flowchart showing the different steps of the methodology; data selection, LiDAR pointcloud analysis, combining and cleaning data, statistical analysis and tree growth modelling.

Extracting tree growth information from LiDAR data

AHN (Actueel Hoogtebestand Nederland; AHN, 2024) is a collaboration between national and regional governments in the Netherlands to provide digital height data for the Netherlands. The AHN consists of a digital surface model (DSM) of the entire Netherlands and is freely available since 1997. The height is measured with laser altimetry: A technique in which an aircraft scans the Earth's surface with a laser beam. 3D point clouds and grids were created from the measured heights (points). The temporal and spatial quality of this data has improved considerably over time (table 8).

For this study we used the point cloud data from AHN-2, AHN-3 and AHN-4. We decided not to use AHN-1 data due to the low and spatially inconsistent point density. AHN-5 was not yet flown completely during time of this study and was therefore not incorporated. The trees that were selected from the databases were extracted from the point clouds from each AHN dataset. We used a density-based segmentation clustering method to further remove outliers and noisy points (e.g. undergrowth). The segment with the highest density is then identified as the tree canopy.

Statistical analysis and tree growth modelling

Before combining the data retrieved from the LiDAR point clouds with that of the municipality databases, some additional cleaning steps were necessary.

- Height decreases in time -> this can occur due to several reasons, such as the quality of AHN-2, a tree that has been pruned or a tree that has been removed or fallen down and replaced by another tree. Trees with a height decrease of more than 10% were removed from the dataset.
- Number of axes not equal to 4: the growth of the crown is

AHN version	Temporal coverage range	Point density	Systematic / stochastic error	Height accuracy (68.2%, 95.4%, 99.7%)
AHN1	1997-2004	1 point per 1-16m^2 depending on acquisition year	5 cm / 15 cm	20cm, 35 cm, 50 cm
AHN2	2007-2012	6-10 points per m^2	5 cm / 5 cm	10 cm, 15 cm, 20 cm
AHN3	2014-2019	6-10 points m2	5 cm / 5 cm	10 cm, 15 cm, 20 cm
AHN4	2020-2022	10-14 points per m2	5 cm / 5 cm	10 cm, 15 cm, 20 cm
AHN5	2023-2024		5 cm / 5 cm	

Table 8. Overview of the differences in AHN versions (AHN, 2023)

measured over 4 axes. Sometimes there is not enough data for having four axes. These trees were removed from the data.
- shape of convex hull: the quality of the data depends on how many points can be fitted on the tree. We suspect that trees with highly elongated convex hull are trees that could not be fitted correctly and might be the result of overlapping crowns from neighboring trees. This was calculated based on the roundness parameter (calculated in QGIS), and was pseudo-arbitrarily set at 0,5 Trees that did not meet this requirement were excluded from the data.

The LiDAR data was combined with data from the municipality tree databases with the planting year, condition and imperviousness as the most important information. This resulted in more than 6.000.000 tree observations. However, we did not take into consideration the trees that lacked a planting year in the database. We further made a selection of trees that were higher than 3 meters. Using the LiDAR monitoring year and planting year, observations were subsequently divided into 8 age classes (table 9).

Not surprisingly, there is high variability in both three height and crown diameter per species and age class. To fit the variations in tree height and crown width over each time period, we used a second-order polynomial model ($y = \beta0 + \beta1X + \beta2X2$), which gives overall the best fit when data is not linear. However, in some cases the fit was hampered by bias in the data, mainly due to insufficient data points, erroneous information or missing updates in municipality databases.

All statistical analysis and modelling was completed using R Statistical Software 4.3 (R Core Team 2023).

Age class	Age period (in years)
1	<14
2	14-23
3	24-33
4	34-43
5	44-53
6	>54

Table 9. Classificatie of tree age

2.3 Results

The resulting dataset contains 177.302 observations, with 28 trees on genus level, 42 trees on species level and 20 trees on cultivar level (see Appendix 3) After cleaning up the data 164.837 trees remained in the dataset. The results for tree growth in tree height and tree crown width for six different tree types on either species or cultivar level are shown in figures 47 to 52 and figures 53 to 58, respectively.

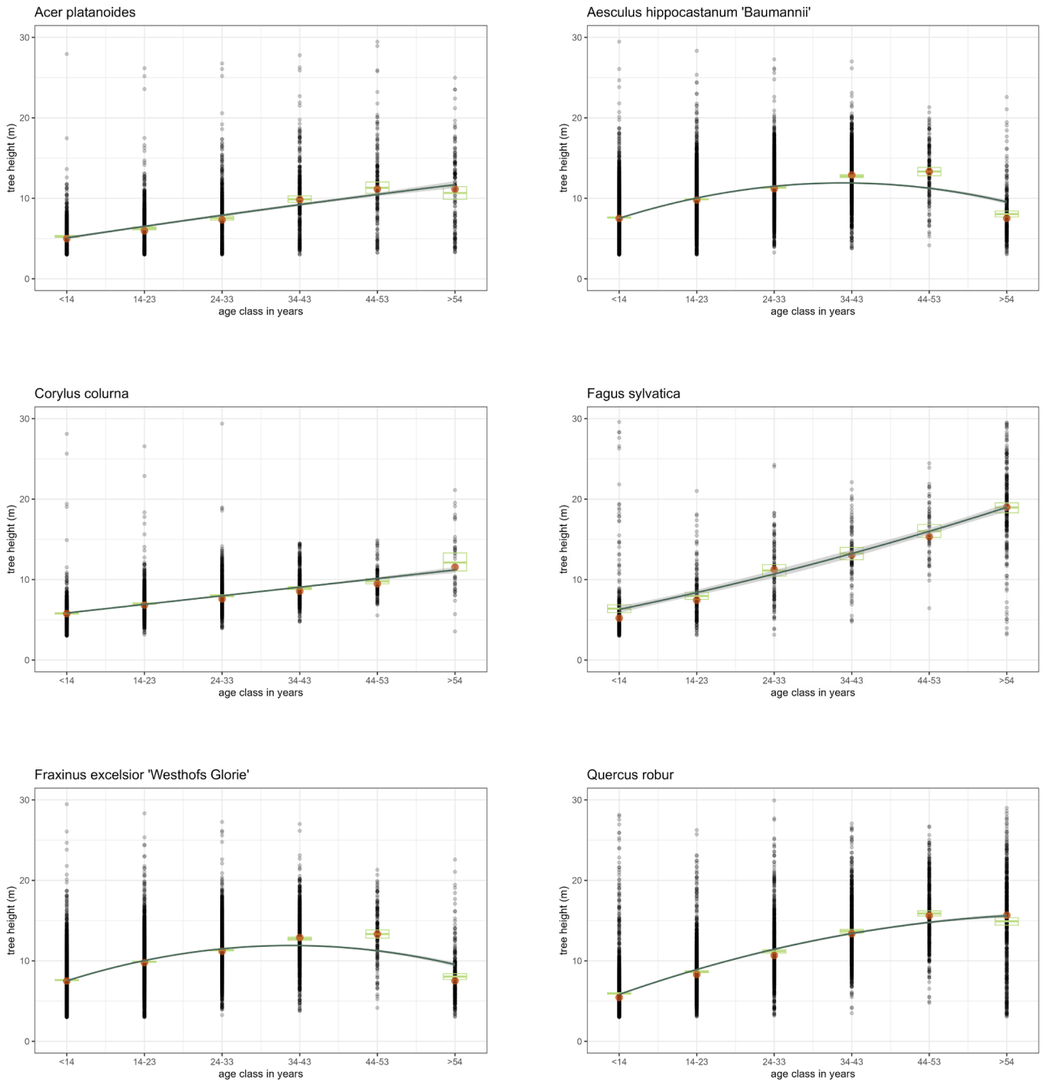
Tree growth

Examples of tree growth are described for 6 species or cultivars, all trees of the first order, which can reach a height of more than 12 meters. The growth curves at the level of cultivar, species or genus are described in Appendix 2. *Acer platanoides*, *Aesculus hippocastanum* 'Baumannii' and *Corylus colurna* have a similar growth rate for tree height. The growth of the crown width of *Corylus colurna* has a slower rate and lower maximum in the highest age class (>54 years) than the other two. *Acer platanoides* and *Aesculus hippocastanum* 'Baumannii' show a similar growth rate for the crown width. *Fagus sylvatica* and *Quercus robur* have the highest growth rate of tree height. *Fagus sylvatica* does not show a decrease in growth rate towards the highest age class, whereas the growth of *Quercus robur* decreases from the age class 44-53 years onwards. The crown width grows in a similar fashion for *Fagus sylvatica* and *Quercus robur*, although *Fagus sylvatica* reaches a wider crown at the highest age class. The growth in tree height for *Fraxinus excelsior* 'Westhof's Glorie' is not as strong and slows down from the age class 34-43 years. Crown width however, seems to increase at this age and older. It should be noted that the variability of crown width for *Fraxinus excelsior* 'Westhof's Glorie' is high at the older age classes.

Effects of location in the Netherlands

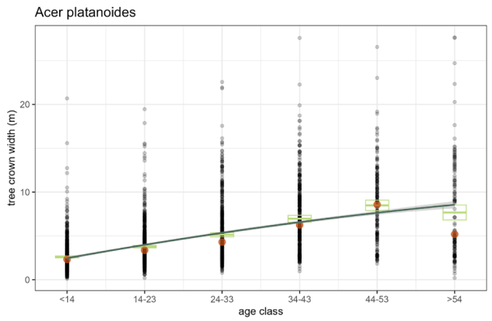
The results show that the growth rate of certain species and cultivars is possibly affected by additional factors, such as location and infiltration type. For example, figures 59 to 65 show the tree height growth for the different Dutch municipalities

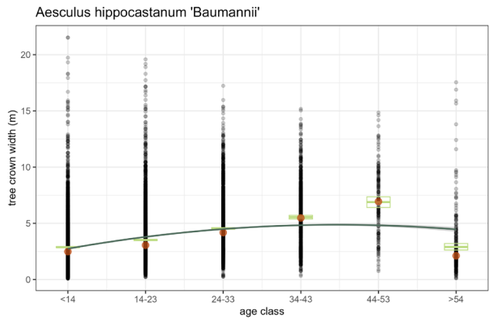
Growth curves Tree height
Various species

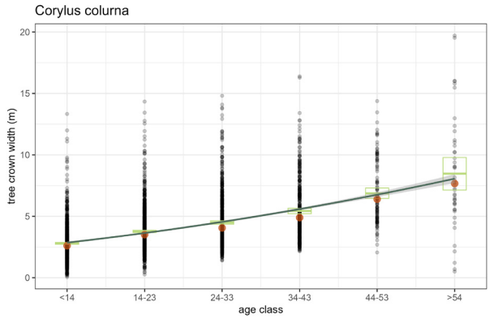


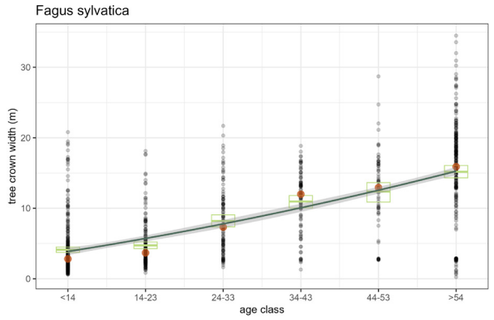
Figures 47-52. Examples of the modelled growth rates in tree height for six tree species and cultivars.

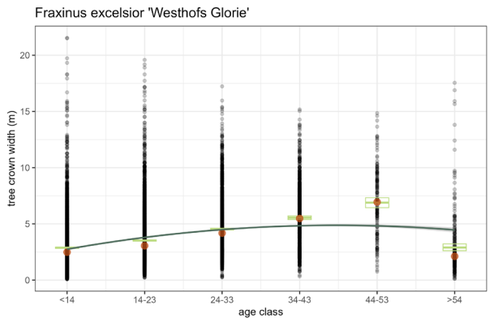
Growth curves Crown width
Various species

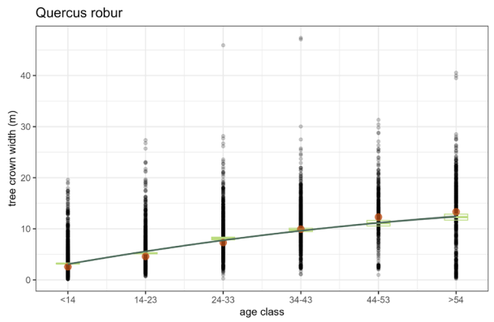












Figures 53-58. Examples of the modelled growth rates in crown width for six tree species and cultivars.

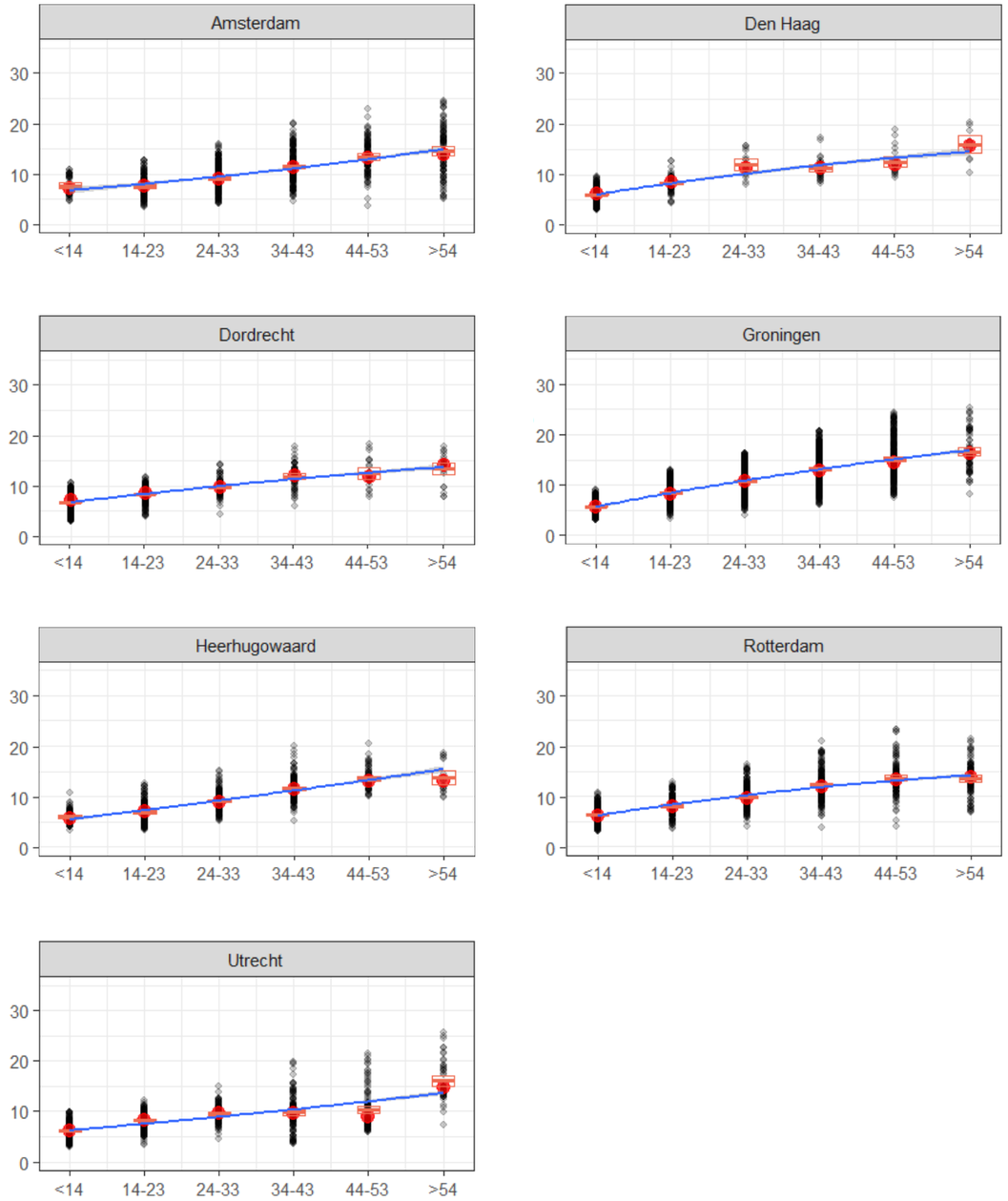
for the *Fraxinus excelsior*. Although a statistically significant difference (5% level) between municipalities was observed, this statement does not hold due to sample bias, information bias and confounding. Moreover, the national coverage of the municipalities in this study is not optimal. For further study it is recommended to expand the coverage by including municipalities from a wider range in national climate and soil types.

Effects of infiltration type

The tree data from the municipalities contains information on the infiltration type of the growth site of the trees. This information could be used to study the potential effect of (im)perviousness of the growth space on growth. For example, figure 66 to 68 show that there is indeed an effect for three tree species, *Tilia cordata*, *Acer platanoides* and *Corylus colurna*. Trees grown in pervious tree site have a higher growth rate of tree height than trees in an impervious tree site. Statistical testing has not been performed due to the possible biases. Considering the observations, further research is important to study this effect in more detail.

Growth curves tree height per municipality

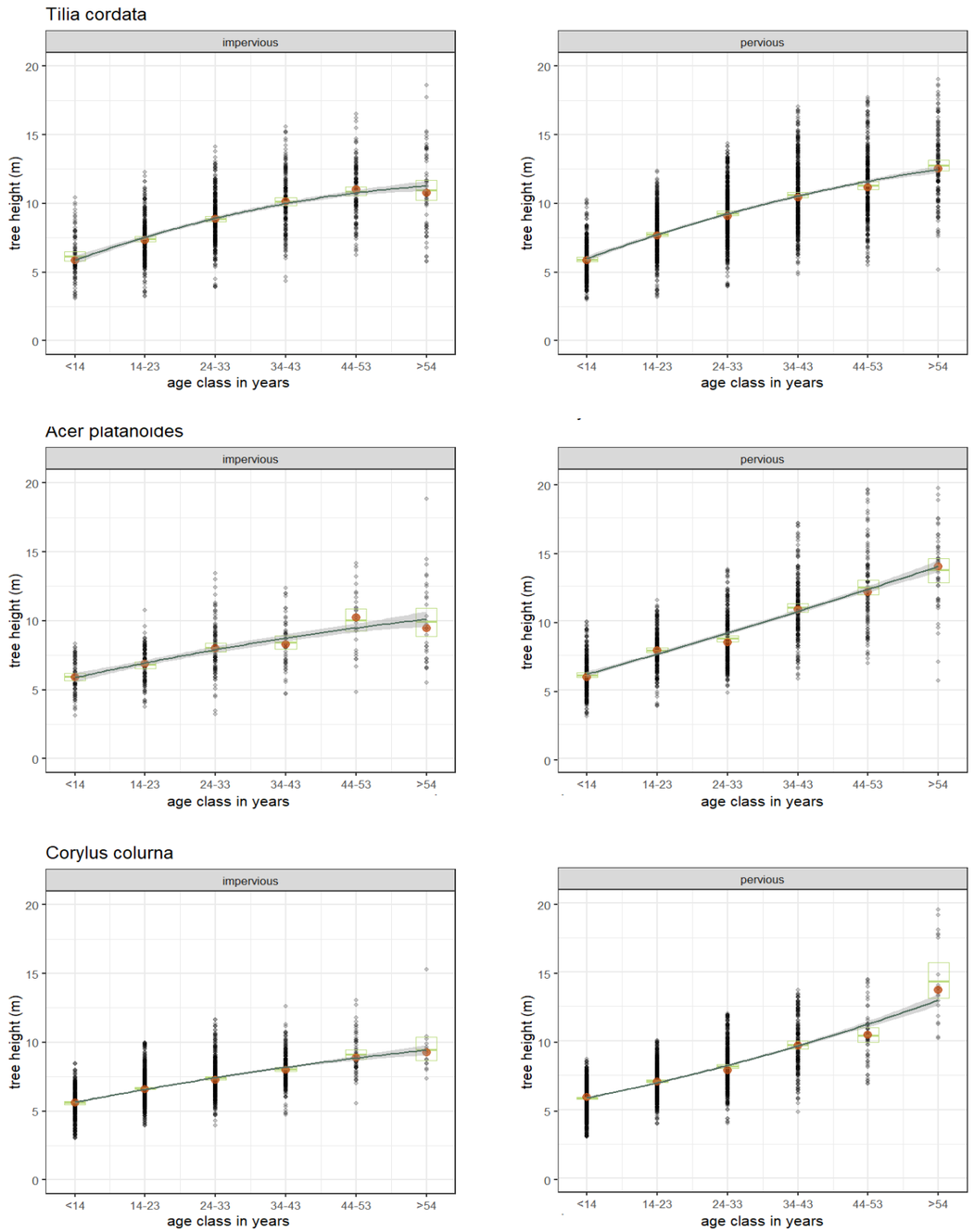
Fraxinus excelsior



Figures 59-65 Modelled tree height growth rates for Fraxinus excelsior for 7 of the participating municipalities. x-axis: age class, y-axis: tree height (m)

Growth curves tree height per infiltration class

Various species



Figures 66-68. Modelled tree height growth rates for Tilia cordata, Acer platanoides, and Corylus colurna, showing higher rates in a site with higher infiltration potential (pervious).

2.4 Limitations

Although data quality and data consistency is of vital importance to come to reliable tree growth models, there are some limitations. The limitations are related to all factors that affect tree growth such as differences in growth site, data which is not updated over the years (unrealistic age of *Pyrus calleryana* ‘Chanticleer’, fig. 69), climate related events such as storms, pest and diseases, light availability, but also a low number of trees in a certain category makes the formulas less reliable. We can detect several forms of bias in the merged data. For instance, the tree height and crown width in older age classes are decreasing in stead of increasing (figures 70 to 72), a trend that is visible at almost all tree levels (genus, species and cultivar) (see also figure 47 to 52). It is still possible that this is the reality of how an urban trees grows.

We have strong indications that a lot of the bias in the data is caused by mismatches and erroneous information in the municipality database, such as:

- Databases are not complete and/or current;
- Tree was replanted after removal, but not updated in the database, causing an erroneous observation of the tree age and possibly tree species;
- Tree species/cultivar was not introduced yet 50 years ago, therefore observations are restricted in the younger age classes;
- Tree species/cultivar does not grow older than 30-40 years;
- Between municipalities there is variation in tree species due to a difference in preference for certain species.
- Variations in pruning through time.

To prevent bias it is highly recommended to incorporate domain knowledge input from tree experts to validate the unexpected results from trees in the databases.

Pyrus calleryana “Chanticleer”

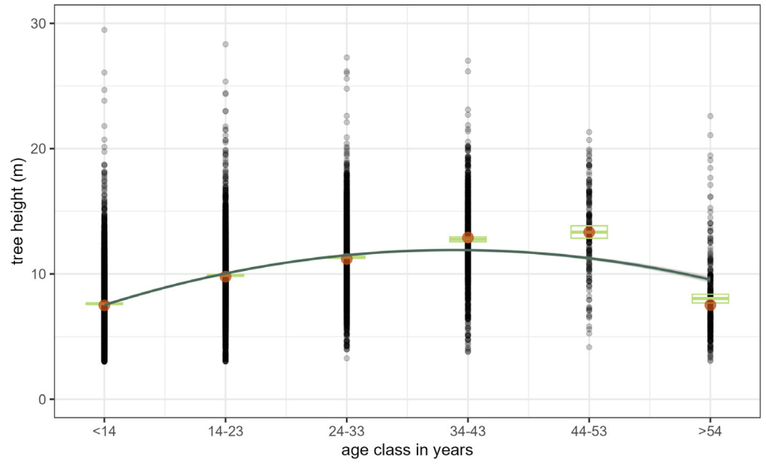
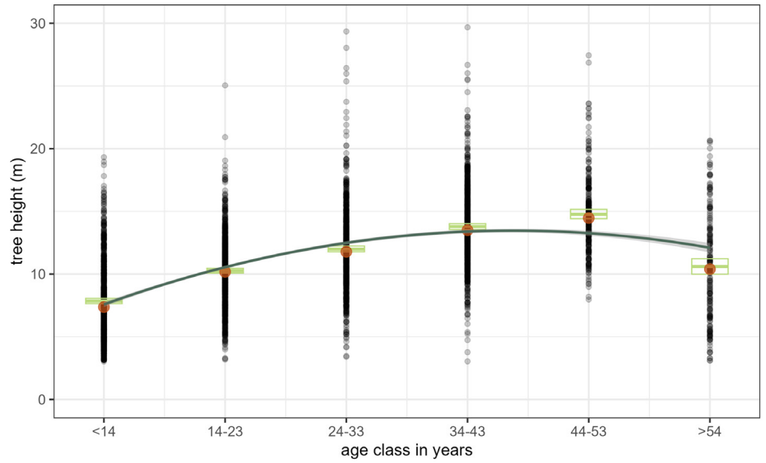
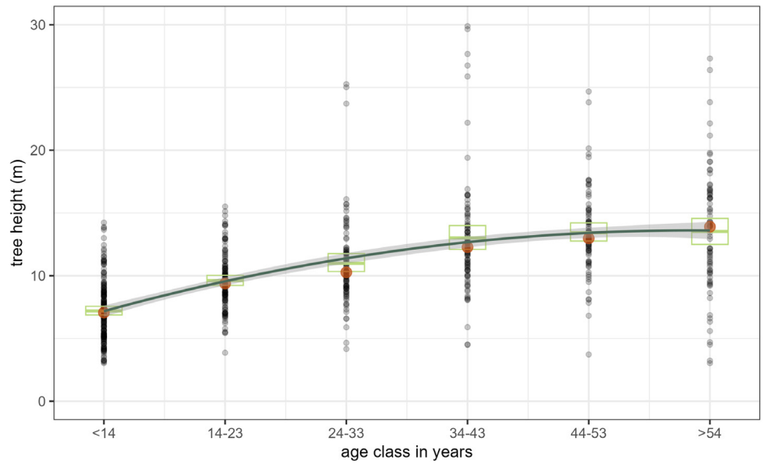


Figure 69. Bias causes difficulty in modelling tree growth for Pyrus calleryana ‘chanticleer’.

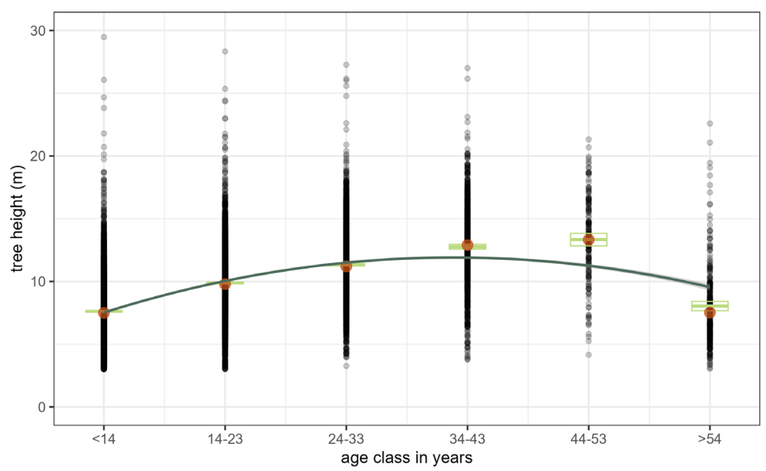
Betula pendula



Betula pubescens



Betula utilis “Doorenbos”



Page 108, Figures 70-72. Bias in the data can greatly hamper the reliability of the modelled growth rates in certain species and cultivars. One problem that occurs quite often is the lower than expected heights (in this example) in the last age classes, here visible for Betula pendula and the lack of observations in higher ager age classes, here visible for Betula utilis ‘Doorenbos’.

2.5 Outlook

The results can be effectively used to model the ecosystem services of urban trees in time. This outcome can also be used in countries with similar climate to the Netherlands. The growth formulas are incorporated in the scenario-tool of the dashboard of workpackage 3. The goal is to include the growth rate of these 60 species in the i-Tree Eco software. This makes the data available for a large group of researchers. I-Tree Eco can use this to more ac-curately calculate ecosystem services of trees in a similar climate zone. The developers of i-Tree Eco, Davey Tree, are interested in the growth formulas to include them in the i-Tree Eco software. However, it will take time, effort and funds to incorporate it in the software. Fur-ther studies can show the impact of pervious of impervious tree planting site. Including trees from more cities can improve the significance of the growth rate of older trees. These are important data because infiltration, soil and growth site are essential predictors of the growth rate and health of an urban tree. In addition, ecosystem services increase exponen-tially when a tree reaches a certain age. It would be crucial to discover at what age this oc-curs for management and awareness of the benefits of old trees.

Summary
The technical potential of I-tree 2.0 as a tool and the integration of cooling performances of urban trees alone do not respond to the needs and values of the relevant stakeholders in the Netherlands. Thus, WP3 aims to develop a dashboard, methodology, policy draft together with the relevant stakeholders to strengthen the planning, design, and management of urban green spaces. WP3 uses a set of data collection from interviews, co-design sessions, fieldwork, and a workshop to offer innovative interventions that harness WP1 and 2 results through systemic design, speculative design, and participatory design.

Phase A, the first stage of WP3, focuses on the values, experiences, and needs of stakeholders to map stakeholder journey in urban green space by analyzing the interviews. Phase B analyzes co-design sessions to prototype dashboard and design methodologies. In addition, field trips contributed to further iterations of the dashboard design. As part of phase C, policy needs and shortcomings are identified in the workshop to develop a policy draft.

Of the result of Wp3 is a operational Dashboard, 8-step Methodology, and Procurement Draft with practical recommendations for strengthening the position of urban green spaces. These methodologies with the integration of cooling data and growth curve of trees provided by WP1 and WP2 provides multiple design interventions which respond to the needs, values, and wants of stakeholders.

WP3 | **From Science to Life**

Authors
dr. G (Gül) Aktürk Hauser, dr. RA (Rebecca) Price

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3.1 Extended problem definition

I-tree is the existing peer-reviewed software suite of the USDA Forest Service that provides urban and rural forestry analysis and benefits assessment tools (i-Tree 2.0-NL). The freely available software estimates the values of trees and quantifies their ecosystem benefits which helps decision-makers to set priorities and improve the management of forestry. The software suit requires inventory import of data on urban trees which is currently missing, incomplete, or inconsistent in the case of the Dutch cities. It does not provide baseline data on local climate and the characteristics and performances of tree species in the Netherlands. Moreover, it is suitable for expert users (tree consultants) to provide technical support, but it is not user-friendly for all the key stakeholders (architects, designers, urban planners, tree nurseries, municipal staff) to incorporate into their work processes.

I-tree is either used by only some of the stakeholders (tree consultants) or is used in combination with other available tools, software, and methods such as Tree effect analysis (BEA), Boommonitor by Norm Instituut Bomen. The incomplete and inconsistent data derived from diverse data sources does not provide a comprehensive overview on existing urban green infrastructure which makes it difficult to forecast future scenarios of urban trees and their ecosystem benefits. It is difficult to bring together data on urban trees which are analyzed and represented in different formats (spatial data, analytical, costs) for stakeholders to have a “shared language” for possible collaborations and to enhance the urban forest and greening management.

In addition, the ecosystem benefits of trees are not adequately quantified and the social values, such as human health and well-being, are not included in the assessments of I-tree software suits. Monetizing the value of urban trees undermines the true value of these social benefits. The municipal stakeholders are willing to take actions to communicate the ecosystem benefits of urban trees. Thus, there is a need for informing communities and other stakeholders about urban greening decisions and incorporating their voices.

Aside from the technical constraints, there is a need for the creation of an urban forestry masterplan (UFM) in consultation with the key stakeholders to support the monitoring the dynamic changes in urban forestry. This would consider the characteristics of the existing urban forest of the cities and their future urban green targets, ambitions, and visions as well as ways to enhance their urban forests. UFM would also advocate long term contracts with nurseries to forecast future demands and trends. Adopting project-level targets for urban green growth in procurements can contribute to the local efforts of urban greening. More clear guidelines, frameworks, and policies are needed for strengthening the position of urban green in the cities.

There is a broken or sometimes missing link between the different stakeholders working in the forestry field in domains of planning, design, management, and policies (fig. 73). The different

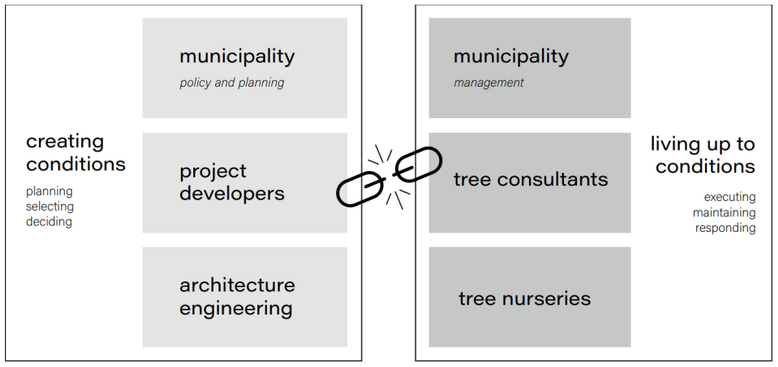


Figure 73. Lost connection between different domains: those creating conditions and those living up to conditions. From “The Future of the Urban Forest: Exploring the systemic granularity of the urban green domain to navigate towards a new paradigm,” by S. Keizer, 2023, Industrial Design Engineering, Delft, TU Delft, master’s thesis. Reprinted with permission.

workflow, values, and interests of stakeholders make it difficult for a meaningful and long-lasting collaboration and cooperation in the field. Therefore, there is a need for raising awareness in different domains of the field through cross-disciplinary and -sectoral collaboration. For this reason, the role of WP3 is to begin connections and amplify existing connections between urban forestry, landscape architecture, urban planning, and architecture and strategic design. It also acts as a mediator between WP1 and WP2 by applying resultant data and models (cooling data and growth curve) as well as contributing to their results (design interventions).

The starting point of the WP3 was to synchronize the potential of the software with the needs and values of the key stakeholders within the consortium. However, only technological innovation development does not adequately address complex and multi-faceted problems related to urban forestry and greening. For a transformative impact of design in urban forestry and greening, WP3 takes a design-led approach to understanding a “system” problem, often being ill-defined, existing at multiple scales, and being interconnected yet interdependent (Irwin, 2018). Multi-levelled meaningful, inspiring, and innovative interventions (Morrison et al., 2022) can situate these complex problems within small and manageable components to develop tailored solutions for adaptation. Therefore, it focuses on the development of a dashboard, methodology, and a policy draft by combining a set of data and using systemic design, speculative design, and participatory design to contribute to this fragmented problem.

Aligning technological innovation with stakeholder expectations and ensuring their alignment is the most significant contribution of this work package in addition to building connection, communication, and trust between diverse stakeholders. It does so by regular updates, feedback loops, and ideation sessions to build trust among stakeholders in order to avoid pushback from stakeholders that may be confronted during implementation phases.

3.2 Materials and Methods

To address the key research objectives, this research applied qualitative methods of systemic, speculative and participatory design and a combination of a set of primary and secondary data sources. The reason behind the use of combined methodologies is to have a broader understanding of the complex problem of urban greening and to come up with multilevel design interventions for designing, monitoring, and policy-making in urban green sector for all stakeholders. This research used the combination of these design methodologies which resulted in the design of dashboard, 8-step methodology, and procurement draft.

3.2.1 Systemic design

Systemic design as a set of methods and methodology combines systemic thinking and design practice to address complex issues to drive transformation (Swat, 2019). Systemic design as a methodology follows the steps: framing, listening to the system, understanding the system, envisioning desired future, exploring the possibility space, planning change process and fostering transition (Jones & Ael, 2022).

The first phase frames the problem scope of the current system to understand the relationships and influencing dynamics driving it. Designers identify and frame the problem within a broader context in the beginning of the design process that stimulates the emergence of design concepts. Second, ‘listening’ to the system is used to understand human interaction within the system by conducting participatory research, including interviews, workshops, and fieldtrips. Third, understanding the system refers to locating the leveraging points, hereon refers to opportunity areas, with the high potential of systems change. Fourth, it focuses on mapping possible futures envisioned by system stakeholders defining total system value. Fifth, we investigate the most influential design intervention for a potential for system change. Sixth, planning change process takes the abstract model to make it more actionable and concrete by providing tools for delivering the system value. Lastly, fostering the transition leads to the implementation of the design interventions for the system change.

3.2.2 Speculative design

Speculative design is used to imagine future possibilities and scenarios and generate new ideas. It is not conducted to have definitive answers but rather to provoke ideas to generate questions that help creative ideas to run. According to the diagram redrawn by Dune and Raby (Dunne & Raby, 2013), it breaks down 3 different possible futures, plausible futures, and probable futures according to the likelihood of their actualization. And preferred version lies in the middle of probable and plausible scenarios.

Speculative design is employed to ask, “what if?” question in urban design and policy. We ask as a means to open up new possibilities:

- What if we could adapt I-tree according to the needs, values, and work processes of the stakeholders?
- What if we planned cities by designing green spaces first?
- What if we had green clauses incorporated in the procurement of urban (re)development projects?
- What if citizens were informed by decisions and have a saying in these decisions?
- What if cities were designed as forests?
- What if we were the designers of our cities?
- What if trees were given a voice?

3.2.3 Participatory Design

Participatory design (PD) is a design methodology which involves future users of the design as co-designers in the process of design and incorporates their values in the design process and outcome which leads to prototype for a product, service, or

design space (van der Velden & Mörtberg, 2015). Unlike user-centred design, the user in the participatory design is active in the design process (Leith et al., 2022). In the co-design and workshop sessions, participants were asked to collaboratively work in an iterative design process, with continuous feedback and refinement. Participants especially helped the assessment of prototypes and testing of the prototype and suggested improvements for ensuring the final design meets the needs of end-users.

Data collection and analysis

A set of data, including semi-structured interviews, co-design sessions, a workshop, and field trips was collected between September 2022 and July 2024. We conducted thirty-seven (37) semi-structured interviews, two (2) co-design sessions, and four (4) field trips with all the stakeholders, involving municipalities, researchers, nurseries, tree consultants, and architecture and engineering firms. Table 11 provides insight into methods, objectives, foci, language, quantity and format, number of participants, number and representation of sectors, duration, and activities of such events. The research question addressed by each of these four methods is different as well as the configuration of the stakeholders (table 11).

While some of these events (co-design session 1 and workshop) occurred in English, some was held in Dutch (co-design session 2) to ensure municipal stakeholders communicated effectively and easily in their mother tongue. When English speaking participants are involved, the language of the event was held in English and in their absence the event took place in Dutch. The reason behind this decision was to make the events inclusive as much as possible for the participants.

Interviews, co-design sessions, field trips, and the workshop were video, and audio recorded, and data derived from these methods were safely stored. The content from these recordings were transcribed and translated to English. The unstructured format was later adopted in the final phase of the project for the follow-up conversations as a check-in to validate assumptions and test proposition with consortium members. A thematic analysis which is a method of analyzing qualitative data was conducted to identify common themes, topics, and patterns identifiable (fig. 74).

Secondary sources such as concept nota from Marine terrain (Amsterdam), explaining the new program for the site, municipality reports and green visions, relevant literature, and websites are reviewed in understanding the broader context. In the analysis of the existing public procurements (open to public), websites such as TenderNed, are reviewed to reveal a lack of "green clauses" in the development of the public spaces.

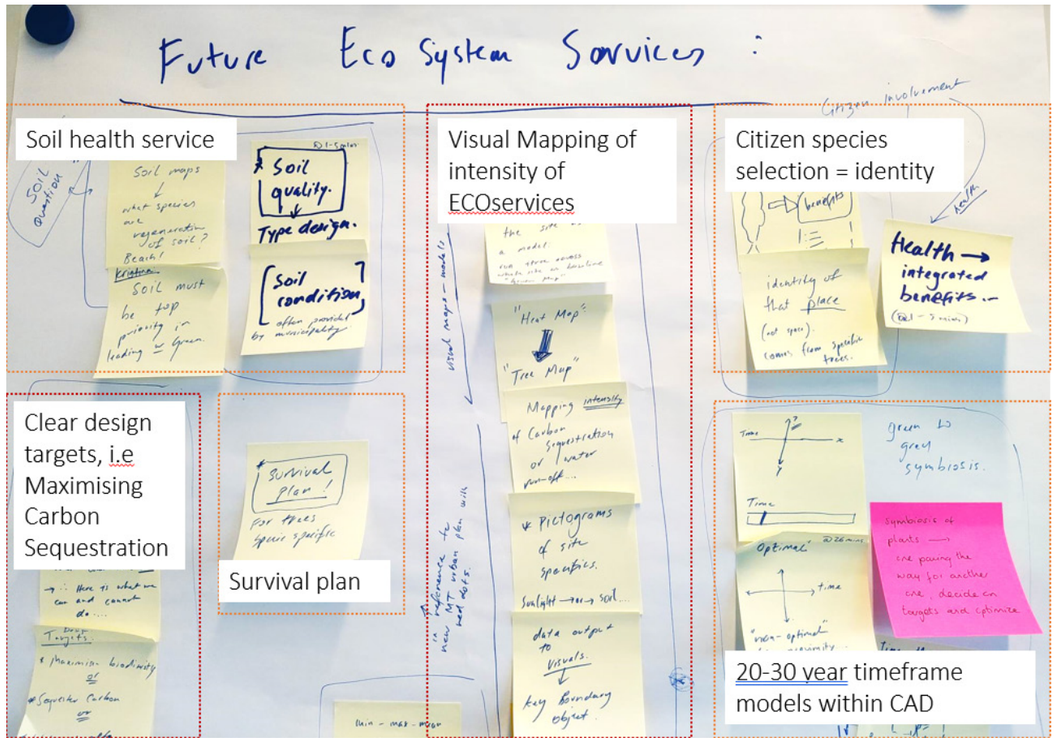


Figure 74. Mapping the stakeholders' views on the missing features and data for incorporating future ecosystem services into design processes from the result of co-design session 1.

Methods	Objectives	Focus	Language	Quantity and Format	No of Participants	No and Representation of Sectors	Time	Activities
Semi-structured interviews	Stakeholder journey mapping Locating five opportunity areas, including dashboard	Overview of current workflow of consortium partners (current tools and places with lack of green space), challenges in greening the city (and keeping it green), and opportunities, expectations, feelings, ideas, and doubts about the software.	English Dutch	37 interviews (17 online and 20 face-to-face)	28 interviewees 7 architect &engineer 8 nursery staff 3 tree consultants 10 municipal officers	All internal and external stakeholders (Architecture and engineering firms, tree nurseries, tree consultants, municipalities, and researchers)	30-90 minutes	Questions on the - Challenges of making cities green - Challenges of keeping cities green - Places of concern - i-tree tool - Opportunities
Co-design sessions	First concept design of dashboard	Co-design session 1 —spatial transformation: Overview of current workflow of architects and designers and first iterations of conceptual spatial design for urban green spaces.	English	1 (face-to-face)	11 participants 6 architect& engineer 2 tree consultants 3 academics	3 architecture and engineering firms 2 tree consultancy firms 1 university & research institution	3 hours	Working in 2 groups for a new design proposal for urban green in Marine terrain. - What would “leading with green” in design look like?
	First concept design of dashboard Validation of stakeholder journey map	Co-design session 2 —The future of the urban forest: Green targets and challenges of each municipality, informing municipalities on the software and Urban Forestry Master Plan of London and Birmingham, potential integration for the software	Dutch	1 (face-to-face)	11 participants 1 tree consultant 6 municipal officers 4 academics	5 municipalities 1 tree consultancy firm 1 university & research institution	3 hours	Discussion on current goals for urban greening and what is required for setting targets and how I-tree software can contribute to the setting targets
Field Trips	Second concept version of dashboard	Iterative sessions to build the nursery process and Identify opportunities for integrating software	English Dutch	4 (face-to-face)	11 participants 8 tree consultants 3 academics	6 tree nurseries 1 university& research institute	Contact hours with stakeholders 2 hours	Discussion on tensions, needs, and challenges of the market
Workshop	Validation of policy draft Aligning the objectives of policy and design interventions	Develop the drafted tender format further with the inclusion of green clauses for increasing ecosystem benefits of urban trees	English	1 (face-to-face)	11 participants 4 architect& engineer 2 tree consultants 3 municipal officers 2 academics	2 architecture and engineering firms 1 tree consultancy firm 3 municipalities, 1 university& research institute	3 hours	Working in 2 groups. Post-it notes in different colors: - pink- when tender is leading, explain the weak points of design - yellow- when design is leading, explain the weak points of tender - white- tender and design are both leading, explain any weaknesses and strengths
Unstructured Interviews for follow-up	Alpha version working prototype of dashboard	Integrate the input of stakeholders based on the tests with them • compare scenarios in graph view • i-Tree API • real time scenario creation and modification • growth curves and cooling data from I-tree 2.0 • include different projects (Oranjeloper, Selwerd, and Handelsplein)	English Dutch	9 interviews (face-to-face)	18 interviewees 3 architect& engineer 5 tree consultants 10 municipal officers	2 architecture and engineering firms 2 tree consultancy firms 5 municipalities		Test design - Explore the dashboard: https://stadsbosportfolio.eu.pythonanywhere.com/map. - Write down what you think you can use this dashboard for? What situation/conversation you encountered? - What kind of objectives would you like to set for the Oranjeloper project, at the moment it is still a ‘neutral’ dashboard without management - Recommendations on the dashboard - What is a must have for the coming period?

Table 11. Methods conducted as part of work package 3 in the development of the several outcomes that are explained in order.

3.3 Results

The results of semi-structured interviews were visualized to map a stakeholder process journey and locate five opportunity areas for public urban green. The stakeholder process journey is used to capture the interrelationships, dynamics, and opportunity areas of the system in four domains, to inform challenges and opportunities.

The first phase frames the problem scope of the current system of urban greening to understand the relationships and influencing dynamics driving the system. Thus, the process of urban development phases was sketched, including the phases of initiative, feasibility, realization, and exploitation and maintenance. Then, the domains of nurseries, tree consultants, municipalities, and architects were incorporated into this sketch along with citizens, landscape contractors, project developers, and execution organizations by expanding their roles within the scheme. The interlinkages and interrelationships between these different domains become visible in the journey map (fig. 75).

For instance, municipalities guide the initiation phase and then architects lead the design process during the feasibility phase when tree consultants also come into the role. There is little to no interaction between the tree consultants and architects to work together in the selection of trees and vegetation in the design phase. All these stakeholders, including tree nurseries, tree consultants, and architects work rarely together and together with municipalities. Similarly, tree nurseries come into the role in realization phase and work through exploitation and maintenance along with landscape contractors and gardeners (fig. 76). But their insights could be invaluable as early as the initiation phase.

As part of the third stage of systemic design, overlapping phases between different domains contributed to identification of five leveraging points which include (fig. 77): 1) management dashboard, 2) inventory match, 3) urban rules by design, 4) abstraction levels, and 5) decision transparency.

First opportunity area is a management dashboard which consists of tree inventories (crown, volume, tree diversity, and ecosystem benefits) which monitors the existing green infrastructure and evaluates scenarios. Second, inventory match corresponds to a better match between nursery inventory and municipality demand. It also shows the ecosystem benefits of larger trees to better inform the stakeholders. Third, urban rules by design focuses on designing a new procurement draft which will align with the urban design processes. Fourth, abstraction levels emphasize on integrating precise design guidelines for urban green spaces as well as buildings in development plans. Lastly, decision transparency informs citizens about the selection of tree

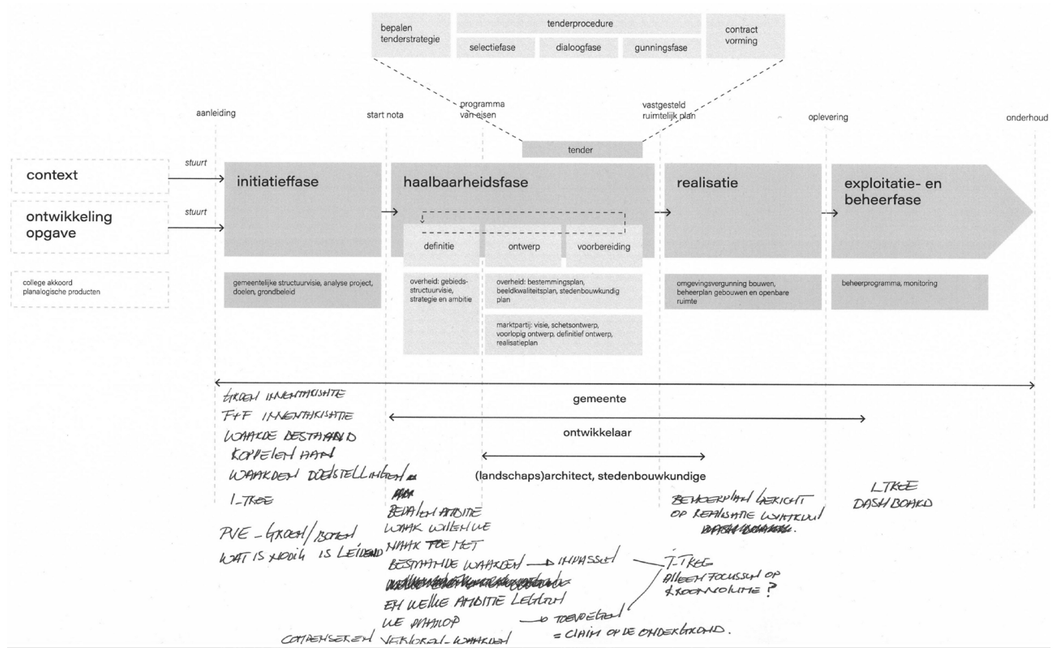


Figure 75. Co-design session 2 focused on the finalization of the stakeholder process journey by receiving feedback from the municipalities.

species and their ecosystem benefits based on the quantified data. Possible futures envisioned by the stakeholders are shown in figure 77.

The most influential design intervention for a potential for system change identified the first opportunity area of dashboard. Opportunity area 1 was selected to further iterate with the integration of key elements, including time, spatialized data, and scenario evaluation which incorporates the data from WP1 and WP2.

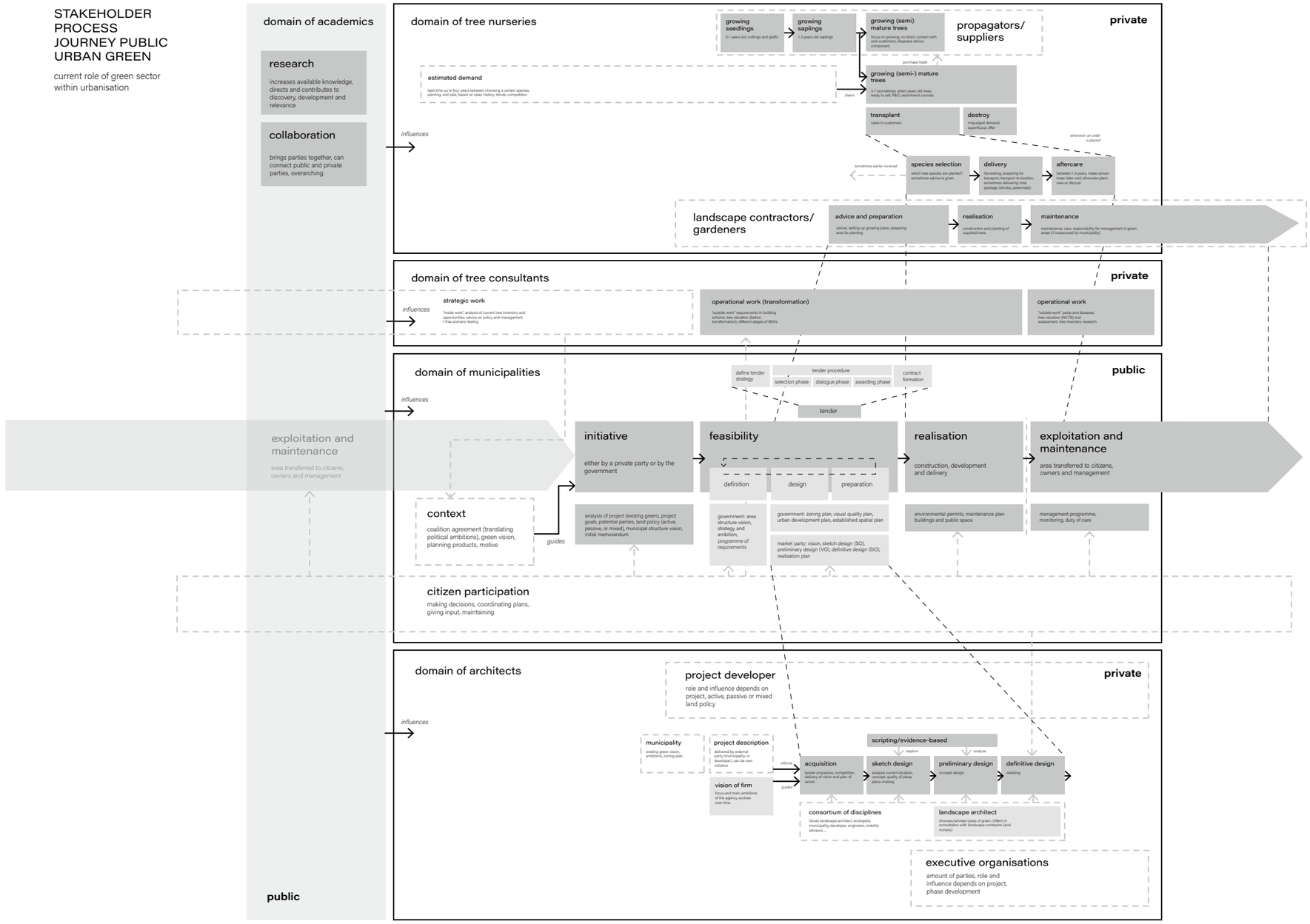


Figure 76. Stakeholder process journey in urban green sector in the urban development phase reveal in which phase stakeholders from four domains intervene.

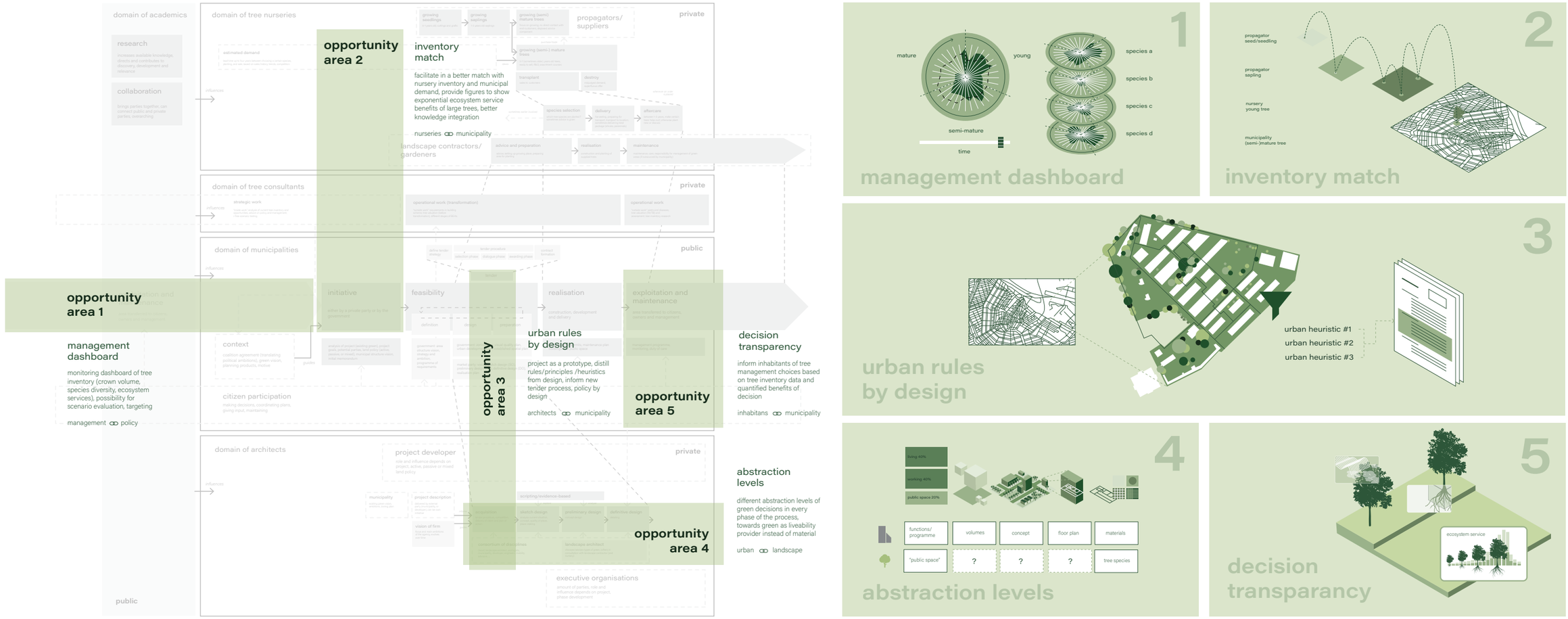


Figure 77. Five opportunity areas derived from the overlapping process journey of four different domains. From "The Future of the Urban Forest: Exploring the systemic granularity of the urban green domain to navigate towards a new paradigm," by S. Keizer, 2023, Industrial Design Engineering, Delft, TU Delft, master's thesis. Reprinted with permission.

3.3.1 Dashboard

Iteration process of dashboard design includes stages: first concept design, second concept design, and alpha version of working prototype. The first concept design is developed with the integration of metrics, including 1) time, 2) site-specific conditions, 3) spatial parameters, 4) tree ecosystem benefits, and 5) scenario evaluations (Keizer, 2023). Crown volume is the foundation for all services, as all performance is related to this metric. Marine terrain in Amsterdam is used to visualize these metrics in the dashboard.

<u>First concept</u>

The first concept design of the dashboard takes a time period of 100-year to set a new target for tree life cycle and divides it into 10 classes (Pretzsch et al., 2023). Even though an average age of

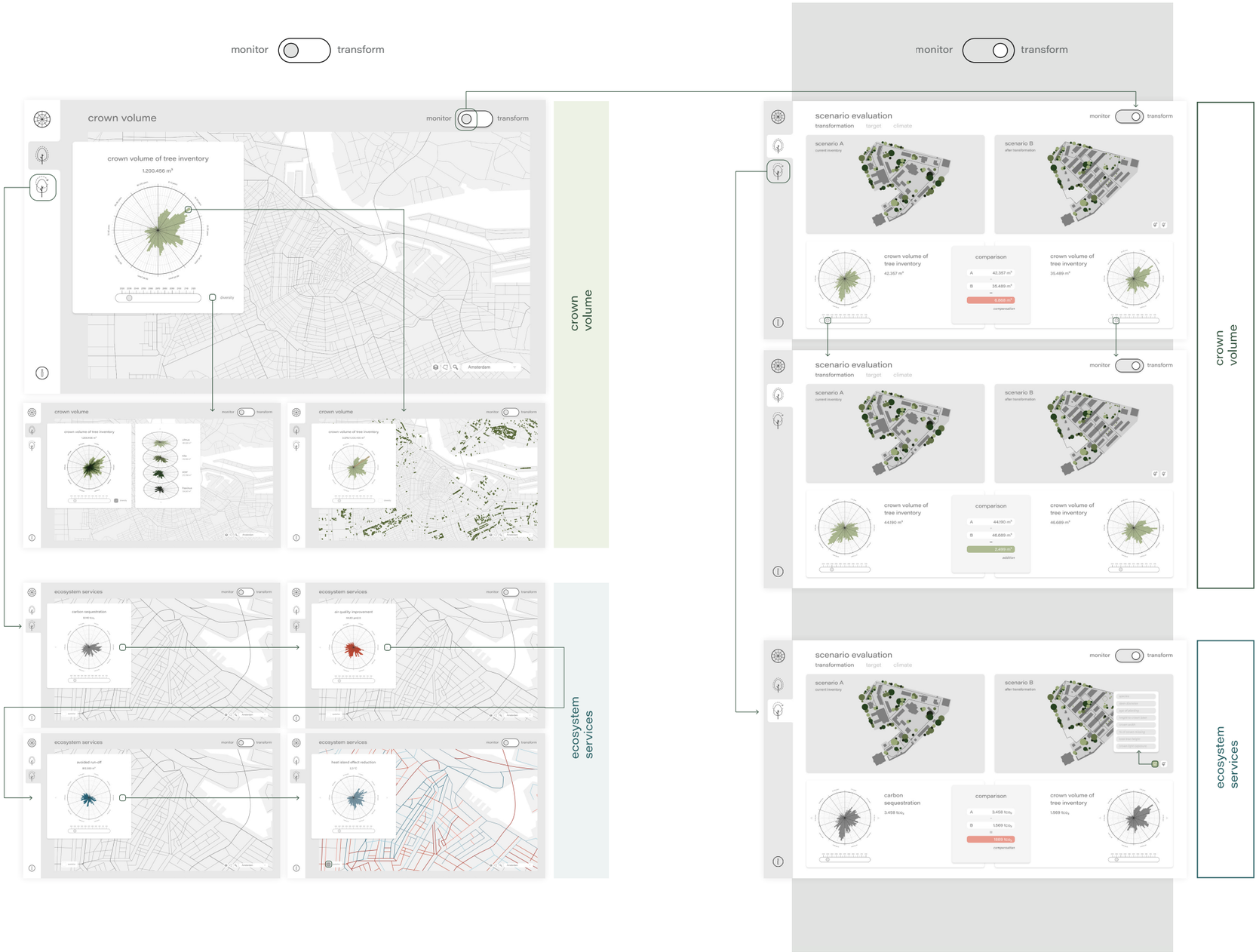


Figure 78. Prototyping the first concept of the dashboard. From "The Future of the Urban Forest: Exploring the systemic granularity of the urban green domain to navigate towards a new paradigm," by S. Keizer, 2023, Industrial Design Engineering, Delft, TU Delft, master's thesis. Reprinted with permission.

trees in the consortium's municipalities is around 30 years (except for monumental trees), a target of 100 years should be the new ambition, looking at the optimum of functional performance in the 70-80 age range.

For ecosystem services, this representation can visually emphasize the exponential increase in performance with age, showing that the majority of an ecosystem service is provided by the mature part of the inventory.

Some ecosystem services can be more location-specific than others. For instance, carbon sequestration is less site-specific than biodiversity. This should be accounted for design processes. In the dashboard, spatial maps of ecosystem services can indicate the site-specific performance of trees in a given area (fig. 78).

I-tree assessment does not spatialize the ecosystem service data of trees. The table provided by i-tree represents the data on how many kilograms of carbon are sequestered and stored, how many pollutants are filtered, and how many cubic metres of water are retained. In order to design and plan for functional performance, services need a spatial component that indicates the location of cooling, retention and filtering.

Also, in terms of claiming space for green, the invisible envelope above and below ground should be considered over time to define the boundaries that cannot be touched based on current and future conditions. Ecosystem benefits focus on cooling, biodiversity, health benefits, soil recovery, carbon storage, air quality, water retention, energy conservation, wind reduction.

Scenario evaluation corresponds to the recommendation of new scenarios based on 'ideal' ecosystem service performance and targets. So far, the focus has been on how the dashboard can track the progress of the urban forest portfolio in terms of crown volume and ecosystem services over time and in relation to space. However, the inventory is in constant flux, not only due to relatively incremental mortality and replanting rates, but more significantly, during transformations. The dashboard therefore has a 'monitor' side to examine the existing portfolio and potential for growth and to track progress towards targets, and a 'transform' side to evaluate and compare different scenarios for transformation, but potentially also for proposed new targets or climate models.

Second concept

Second concept was iterated with the incorporation of seven new functions after receiving feedback by the stakeholders (fig. 79).

- Targets and ambitions (diversity and equity): A target is set for a unified distribution of crown volume across different age classes of the inventory. The targets can be entered manually or existing targets such as the derivation of the 3-30-300 rule (Konijnendijk, 2021) which fosters equity or the 10-20-30 rule (Kendal et al., 2014) for diversity can be used. In addition, new targets can be proposed, such as a constant stock of urban trees between 50 and 100 years old, or a fixed ratio between age classes.

  The graph now includes targets to give more context to the data. In practice, the target would be more like a helix shape, as the mature part (60-80 years) of the inventory should be proportionally larger.

- Tree equity and the potential for green: Crown volume potential could be used as a reference for areas in the city which requires more attention for spatial equity. This idea gets its inspiration from the Birmingham Urban Forestry Masterplan (Birmingham City Council et al., 2021) and the Forestami project in Milan (Forestami, 2020). When zooming in to a particular neighbourghood, cells of manually adjustable size reveal the percentages of crown volume potential.

- Scale levels and granularity: The dashboard focuses on three different scales, including municipal, area, and asset level. From municipal to asset level, the crown view of the trees appears in more detail from dots to roughly rounded shapes to corresponding silhouettes.

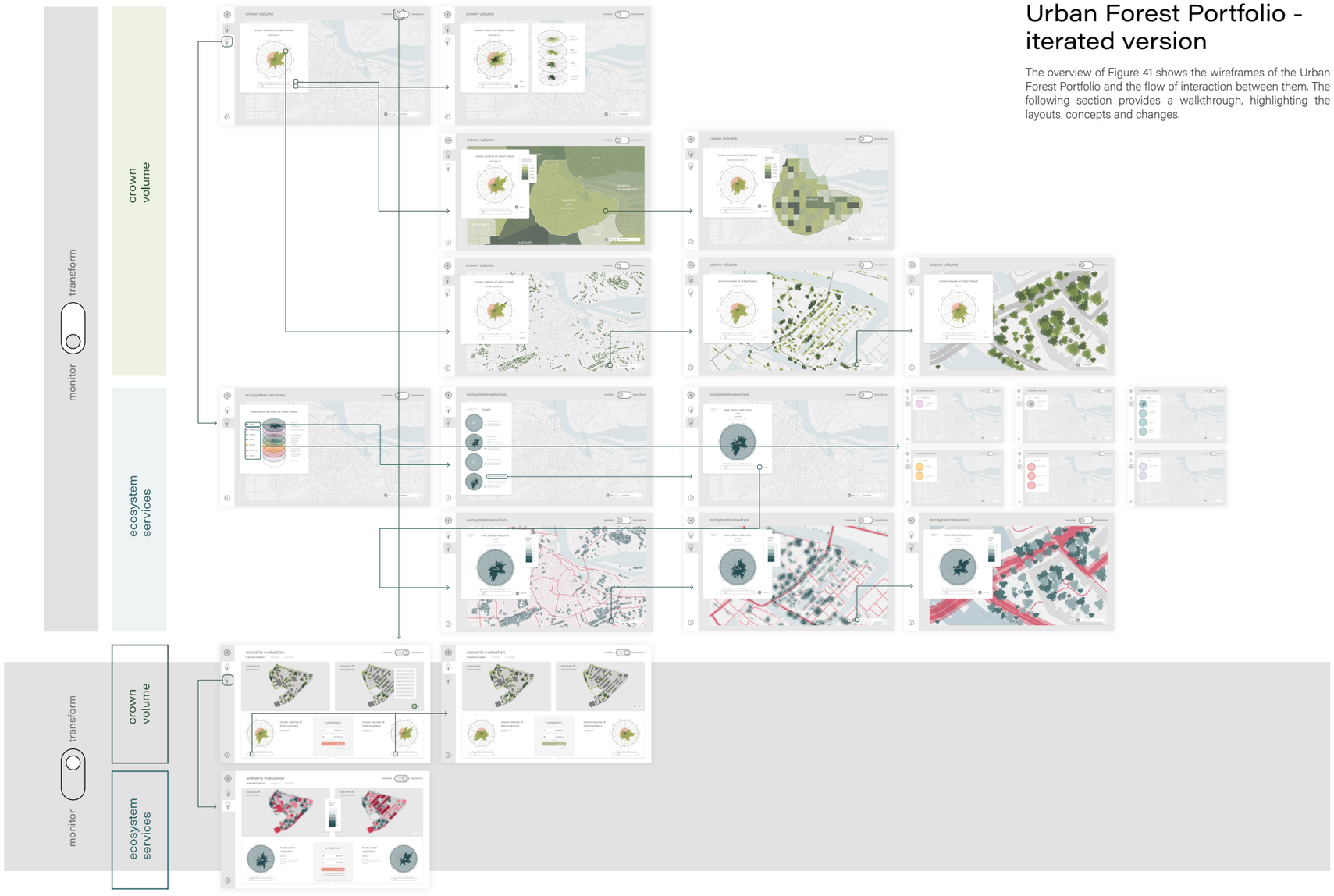
- Quantitative and qualitative ecosystem services: The initial version of the dashboard only showed the quantified ecosystem services provided by i-Tree. The absence of some services in the dashboard makes these services not be counted for in the decision making. Thus, based on the feedback from one of the stakeholders and updated list of all the recognized ecosystem services (Dark Matter Labs, 2020) were provided including aesthetic and cultural values. Seventeen ecosystem services have been categorized into seven domains and each is visualized using the same format. A graph is shown when quantifiable data is available.

- Beneficiaries and contextualized money: The costs of the trees were deliberately included to help with complex management decision processes even though the decisions made solely on the costs undermines the benefits and values of trees, especially in the long-term.

- Spatial services and granularity: As the cooling performance and reduction of the heat island effect is the focus of the consortium, this service is selected for further visualization and granularity is applied at the three different scales. It is important to note again that the maps are based on

hypothetical data, but they were inspired by the work of (Paulin et al., 2020), on a standardized national approach to mapping and quantifying ecosystem services. The mapping of the heat island effect is currently simplified and based on the pavement of the roads in Amsterdam, but in order to more accurately simulate the situation, all paved areas and buildings should be considered.

- Transformation and consequences: The Urban Forest Portfolio's transformation side has been extended to include a spatial comparison of the tree inventory between the two Marine terrein scenarios and their impact on the heat island effect. This offers a comprehensive view of the consequences of an intervention and the time required to either reach or surpass the baseline situation. The new transform side of the dashboard is also illustrated.



Urban Forest Portfolio - iterated version

The overview of Figure 41 shows the wireframes of the Urban Forest Portfolio and the flow of interaction between them. The following section provides a walkthrough, highlighting the layouts, concepts and changes.

Figure 79. Second concept design of the dashboard with new functions. From "The Future of the Urban Forest: Exploring the systemic granularity of the urban green domain to navigate towards a new paradigm," by S. Keizer, 2023, Industrial Design Engineering, Delft, TU Delft, master's thesis. Reprinted with permission.

Alpha version of working prototype
As part of the sixth step in systemic design methodology, planning change process takes the abstract model of dashboard which is the second concept design toward an actionable working alpha prototype.

The dashboard is built in Python using the Dash package, a low-code framework for rapidly creating data-driven applications in Python [https://dash.plotly.com/]. This framework was chosen for its ability to facilitate quick prototype development while providing the flexibility to incorporate custom Python code. This flexibility is particularly useful for interactive features, such as allowing users to add or remove trees within their projects on the interactive maps.

The website is hosted on PythonAnywhere [https://www.pythonanywhere.com/], which simplifies the hosting process for a Dash-based Python project. PythonAnywhere handles the web server configuration and maintenance, enabling us to focus solely on developing the application.

The following data sources are utilized:
- User input: Tree species, diameter at breast height and location
- Growth Curves: Continuous graphs derived from discrete growth curves as part of WP1 and WP2 within the iTree 2.0 project.
- Ecosystem Benefits: Data obtained via the iTree API (fig. 80).

The Alpha version of working prototype focuses on comparing scenarios in graph view for long term decision making. I-tree Application programming interface (API) is incorporated to extract and share data on ecosystem benefits with input on tree crown width. Growth curves and cooling data from the WP1 and WP2 are incorporated into the dashboard. Different projects from Oranjeloper (see Appendix 6), Selwerd, and Handelsplein are included with the tree inventory provided from the respective

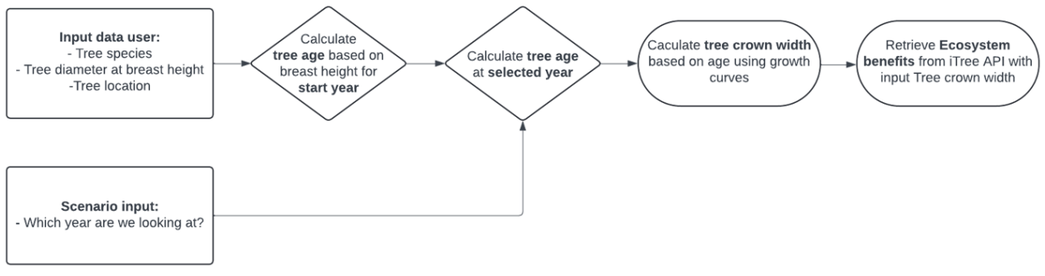


Figure 80. Flowchart of data integration into the alpha working version of the dashboard

municipalities. Real time scenario creation and modification are provided in the working prototype. A link to the operational alpha version is available here. The working prototype of the dashboard could be better used in monitoring and management of urban green spaces while 8-step methodology could be more useful in design processes.

3.3.2 8-Step methodology

While the dashboard utilizes a data driven approach and works at opportunity area 1, in WP3 we also worked with MVRDV to consider ways to design with 'green in the lead'. MVRDV approached the urban greening problem in design field from the development of a methodology through the collaboration of MVRDV's Urban Studio and the in-house research and development unit MVRDV Next.

The proposed design according to new program for Marine terrain in Amsterdam revealed the removal of some of the existing trees which could cause canyon effect on the site. The design challenge of the co-design session 1 was to come up with a better proposal for the site (fig. 81).

Co-design session 1 yielded concept designs to show how the new urban design in the case would look like if we maximize each ecosystem benefits, including cooling, biodiversity, health, air



Figure 81. Urban trees are removed to open up space for buildings according to the new development of Marine terrain in Amsterdam. https://energie-inventarisatie-en-bodemonderzoek-marineterrein-rps.hub.arcgis.com/



Figure 82. One of the groups involving designers and tree consultants in Co-design session 1 working together for developing urban concept design for Marine terrain. Participants are anonymized as part of the ethics approval. The design proposal of the first group focuses on different urban layouts for different ecosystem services.



Figure 83. One of the groups involving designers and tree consultants in Co-design session 1 working together for developing urban concept design for Marine terrein. Participants are anonymized as part of the ethics agreement. The design proposal of the second group considers a version in which every built area was covered with trees and grass cover and another version where urban green spaces were dedicated to built areas.

filtration, and carbon sequestration. These concept designs were a starting point to design cities like forests and inform designers, urban planners, landscape architects, and architects about the design processes of urban green (fig. 82 and 83).

The concept designs used from the results of the co-design session 1 are: maximizing cooling, biodiversity, health, air filtration, and carbon sequestration (fig. 84).

The 8-step methodology was created to design for and with forests creating new urban scenarios by using Grasshopper (architectural CAD) in a way that the design process is reversed by designing urban trees first, leaving the remaining spaces for building envelopes. Thus, the focus of the design process is twofold: the spatial effects of ecosystem services as a driver to building policy and policy-driven targets for the integration of ecosystem services in spatial planning.

Even though this type of design glimpses at parametric design where computer algorithms are used to create new design solutions, designers can use this new methodology as a communication tool to ease the process of visualizing the ecosystem benefits of urban trees.

Marine terrain is taken as an example in the creation of the 8-step methodology which later became applicable and transferable to other cases. The process of the design is as follows:

1. Information needs to be accessible to be applied;
2. Combinations of tree performances act as filters;
3. The Noli map of trees reveals urban morphology;
4. The dashboard evaluates what is lost and what can be gained;
5. Areas that remain can be built upon;
6. Trees that were lost need to be replanted;
7. The new architectural brief is centered around trees;
8. As trees and buildings age, the model evolves.

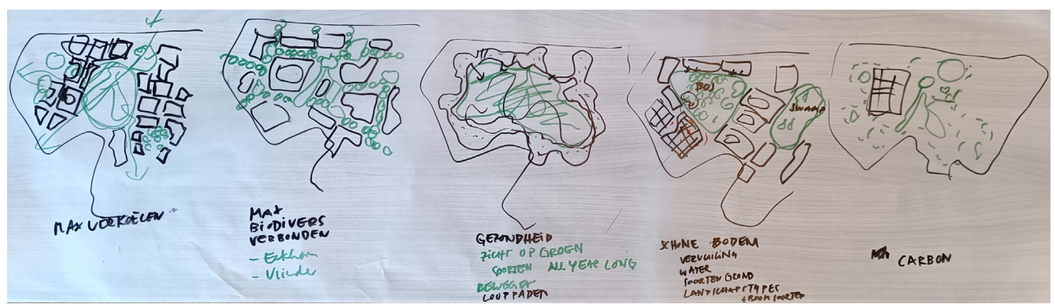


Figure 84. Concept designs of co-design session 1 from the proposal of the first group.



Tree parameters | Genus assumption, Total height, Height to live top, Stemdiameter, Crowndiameter N/S, Crowndiameter E/W, Baseh heigt, Depth rootball, Radius rootball, Canopy cover GIS (m^2), Canopy cover (m^2), Leaf area (m^2), Leaf Area Index (LAI), Carbon storage (kg), Carbon sequestration (kg/year), Avoided runoff (m^3/year), pollution removal (g/year), oxygen production (kg/year)

Figure 85. First step of obtaining data on tree parameters. From MVRDV's the collaboration of Urban Studio and the in-house research and development unit MVRDV Next. Reprinted with permission.

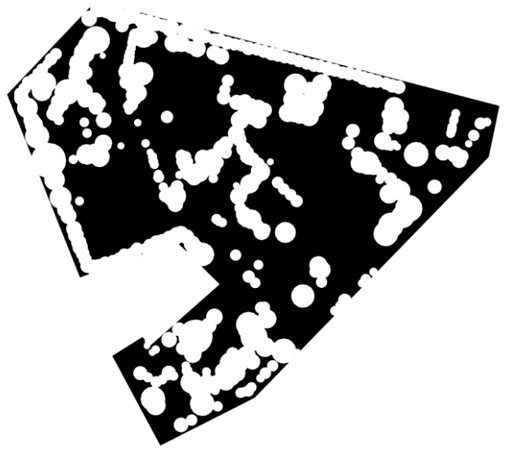


Figure 86. After the application of Noli map, trees are represented in white and built up areas are shown in black. From MVRDV's the collaboration of Urban Studio and the in-house research and development unit MVRDV Next. Reprinted with permission.

The first step is to obtain information on urban green spaces to create a green space inventory to understand the existing green structure of a specific area. Information should be readily available considering the fast design process. Trees are mapped in GIS and the metrics, including tree species, condition and age can be estimated through site visits or through remote sensing. In the case of Marine terrain, the metrics involved in the mapping are: total height, height to live top, stem diameter, crown diameter N/S, crown diameter E/W, base height, root ball depth, root ball diameter, canopy cover GIS (m^2), canopy cover (m^2), leaf area (m^2), leaf area index (LAI), carbon storage (kg), carbon sequestration (kg/year), avoided runoff (m^3/year), pollution removal (g/year), and oxygen production (kg/year). Each of these metrics can be visualized as a series of performances in GIS, including oxygen production, pollution removal, avoided runoff, carbon sequestration, carbon storage, and leaf index (fig. 85).

A Noli map can be implemented to the trees on the site rather than to the buildings (fig. 86). Noli map method is a used to understand and document the accessibility and flow of space within the site. In this method, the built area is shown in black while the ground is left empty or white but, in this case, the white represents the trees and black shows the public space. A variety of tree species provides a variety of ecosystem benefits.

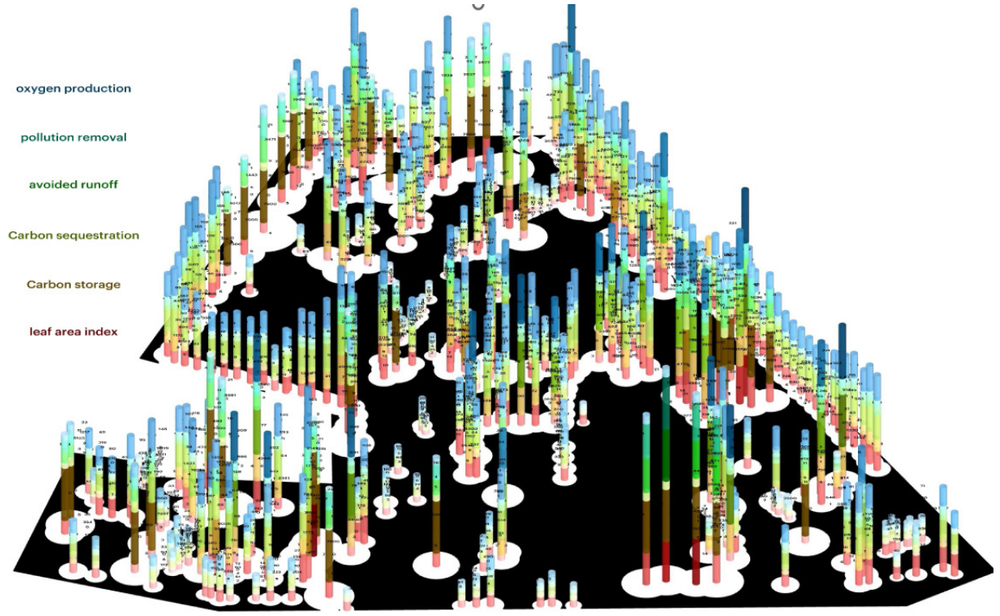


Figure 87. The correlation of different metrics shown in bar on the location of urban trees. From MVRDV's the collaboration of Urban Studio and the in-house research and development unit MVRDV Next. Reprinted with permission.

Each tree depending on its location, species, age, growth rate, lifespan, and condition provides more benefits in some ecosystem services than others. Thus, a bar visualizes each of the services (oxygen production, pollution removal, avoided runoff, carbon sequestration, carbon storage, and leaf index) that each tree delivers in Noli map. The correlation of these metrics can help us to make decisions on which trees to maintain and which trees to remove to free up space (fig. 87).

Secondly, weighted combinations of these aforementioned metrics can act as filters and reveal new forms of urban morphologies, such as the cool city, compact city, and healthy city (fig. 87). Applying these filters transforms the urban layout of the neighbourhood in various ways. For instance, when the combination of the metrics of tree canopy cover and leaf area index is used as a filter, 257 trees out of 363 in Marine terrein perform better in cooling which represents the cool city urban layout (fig. 88). For a healthy city layout, oxygen production and pollution removal can be taken as a reference which yields 221 trees to be kept. This principle can be implemented for enhancing biodiversity by combining biodiversity index and clustering which results in 237 trees while 183 trees would provide better runoff protection by combining avoided runoff and leaf area. 202 trees



Figure 88. The application of these filters reveals different urban lay outs. From MVRDV's the collaboration of Urban Studio and the in-house research and development unit MVRDV Next. Reprinted with permission.



Figure 89. All components, including streets, green forms and existing buildings were merged to reveal the potential areas to dedicate to urban green. From MVRDV's the collaboration of Urban Studio and the in-house research and development unit MVRDV Next. Reprinted with permission.



Figure 90. In the left over space from merging these components, 250 existing trees can be maintained. From MVRDV's the collaboration of Urban Studio and the in-house research and development unit MVRDV Next. Reprinted with permission.



Figure 91. 200 new trees can be planted in addition to the existing 250 trees. From MVRDV's the collaboration of Urban Studio and the in-house research and development unit MVRDV Next. Reprinted with permission.

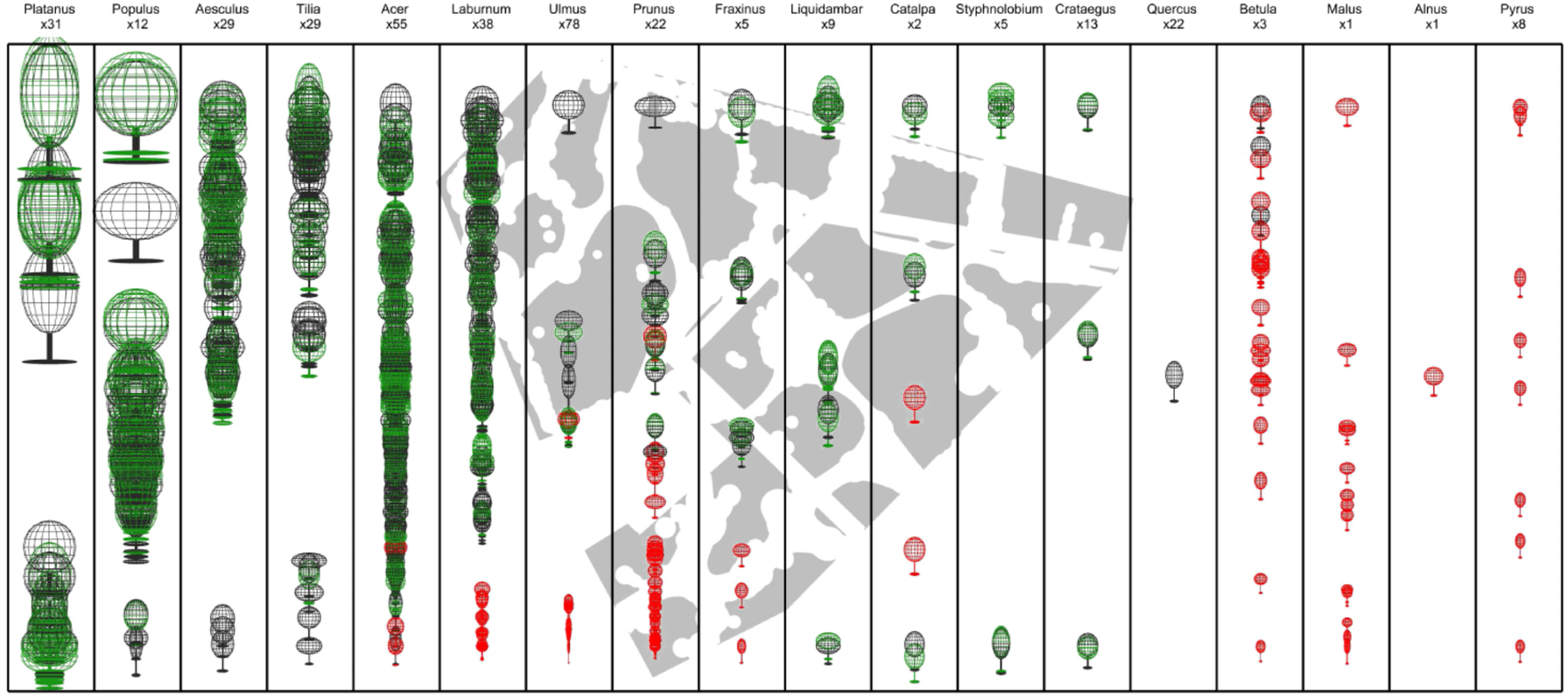


Figure 92. Dashboard could keep track of existing trees, the plantation of new trees (shown in green), and the removal of trees (presented in red). From MVRDV's the collaboration of Urban Studio and the in-house research and development unit MVRDV Next. Reprinted with permission.

would offset carbon emissions by combining metrics of carbon storage and carbon sequestration.

Thirdly, the resulting configuration of different metrics can be used to envision an urban morphology that focuses on the designing of urban trees as a starting point (fig. 89). An urban layout emerges without drawing a single road or building in which trees play a central role (fig. 90 and 91). Designing for and with the Green: Cooling corridors, pocket parks or green perimeters, and other elements of green.

Fourth, a dashboard keeps a track of trees which are kept, which are removed (trees in red), and which are planted (trees in green). It evaluates what has been lost and what can be gained to guide design decisions (fig. 92).

Fifth, areas which are not occupied by trees determine potential building envelopes which could be used to meet the requirements of development program (fig. 93). These envelopes are not fixed or definitive which allows flexibility in planning and designing built area surrounding urban green spaces.

Sixth, the inevitable loss of trees (degraded soil, dieback, and

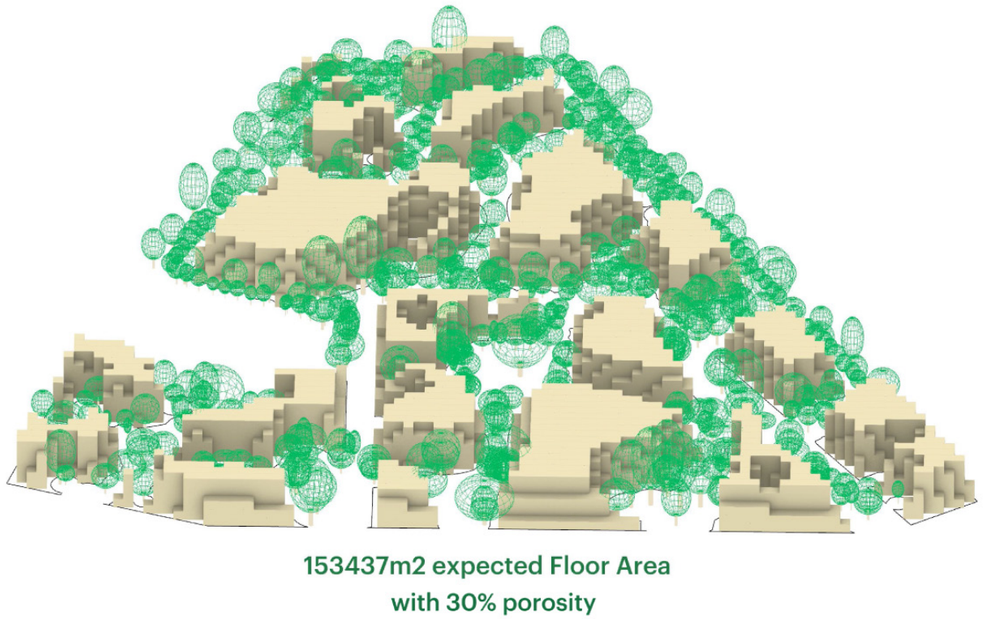


Figure 93. In the 3d view of the site, the building envelopes represented in blocks elevate in a descending way to give space for the growth of the trees. From MVRDV's the collaboration of Urban Studio and the in-house research and development unit MVRDV Next. Reprinted with permission.

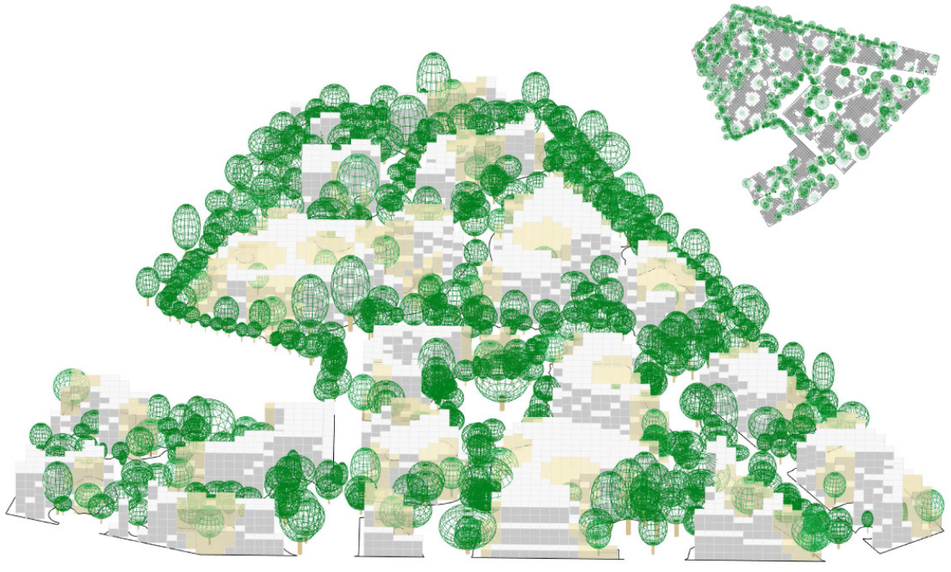


Figure 94. New trees and other green elements could be implemented on the top of these building blocks or facades to enhance the urban greening efforts. From MVRDV's the collaboration of Urban Studio and the in-house research and development unit MVRDV Next. Reprinted with permission.

damage to roots etc.) can be compensated by the plantation of new trees within or on top of these building envelopes (fig. 94).

Seventh, a new architectural brief can be created with the inclusion of precise design requirements for trees and vegetation (fig. 95). Moving from the urban to the building scale, the architectural brief could outline the requirements for materializing, visualizing, and designing trees and vegetation by including parameters such as, programmatic mix, building codes, carbon emissions of buildings and building materials, urban green culture of the site, and user activities and functional spaces surrounding urban green spaces.

Eight, growth is monitored over time. Modular, demountable buildings can be adapted to realign the relation between city and green infrastructure. Considering the ever-growing structure of trees, these building envelopes recedes (shown in red) towards upper floors to accommodate space for the healthy growth of urban trees (fig. 96). Where urban green spaces diminish or disappears, the space dedicated to built-up areas expand. A circular, dynamic neighbourhood constantly negotiates livable spaces for humans and other species.

8-step methodology promotes design of urban green spaces by taking the ecosystem benefits of urban trees as a focal point in the design process. As designers work with tight deadlines in projects, 8-step methodology makes use of computational design and contributes to urban green design processes by incorporating data on tree inventory and ecosystem benefits of

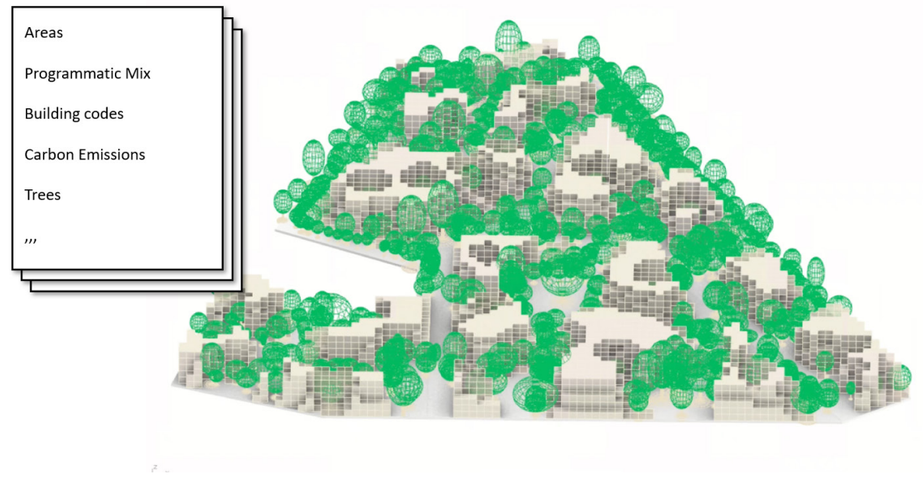


Figure 95. A new architectural brief could give precision to the design of urban green spaces. From MVRDV's the collaboration of Urban Studio and the in-house research and development unit MVRDV Next. Reprinted with permission.

trees. The development of dashboard and 8-step methodology led to the discussion around the need for green clauses in procurements to better inform about urban trees and their benefits at all levels.

3.3.3 Procurement

Using the analysis of existing public procurements as input, a new format of a public procurement is drafted based on the existing program for the redevelopment of Marine Terrein. This draft was brought to the workshop for participants to work together on its applicability, practicality, and feasibility. The architects brought the results of their concept designs for each ecosystem services to the workshop with the aim of aligning their urban designs with “green clauses” in the draft. The scenarios for maximum cooling were chosen by participants to further discuss the green clauses (fig. 97).

The design proposal of green corridors was chosen because it keeps the majority of existing trees with the plantation of new trees. This design proposal is found to be more feasible for the selected case (fig. 98). Green corridors leverage wind direction and distance to building facades which is proposed with an aim to maximize cooling.

Applying speculative design in the crafting of the tender, the participants were asked to reveal the strengths and weaknesses of design-informed policy (when urban design scenarios inform policy decisions) versus policy-informed design (when policies inform the urban design decisions) (fig. 99 and 100).

Procurement draft includes sections of tender procedure, location description and the contract which refers to the program requirements (Atelier Rijkbouwmeester et al., 2021) (fig. 101 and 102) and most importantly green clauses (fig. 103) with the

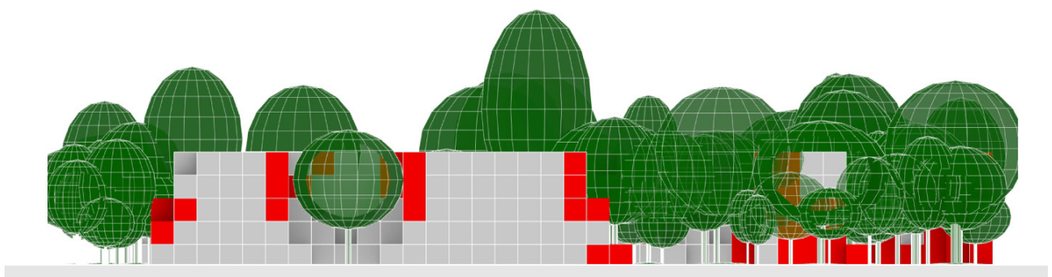


Figure 96. A section is taken vertically from Marine terrein to reveal the descending building blocks to allow space for the growth of urban trees. From MVRDV’s the collaboration of Urban Studio and the in-house research and development unit MVRDV Next. Reprinted with permission.

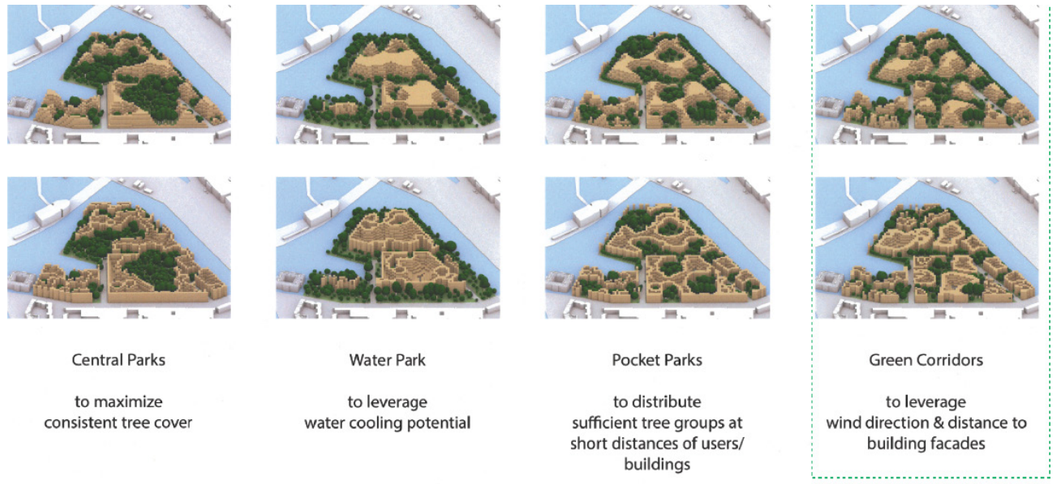


Figure 97. Among four different cooling scenarios, green corridors were chosen by participants to further discuss the alignment of design and green clauses. From MVRDV’s the collaboration of Urban Studio and the in-house research and development unit MVRDV Next. Reprinted with permission.

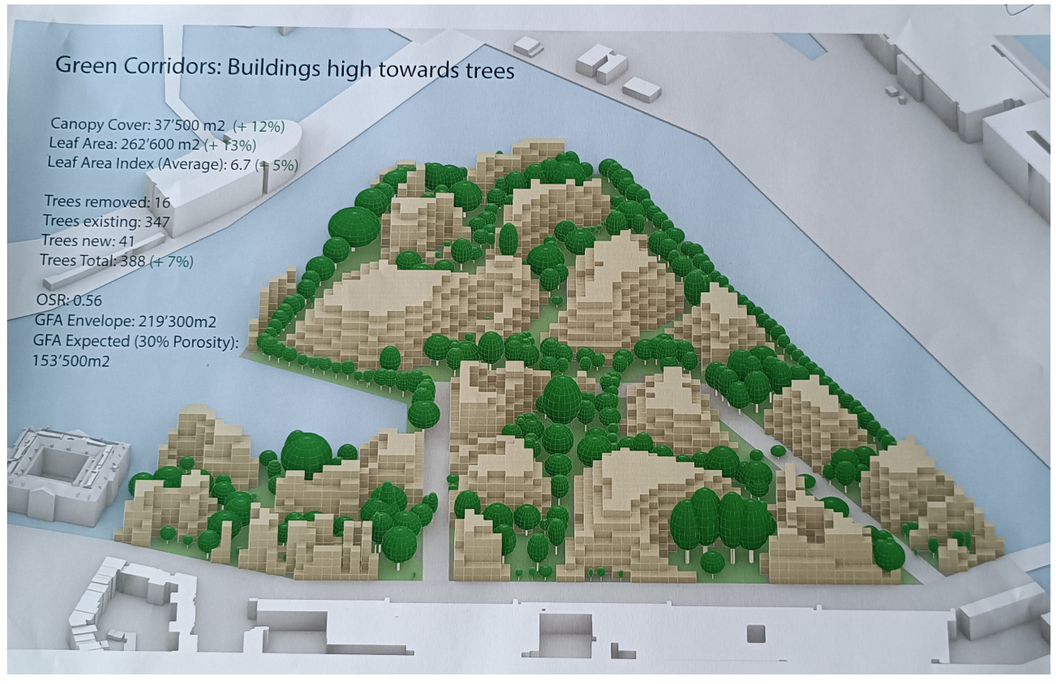


Figure 98. The proposal “Green corridors: Buildings high towards trees” suggests more feasible plan of keeping the existing trees as much as possible with the removal of few number of trees and plantation of new trees which is in aligned with the green clauses discussed above. From MVRDV’s Urban Studio and the in-house research and development unit MVRDV Next. Reprinted with permission.

exemplary quotations from the participants (fig. 104). While some clauses were open to debate and received a lot of reactions by participants, some clauses were agreed by the participants which do not include quotations (fig. 105). In some cases, clauses could not be generalized which would require recrafting for some other sites with their own specificities (fig. 106). Additional feedback from external partners helped further development of “green clauses.” The focus of the ending clauses were given to the survival plan and health of trees (fig. 107 and 108).

The result of the workshop revealed the interest in the investment on the existing tree health to maintain existing green infrastructure with a plan of planting new trees (fig. 109).



Figure 99. Workshop activity in two groups: The first group discusses the strong and weak points of different scenarios where 1) green clauses driven design, 2) design driven green clauses, and 3) both green clauses and design are both drivers.



Figure 100. Workshop activity in two groups: The second group discusses the strong and weak points of different scenarios where 1) green clauses driven design, 2) design driven green clauses, and 3) both green clauses and design are both drivers .

Aanbestedingsleidraad van de procedure voor de ontwikkeling van Marine terrein

Criteria voor Groene Ruimte

Version 2.0

Datum: Maart 2023

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Figure 101. The cover and table of contents of the speculative design of public procurement for Marine terrein.

1. Introduction

1.1. Tender procedure

The Municipality of Amsterdam is going through a national public tender in accordance with the Public Procurement Act 2012 and the Public Procurement Decree to select a developer who will develop Marine Terrein which will be taken over by the municipality (see the contract). The tender consists of two phases in which everyone, who can meet the requirements set in this document and the accompanying appendices register.

2. Location description and the contract

2.1. Location

The surface of the plan area of Marine terrain in Amsterdam covers 13 hectares (ha), of which 10 ha is undeveloped. The harbour has an area of about 1 ha. The Marine terrein has a ship building and military history dating back to the seventeenth century. The isolated development and the presence of many preserved built heritage led to the current special enclave-like atmosphere. The Ministry of Defense will concentrate its activities on a limited part of the site, freeing up space for redevelopment in the area. The Marine terrein is strategically located at the intersection of the Oostelijke Eilanden and the historic city centre and can develop from enclave to connector.

2.2. The contract

The development plan includes, among other things, urban planning preconditions for the development to ensure the strengthening of blue-green infrastructure combined with the development of an additional mix of functions: housing, sports, meeting, and culture. Particularly on the western flank of the site, the greenery will be protected within a new construction program for approximately 800 homes, 2300 jobs for smaller innovative companies and for approximately 1400 students and teaching staff. The distribution of the program is 40% housing (60.000m²), 40% working (60.000m²) in various sizes and price ranges, 20% learning (30.000m²), and 35.000 m² defense (Atelier Rijkbouwmeester et al., 2021).

The Marineterrein will soon consist of three sub-areas: the Stadspark along the water at the Oosterdok, the Dok where the majority of the buildings will be built, and the new Defense barracks in the northeast corner of the site. There are many views of the water and many public quays. The City Park will have a campus-like layout with lots of greenery around the buildings. The Dokplein will become a central meeting square. Only the Defense barracks, with the exception of the sports field, remain a non-public area.

All monuments, including the Poortgebouw, the former carpentry workshop, the Officers' Building and the Commandant's House and Building, will be preserved. Characteristic buildings are preserved as much as

Figure 102. The information on the introduction and location description and the contract were adopted from the program requirements of Marine terrain.

possible, as are trees that have been there for a long time and determine the image.

The Dok and Stadspark will become car-free areas with logistics hubs on the Dijksgracht (with mooring area) and Kattenburgerstraat. Logistics and distribution take place by water as much as possible. There is a lot of room for art and culture, and for sports. The new neighborhood is located in a green, water-rich and car-free environment, with a park on the water of the Oosterdok.

2.3. Green Clause

The developer has high ambitions for preserving and strengthening the unique character of urban forestry in Marine terrain in accordance with The National Ecological Network (NEN) and Natura 2000, for increasing the cooling performance and biodiversity. A holistic urban forestry plan recognizes the need for healthy tree canopy cover and diverse tree species. Blue infrastructure contributes to cooling potential of trees by ensuring water availability and storage while green infrastructure improves air and water quality while providing shade and integrating wildlife habitat (Williams, 2022). Urban scale heat sensitive design shall consider existing breezes to improve the urban-scale ventilation.

3

4

Figure 103. Green clauses were crafted following the principles of speculative design.

1

Existing canopy cover must reach to a minimum 30 % at the neighbourghood level (Konijnendijk, 2023) by 2048. Existing canopy cover must be enhanced by retaining the existing mature and healthy trees with high leaf area index (e.g., broader leaves) and denser crowns to provide shading (Stephenson et al., 2014). The design of the new construction of sport fields, streets, and buildings must recognize the growth of trees e.g., space to grow, soil volume and quality, rooting space, sufficient light, permeable and porous pavements, and vegetated surfaces. The soil improvement shall be done if the existing soil conditions are poor (e.g., compacted, or polluted soil) for mature and healthy trees.

Workshop Participant 6:

"*Maximum canopy cover is not the ideal…actually site-specific design targets*"

Workshop Participant 3:

"*Set minimums but show potential. Design at min 25 percentage but allow growth to x percentage.*"

"*We need design concepts where it is possible to grow to xyz canopy cover and abc leaf area index in x years.*"

5

2

Rooting space of minimum 20 cubic meter shall be provided for the first size tree, 15 cubic meter for second size tree, and 10 cubic meters for the third size trees and a cubic meter per year shall be planned for their future growth.

Workshop Participant 2:

"*20 cubic meter is quite excessive… based on what?*"

"*Can it be specific? MVRDV planned 3 cubic meters.*"

Workshop Participant 1:

"*Not possible in 9 out of 10 cases! [referring to 20 cubic meter rooting space]* "

3

Municipalities shall determine which existing trees to grow maturity (e.g., 75 years old) and provide rooting space according to their target age in consultation with the green contractors.

6

Figure 104. First three clauses refer to the most discussed points related to canopy cover and rooting space.

4

Water level and soil conditions will be checked, if needed, a water drainage system for existing mature trees will be provided. Budget for the maintenance of the green infrastructure will be allocated within the development plan. Yearly soil improvement will be budgeted over 35 years.

Workshop Participant 3:

"*Yearly soil improvement budgeted over x number of years. …But maintenance not planned (euros).*"

"*Demand budget for audit- evaluations and maintenance.*"

Workshop Participant 1:

"*Grass cover becomes space to plant new trees if one dies. Grass is important.*"

"*We make sure grass is useful if tree dies.*"

7

5

A survival plan for the existing canopy cover shall be prepared with the development plan.

Workshop Participant 7:

"100 new trees in what proximity and what type? Survival plan is needed otherwise tender is not achievable."

"Tree survival plan for 20 years in Utrecht wonder woods"

6

The canopy cover must be increased and well distributed to achieve cooling by incorporating nature-based solutions (e.g., bio corridors, pocket parks, green roofs, and vertical forests in façade systems) and multiplying factor of blue infrastructure (e.g., wind and water).

8

Figure 105. Quotations were included in clauses which received the most reactions from the participants while some clauses such as number 6 did not receive any reactions because the participants agreed with it.

7

A resilient urban forest should consist of no more than 10 percent of the same species, 20 percent of the same genera, and 30 percent of the same taxonomic family (Santamour, 1990). Furthermore, genera known to be susceptible to a certain pest or disease should make up less than 10 percent of an urban forest. The biodiversity shall be enhanced by the creation of microhabitats.

8

Wet tolerant trees with various types, age, and size shall be planted to create seasonal variations wherever possible. The type, age, and size of each newly planted tree shall be determined in consultation with the arborists, landscape architects, and tree officers in the municipality.

Workshop Participant 5:

"Tender presumes drought tolerant trees for Amsterdam but should consider wet tolerant in the case of Amsterdam or both wet and drought tolerant. It is site specific because in the case of Eindhoven it could be drought tolerant trees."

9

9

Trees shall be planted, in clusters rather than stand alone, along with grassy vegetation, shrubs, and other vegetations for their well establishment. The citizens shall be informed by the plantation of the trees.

Workshop Participant 3:

"What if we could prune the buildings in order to grow trees?"

10

The new buildings shall set back minimum 10 meters from the existing mature trees to allow their successful retention. A tree affect analysis (Boomeffectanalyse/BEA) shall be carried out to assess the impact to trees on an individual level from the proposed development and the construction of new buildings.

10

Figure 106. Case specific examples may change the clauses number 7 and 8.

11

In accordance with EU Ecolabels and many biobased initiatives as part of national circular policies, the use of biobased materials is required in the construction of the new buildings.

12

In the redevelopment and the construction of new buildings and infrastructure, containers shall be placed to ensure the protection of the trees. A tree protection plan needs to be made customized to the trees affected in the redevelopment and construction. The root system of the tree needs to be mapped, especially of its vulnerable roots.

Workshop Participant 4:

"…for protection fences under canopy increase ratio of canopy."

11

Survival Plan

13

Any trees or plants (including those retained as part of the development) which within a period of 4 years from the completion of the development die, are removed, or, in the opinion of the tree officers of the municipality, become seriously damaged or does not show any growth or infected by diseases and pests shall be replaced by the contractor in the next planting season with others of similar size and species, unless the municipality give written consent to any variation. If the replacement of the similar size of tree costs high, the tree with a similar specie with 20-25 cm stem diameter shall be planted.

Workshop Participant 1:

"Let's not plant trees everywhere, but show restraint first to allow room for growing space."

12

Figure 107. The importance of survival plan was emphasized throughout the drafting process which is why it was included as a subtitle to the green clauses.

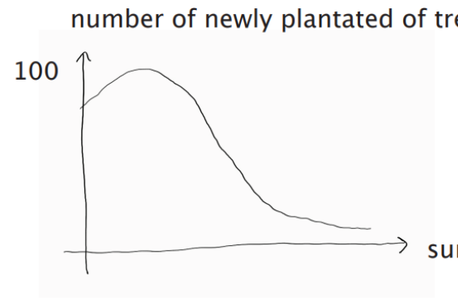
14

The supervision, monitoring, and reporting of the existing and newly planted trees shall be undertaken by managers and supervisors and in accordance with the approved details. Any threats, diseases, insects shall be anticipated by tree officers (and maintained with short- and long-term planning.)

15

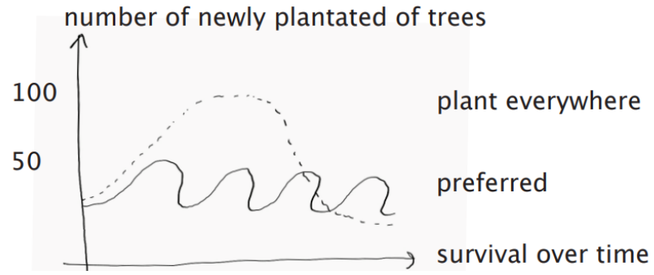
In a proposal of the redevelopment or new construction in Marine terrein within 20 years, the transplantation of the trees older than 30 years shall be planned and done with the agreement of the urbanists, landscape architects, the asset owner of the trees.

13



poor plan

clear plan



Page 166, Figure 108. The tree health is the most important clause as well as what happens to a tree in the case of a redevelopment or a new construction which finalizes the green clauses in the public procurement draft.

Figure 109. The sketch shows that we do not need to plant a lot of new trees, instead we need to plant a feasible number of trees which would die off and an another plant grows in the place of the tree. This would allow the natural lifecycle of the trees to take action. Insight from a workshop participant from consortium member: idverde.

3.4 Discussion and Action Plan

Rather than use the terminology of roadmapping, which designates roads as stable entities, we opt for the language of Action Plan. A good plan is open to change and this is important for us to appreciate given the number of stakeholders within our consortium and how these are all individually shaped by external forces.There are short-and long-term action plans to be taken to realise the three results of WP3, three results, 1) the dashboard, 2) the 8-step methodology, and 3) public procurement draft with the involvement of consortium and external partners. There is a need for the integration of more data into the dashboard, including more diverse tree species as currently only few common trees are included, more ecosystem benefits (aesthetic and societal values), trees in private lots, soil type and condition (which is missing for most of the municipalities' inventory), and blue infrastructure (such as rivers, streams, canals, and their banks) must be considered in further iterations. On the long term, more test cases from other municipalities could be integrated into the dashboard for establishing "a shared language" among municipal staff. More features such as 3D view of a neighbourhood and citizen reviews on trees' health could be incorporated into the dashboard for citizen involvement. Also, aforementioned four other opportunity areas (fig. 76) among five could be further developed as a long term goal.

The 8-step methodology was tested in the case of Marine terrein. But it would greatly benefit from the incorporation of more data in terms of soil type and condition, materialisation of building envelopes (building material and performance and filling in envelopes with other elements of built areas) and blue infrastructure. This would also contribute to more precise guidelines for urban green spaces in an architectural brief. In the long term, more test cases are needed for the further development of the methodology to be used as a communication tool not only among designers but also other partners, involving citizens through these steps.

The public procurement draft in the short term needs further crafting of green clauses and communicating them with other municipalities. These clauses should be aligned with government and city-level policies and with guidelines on climate adaptation, enhancing biodiversity and energy efficiency and urban water management. In the long horizon, more funds would have to be allocated which could drive from public-private investments and joined-sector funds.

Stakeholders involvement is critical during these actions as currently interactions between some of them are missing and their collaborative efforts do not go beyond conventional partnerships between such as municipalities and citizens or municipalities and nurseries. More unconventional partnerships between designers and nurseries or designers and tree consultants could provide valuable addition to the urban green domains (fig 110).

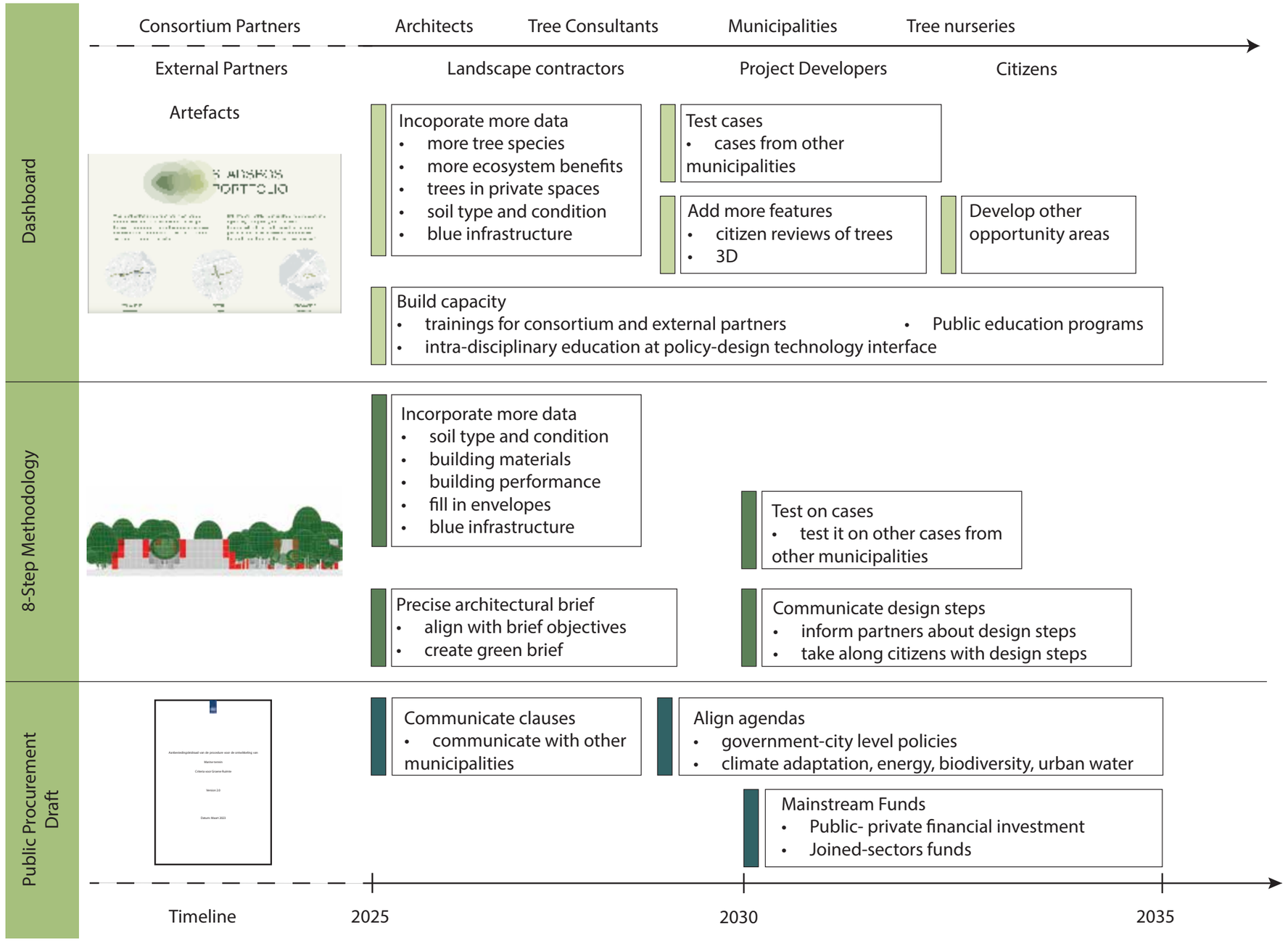


Figure 110. Action plan for a span of 2035 years for the further development of dashboard, 8-step methodology, and procurement draft.

3.5 Limitations

Incomplete data
Tree inventories of the municipalities are for some areas incomplete. Tree location and age in the projects ‘Oranjeloper, Amsterdam’ and ‘Selward, Groningen,’ are obtained from the respective municipalities. Some of the parameters such as the age of trees were missing while other parameters, such as crown width and tree diameter were available. It was possible to estimate the age of trees by applying tree growth curves in reverse by using the crown diameter as an input.

There are currently no standardized methods for assessing site quality for tree growth. These assessment methods were determined by a tree expert in the case of the aforementioned projects. So, a binary system of ‘Good’ and ‘Poor’ was adopted. The information on site quality for growth is absent mainly because the municipalities have not registered or documented it. Additionally, the current growth curves do not consider growth site quality as an input.

Nonprecise data
The continuous growth curves used in the dashboard are derived from the discrete growth curves developed in this research. The midpoints of each tree age interval are used to create a continuous curve (refer to the research section on discrete growth curves). These discrete growth curves are based on empirical data from the same species of trees but sourced from different geographical locations, soil types, and other environmental factors that impact growth site quality.

To calculate the tree’s crown width for each year in the scenario, we use a general formula to derive the tree’s age at the start year based on the user’s input of tree diameter at breast height. However, this formula does not differentiate between tree species, even though growth rates vary among species. As a result, the calculated tree ages at the start year may be less precise.

Wishes, fears, points of attention etc. stemming from participatory design process
The participatory design present limitations as it can be often time-consuming. It takes time to prepare for the co-design sessions and workshop and send invitations to set a date for everyone’s availability. The preparations for these events often involved presentation of i-tree software and its capabilities to have a basic understanding for all the stakeholders. As there were a lot of participants from diverse subfields in the urban green sector, the language and approach in these events sometimes became more design oriented and other times more policy oriented or practice oriented. Coming from design and architecture discipline, this was challenging for organizers to manage the sessions with different configurations of stakeholder. The terminology used among several stakeholders involved in design, maintenance, policy and management as well as urban development sometimes made it difficult for them to share knowledge as there was little overlap between some of their works. For instance, there is little conversation between designers and tree nurseries while the latter collaborate more with municipalities.

One significant point of attention and wish is to ensure that these stakeholders build consistent and ongoing communication to forge mutual learning and development in the urban green sector.

Dissemination

A central component of the i-Tree 2.0-NL project was dissemination and valorization of results. These objectives were elaborated in the following strategies, initiatives and activities.

Marineterrein Amsterdam
The former Amsterdam naval base (Marineterrein) forms the setting for forecasting and prototyping of various i-Tree applications in WP3. The future conversion of the site to a mixed use residential area is the impetus for dissemination and innovative transition and exploitation of research results. During the urban redevelopment phase, the site functions as an R&D zone for collaboration between science, industry, government agencies and citizens on various sustainability challenges in the urban realm, as Marineterrein Amsterdam Living Lab (MALL).

Test-beds in Amsterdam and Groningen
Two test-bed projects were set up to trial ‘before’ and ‘after’ results of the project. In Amsterdam, state-of-the-art i-Tree ECO software was trialled on trees along the so-called ‘Oranjeloper’ (array of streets Rozengracht-De Clercqstraat-Admiraal de Ruijterweg-Jan Evertsenstraat), and again at the finish of the project using the newly-developed dashboard application. In Groningen, the newly-developed dashboard application was trialled on trees in the Selwerd neighbourhood.

Feedback moments and demo days
Dissemination and valorization followed a snowball strategy. Updates on the project were given regularly to involve partners in development and uptake. Sessions were open to (passive) participation by key invited industry and government partners. Workshops were organized around key steps and outcomes in the various work packages, with active participation by researchers and consortium members. Ongoing informal interaction between other MALL projects on the campus is a fourth strategy, with expected results in iterative development of i-Tree 2.0-NL and business development spin-offs. Demo days encourage stakeholders to use results like the dashboard.

Conferences and publications
Results were regularly disseminated at national events such as Netherlands tree-info days, and presentations given at international scientific conferences and in knowledge exchange networks of research team members and consortium partners. Given the international profile of i-Tree and the considerable scientific and industry community working in and with the tool, the project garnered significant international attention. Various scientific, industry and journalistic publications were developed during the course of the project.

iTree on tour
i-Tree 2.0 project results will be taken ‘on tour’ around the Netherlands in 2025. An interactive panel installation will be installed around a large tree located in a central point in participating cities. This travelling exhibition will move from city to city in the spring of 2025 and have 24-hour public accessibility.

Web-based platform on the research project
A web-based platform on the research project with results and links to related projects and initiatives will be launched in the final stages of the project (spring 2025) and remain online for a period beyond the project’s completion.

Conclusions

WP1 quantified the cooling effects of various tree species in the Netherlands, focusing on how physiognomic characteristics of trees – or tree architecture—affect their cooling capacity. Five key traits of trees were established that impact reflection, absorption and transmission of radiation including Foliage Trans-luminescense, Foliage Porosity, Crown Density, Wood Zoning and Wood Grain. The categorization of trees into “Cool Tree Architecture Types” (C-TAT) based on cluster analysis resulted in 51 types (from a total of 69 species and cultivars). A further typology consisting of nine types was derived from a cluster analysis of the two most complementary traits Foliage Trans-luminescense and Crown Density. Field measurements taken from 69 trees during the summer of 2022, monitored the variables air temperature, relative humidity, wind speed, and globe temperature. These data were used to calculate Mean Radiant Temperature (MRT) and Physiological Equivalent Temperature (PET), which determine human thermal comfort. Results indicated that trees significantly lower air temperature, reduce wind speed, and increase humidity under their canopies, with MRT showing the most pronounced cooling effect. However, tree cooling performance varied with weather conditions, and factors like wind speed and tree spacing affected the results. Comparison of measurement data and C-TAT types (both the large set of 59 and the smaller set of 9) revealed few significant correlations. Despite limitations such as sample size and environmental constraints, the study provides valuable insights for urban planners seeking to optimize tree species selection for climate mitigation in cities.

WP2 developed generic growth curves to cover the range of city tree species in the Netherlands, to allow reverse calculations from optimal cooling performances metrics determined for mature trees in WP1. Tree data, containing tree species, condition, planting year, growth site and location, were collected from the 8 participating municipalities. Only solitary trees were selected and divided in 8 age classes per tree species. The point clouds from the trees were extracted from 3 collection years, spanning from 2009 to 2022 (Actueel hoogtebestand Nederland, AHN2, AHN3 and AHN4) to calculate growth curves. Growth curves for tree height and crown width in relation to age were created. Growth curves were successfully calculated for 60 species. The results of this work package were implemented in the Dashboard created in WP3.

WP3 developed a dashboard, methodology and policy draft with relevant stakeholders to strengthen the planning, design, and management of urban green spaces. WP3 used a set of data collected from interviews, co-design sessions, fieldwork, and a workshop to offer innovative interventions that harness WP1 and WP2 results through systemic design, speculative design, and participatory design. Phase A, the first stage of WP3, focused on the values, experiences, and needs of stakeholders to map stakeholder journeys in urban green space by analyzing the interviews. Phase B drew on co-design sessions to prototype a dashboard and design methodologies. As part of phase C, policy needs and shortcomings were identified in the workshop to develop a policy draft. Wp3 resulted in an operational Dashboard, 8-step Methodology, and Procurement Draft with practical recommendations for strengthening the position of urban green spaces. These methodologies, with the integration of cooling data and growth curve of trees provided by WP1 and WP2, provide multiple design interventions which respond to the needs, values, and wants of stakeholders.

Checklist of Specific Outcomes

i. Original: *Scientific classification system for tree architecture, relevant to urban thermal microclimate amelioration*;
- Revised outcome: **Development of a descriptive framework for tree architecture, relevant to urban thermal microclimate amelioration**; [Completed, WP1];

ii. **An innovative methodology to categorize the most relevant characteristics of urban trees for thermal microclimate amelioration**; [Completed, WP1, additions and elaborations in 2025; see report addendum summer 2025];

iii. **Scientific data on tree cooling performances, which quantify the contribution of different tree species to cooling in Cfb climate zone cities, and these performances under varying subsurface conditions**; [Completed, WP1, supplementary additions expected in 2025, see forthcoming report addendum 2025];
iv. **Metrics on species-specific growth curves that allow for the assessment of existing urban forest assets and the modelling of performances over the life-span of urban trees**; [Completed, WP2];
v. **Integration of these metrics into i-Tree source-code(s), for release as public domain software**; [Completed as dashboard in WP3, back-end software additions in 2025; see forthcoming report addendum 2025];
vi. **Context mappings of values, experiences and needs of stakeholders in relation to urban (thermal) climate resilience**; [Completed, WP3];
vii. **Speculative elaborations for resilient urban forests, city landscapes and communities**; [Completed, WP3];
viii. **Implementation prototypes from these visions using back-casting**; [Completed, WP3];
ix. **A roadmap for implementation and development of i-Tree 2.0**; [Completed, WP3, supplementary additions expected in 2025, see forthcoming report addendum 2025];
x. Original: *Scientific publications around tree architecture, urban microclimate amelioration, urban tree growth curves, adoption strategies, modelling tools, and citizen resilience*;
- Revised outcome: **Dissemination around tree architecture, urban microclimate amelioration, urban tree growth curves, adoption strategies, modelling tools, and citizen resilience**; [Completed all WPs, extra activities and additions in 2025]
xi. Original: *Demonstration arboretum' Marineterrein Amsterdam Living Lab (MALL).*
- Revised outcome: **Test-bed projects 'Oranjeloper', Amsterdam & Selward, Groningen, with key government, industry, research and societal partners to test research results and tools**; [Ongoing, to be completed in 2025]
xii. **Web-based platform on the research project, with regular updates of results and links to related projects and initiatives**. [Completed, WP3; dashboard and Wordpress hosted website due 2025]
xiii. Original: *Workshops on location in collaboration with MALL, around key steps and outcomes in the various work packages.*
- Revised outcome: **Consortium meetings and around key milestones and outcomes of the various work packages**; [Completed];
xiv. **Informal interaction between other projects, with expected iterative development of i-Tree 2.0-NL and business development spin-offs**; [Ongoing into 2025, WP1, WP2 & WP3; dashboard development from summer 2025]
xv. Original: *On-site demonstrations and 'trialing days' with key government, industry, research and societal partners invited to test research results in personal case studies*;
- Revised outcome: **Travelling exhibition of results in 2025 at participating municipalities**; [Planned for spring 2025]
- Revised outcome: **Dashboard application workshops**; [Planned for spring 2025]

Reflecting on ClickNL Key Enabling Methodologies (KEMs)

This project connects to multiple mission themes, roadmaps, and Key Enabling Methodologies that are presented in the ClickNL Knowledge and Innovation Agenda 2020-2023.
WP3 is planned in three phases, with the following KEM alignments identified:

- Phase 1: Identifying and mapping high-level values related to the livability and resilience of Dutch cities from internal and external project partners (KEM: Experimental Environments)
- Phase 2: Synthesizing a shared vision for the future livability and resilience of Dutch cities (KEM: Vision and imagination, participation and co-creation and experimental environment)
- Phase 3: Co-design i-Tree 2.0 technological use cases for test-city locations, operationalizing the vision, by understanding the needs of various stakeholders in this contexts. Build a framework for adoption of the iTree 2.0 in test locations. (KEM: Experimental environments, Institutional change, system change, value creation and upscaling)

<u>Mission themes</u>
By measuring the impact that trees can have on several factors in the urban environment, the involvement of multiple stakeholders, and ensuring that these results can be used by municipalities in their future planning, this project connects to the theme Energy Transition and Sustainability. This includes making sure that citizens are actively involved as a valued party in the process and end result of the project. In a way, this project also aims to connect to the mission theme Health and Care. This project has discovered which impact the usage of trees in an urban environment has on several topics. Amongst them is the wellbeing of a cities' inhabitants. As a point of reflection, while the mission to improve climate resilience was the founding direction, this mission in practice interacts with other missions as the project develops multi-dimensionality. For example, a health and care mission that emerges in the projects helps the consortium align to and understand the needs of citizens living in increasingly hot urban environments. While one mission may guide the start of a

project, creating impact requires us to interact with and support other organisations in pursuit of their mission too. Future projects must anticipate this dynamic interplay of missions throughout their timeline of activities.

Context-Mapping, Co-Design and Action Plans Toward Change
Facilitating a transition in an urban setting is a complex problem, with a multitude of actors who carry self-interest. Our context mapping has demonstrated the true complexity of this challenge. It has also established opportunity areas form which data collected in WP1 and WP2 can be translated into impact in WP3. Without context mapping at the start of the project, this endeavour might have quickly become a technical challenge of getting more accurate data and models only. Translating what these data mean, and how that can be practically applicable for various stakeholders has required ongoing co-design efforts to work together, rather than in silos of traditional knowledge creation. As a project structure, this means that WP3 runs in parallel to WP1 and WP2, rather than waiting for these work packages to 'complete' their data collection as a more traditional water-fall project structure. WP3 therefore helps to locate the value of the novel and high quality data collection of WP1 and WP2 during development, not at point of completion.

Throughout our project, we have guided stakeholders to look forward in time toward preferred futures together through co-design. Because we have such a diverse group of stakeholders, it is crucial to weave together their stories of what a preferred future looks like, to form a collective understanding of how climate resilience can be created here in the Netherlands. WP1 and WP2 empirical work also allows the consortium to pause and ground their views of the future with real insights from today to prevent uninformed or bias driven future thinking.

At all times, co-design in practice for us has meant, listening to different voices, allowing these voices to have agency, ensuring that we can think beyond current rules and norms, quickly visualising ideas as boundary objects, identifying deeper unspoken core values and aligning these values through improved data collection and modelling techniques in WP1 and WP2, or concepts in WP3. While the implementation plan of the dashboard and the presence of the 8-step methodology and early policy draft proposal give guidance to what a future could look like, it is the continued collaboration and dialogue of partners that will be key to ensuring value created in this project becomes impactful.

Impact

Research institutes
This project equips participating research institutes with novel methodologies and classification systems on and around tree architecture in relation to urban microclimate amelioration. It also provides participating research institutes with specific datasets on cooling performances of various urban tree species and their growth curves in the Cfb climate zone. These datasets will contribute to the international scientific community initiative i-Tree, an initiative developed by urban forestry and greenspace researchers and practitioners on five continents.

Urban administrations
The development of data on the cooling performances of different tree species, over the life cycle of the tree, equips greenspaces managers, planners and development teams with metrics to accurately quantify the performance of the existing and proposed urban forest in ameliorating extremes in urban heat cycles. The application of this data via its embedding in user-friendly tools based around the i-Tree platform supports the resilience of Dutch cities to future climate change impacts and urban liveability generally by improving inputs for greenspace management. Insights from WP3 demonstrate that planning and design processes are also supported by not only providing a modelling tool with data to predict the performance of proposed urban forestry measures, but to incorporate broad stakeholder participation at various stages of design and implementation. Moreover, the results of this project – both the scientific data and the application tool(s) – provide objective reasoning and faster decision-making in discussions on existing as well as future greenspace.

Urban tree/greenspace consultancies
Participating arboriculture firms, as key advisors in various aspects urban greenspace management, planning and design have been equipped with scientifically sound data and toolsets to help cities make accurate predictions of ecosystem services over the entire life cycle of trees, and better arguments for conservation and creation of green space in relation to climate objectives when considering urban development. The connection which the project sets up between industry partners and participating large, medium and small cities can be seen as a significant spinoff of value to participating firms in its own right. New avenues for business in related urban planning, design and greenspace management areas have emerged, for example MVRDVs 8-step methodology, or the greenspace policy that can be furthered into new research projects or for immediate business growth.

Tree nurseries

The project provides tree nurseries with insights in the micro-climatic best performing tree characteristics, which enables them to timely adapt their assortment to emerging changes in the purchase policies of green asset managers in cities. Connecting the network of participating large, medium and small cities partners throughout project milestone meetings and through informal collaboration has fostered closer ties within the ‘green’ sector.

Design & Engineering firms

The new i-Tree module enables design and engineering firms to accurately assess the real impact and value of their own design proposals in a world where clients (urban administrations, private developers) increasingly demand objective information for societal discussions on the best ideas and choices to be made. The dashboard, based on real data, provides new insights on the performance of the urban forest and also on new visionary plans. Stakeholder collaboration within the project has been continuing and has fuelled opportunities for ongoing value to participating firms. This value comes from closer networks of stakeholders and stronger ties, but also from the outcomes of the project, for example from the value of empirical data, and the incorporation of that data via models into the functional dashboard outcome located in WP3.

Final Words

In future we hope to see a smarter greening of Dutch cities to prepare for a changing climate - one that is increasingly warm with more extreme weather events. Rather than the ‘let’s plant a million trees’ promise often outlined during political campaigns, our research shows that diligent specifies-specific planning, planting care and maintenance of green space that grows with cities built infrastructure and citizens, not against them, must be the true objective of urban climate resilience. This research investigates the contribution of trees to the livability of our urban environment in a Dutch specific context.

The output of this project makes theoretical and practical contributions that allow all invested in developing climate resilient futures to enact such change. With so many thanks to our consortium members. Without whom this project would not have been so impactful. Their generosity and care for trees, citizens and their work has made this project possible.

With final thanks and gratitude to the trees.

References

AHN. (2023, March 27). *Kwaliteitsbeschrijving*. https://www.ahn.nl/kwaliteitsbeschrijving

AHN. (2024, June 4). *Home*. https://www.ahn.nl/

Atelier Rijkbouwmeester, Gemeente Amsterdam, & Marineterrein Amsterdam. (2021). *Marineterrein Amsterdam Poort Naar de Toekomst, Concept Nota van Uitgangspunten Inspraakversie* https://www.omgevingsweb.nl/nieuws/marineterrein-amsterdam-wordt-groene-duurzame-wijk-met-zon-800-woningen-ruim-2000-banen-en-een-stadspark-aan-het-oosterdok/

Birmingham City Council, Birmingham Tree People, Nature Based Solutions Institute, & Treeconomics. (2021). *An Urban Forest Master Plan for Birmingham 2021-2051: Executive Report*. Retrieved from http://birminghamtreepeople.org.uk/birminghams-urban-forest-master-plan/

Dark Matter Labs. (2020). *Trees As Infrastructure*. Dark Matter. Retrieved 28 October 2024 from https://provocations.darkmatterlabs.org/trees-as-infrastructure-1dd94e1cfedf

Dunne, A., & Raby, F. (2013). *Speculative Everything Design, Fiction, and Social Dreaming*. The MIT Press. http://www.jstor.org/stable/j.ctt9qf7j7

Forestami. (2020). *3 million trees by 2030*. Retrieved 28 October 2024 from https://forestami.org/en/

i-Tree. (n.d.). *UFORE methods*. https://www.itreetools.org/documents/53/UFORE%20Methods.pdf

i-Tree 2.0-NL.Retrieved 07/07/2023 from https://www.tudelft.nl/io/onderzoek/sustainability/i-tree-20-nl

Irwin, T. (2018). The Emerging Transition Design Approach. https://doi.org/10.21606/dma.2017.210

Jones, P., & Ael, K. V. (2022). *Design Journeys through Complex System Practice Tools for Systemic Design*.

Keizer, S. (2023). *The Future of the Urban Forest: Exploring the systemic granularity of the urban green domain to navigate towards a new paradigm* TU Delft]. Delft.

Kendal, D., Dobbs, C., & Lohr, V. I. (2014). Global patterns of diversity in the urban forest: Is there evidence to support the 10/20/30 rule? *Urban Forestry & Urban Greening, 13*(3), 411-417. https://doi.org/https://doi.org/10.1016/j.ufug.2014.04.004

KNMI. (n.d.). *KNMI - Warme dagen*. Retrieved October 28, 2024, from https://www.knmi.nl/kennis-en-datacentrum/uitleg/warme-dagen

Konijnendijk, C. (2021). The 3-30-300 Rule for Urban Forestry and Greener Cities. *Biophilic Cities Journal, 4*.

Konijnendijk, C. C. (2023). Evidence-based guidelines for greener, healthier, more resilient neighbourhoods: Introducing the 3–30–300 rule. *Journal of Forestry Research, 34*(3), 821-830. https://doi.org/10.1007/s11676-022-01523-z

Leith, K., Vogel, S., & Mehta, K. (2022). The participatory design spectrum: design for, with, and by. In *Handbook of Innovation & Appropriate Technologies for International Development* (pp. 125-139). https://doi.org/10.4337/9781800887824.00017

Morrison, T., Adger, W., Agrawal, A., Brown, K., Hornsey, M., Hughes, T., Jain, M., Lemos, M., Holmes McHugh, L., O'Neill, S., & Van Berkel, D. (2022). Radical interventions for climate-impacted systems. *Nature Climate Change, 12*. https://doi.org/10.1038/s41558-022-01542-y

Paulin, M. J., Remme, R. P., van der Hoek, D. C. J., de Knegt, B., Koopman, K. R., Breure, A. M., Rutgers, M., & de Nijs, T. (2020). Towards nationally harmonized mapping and quantification of ecosystem services. *Science of The Total Environment, 703*, 134973. https://doi.org/https://doi.org/10.1016/j.scitotenv.2019.134973

Platform i-Tree Nederland, (2019), De baten van Bomen: Resultaten van i-Tree in Nederland.

Pretzsch, H., Moser-Reischl, A., Rahman, M. A., Pauleit, S., & Rötzer, T. (2023). Towards sustainable management of the stock and ecosystem services of urban trees. From theory to model and application. *Trees, 37*(1), 177-196. https://doi.org/10.1007/s00468-021-02100-3

Price, R., Van Erp, J., Fuentes Flores, N., Kesisoglou, J. & Becks, M. (2020). *Initiating a Multi-Party Collaboration for Adaption and Resilience to Urban Heatwave*s. NWO KIEM Report “Urban Heatwaves” KI.18.043

Santamour, F. (1990). Trees for urban planting: Diversity, uniformity and common sense*. Proceedings of the 7th Conference of the Metropolitan Tree Improvement Alliance, 7*.

Stephenson, N. L., Das, A. J., Condit, R., Russo, S. E., Baker, P. J., Beckman, N. G., Coomes, D. A., Lines, E. R., Morris, W. K., Rüger, N., Álvarez, E., Blundo, C., Bunyavejchewin, S., Chuyong, G., Davies, S. J., Duque, Á., Ewango, C. N., Flores, O., Franklin, J. F., Zavala, M. A. (2014). Rate of tree carbon accumulation increases continuously with tree size. *Nature, 507*(7490), 90-93. https://doi.org/10.1038/nature12914

Swat, J., Sevaldson, Birger and Luthe, Tobias. (2019, Oct 13-15 2019). *When Is systemic design regenerative? Values, direction and currencies in systemic design methodology* Relating Systems Thinking and Design (RSD8) 2019 Symposium, Chicago, USA. http://openresearch.ocadu.ca/id/eprint/3249/

The Green Village. (n.d.). T*he Green Village, Fieldlab voor duurzame innovatie*. Retrieved October 21, 2024, from https://www.thegreenvillage.org/

van der Velden, M., & Mörtberg, C. (2015). Participatory Design and Design for Values. In H. Jeroen van den, E. V. Pieter, & P. Ibo van de (Eds.), *Handbook of Ethics, Values, and Technological Design : Sources, Theory, Values and Application Domains* (pp. 41-66). Springer. https://doi.org/10.1007/978-94-007-6970-0_33

Van Der Velde, R., De Wit, S., & Pouderoijen, M. (2023). Cool Tree Architecture: A descriptive framework for a tree architecture typology to temper urban microclimates. *Landscape Architecture Frontiers, 11*(5), 30. https://doi.org/10.15302/j-laf-1-020084

Appendix 1. | Overview C-TAT ranking, including individual rankings and categorisations per trait.

Table A: Ranking and category of each "tree architecture" trait per tree species, including the overall ordered, weighted and abbreviated C-TAT ranking

	Foliage				**Crown**		**Wood**				**C-TAT**	
	Transluminescense		Porosity		Density		Zoning		Grain			
Species	*Ranking*	*Category*	*Ranking*	*Category*	*Ranking*	*Category*	*Ranking*	*Category*	*Ranking*	*Category*	*Weighted*	*Abbreviated*
Acer campestere	29	2	31	2	42	2	43	2	50	2	22222	22
Acer cappdadocium "Rubrum"	54	3	33	2	60	3	35	2	29	2	32232	33
Acer platanoides "Emerlad Queen"	57	3	49	2	65	3	25	2	8	1	32231	33
Acer pseudoplatanus	3	1	56	3	32	2	7	1	10	1	21311	21
Acer saccharinum	5	1	22	2	33	2	18	1	9	1	21211	21
Alnus x spaethii "Spaeth"	49	2	47	2	30	2	36	2	37	2	22222	22
Amelanchier lamarckii	17	1	25	2	24	2	42	2	44	2	22212	21
Betula nigra "BNTF" Dura Heat	4	1	15	1	15	1	24	2	65	3	12113	11
Betula pendula	20	1	24	2	20	2	19	1	56	3	21213	21
Betula pubescens	32	2	7	1	4	1	22	2	58	3	12123	12
Betula utilis "Jacquemontii"	19	1	4	1	8	1	31	2	59	3	12113	11
Carpinus betulus	13	1	61	3	61	3	34	2	54	3	32313	31
Castanea sativa	9	1	59	3	49	3	52	3	24	1	33311	31
Catalpa bignonioides	11	1	53	3	25	2	8	1	2	1	21311	21
Cedrus libani	68	3	62	3	11	1	1	1	11	1	11331	13
Celtis occdientalis	1	1	63	3	52	3	5	1	39	2	31312	31
Chamaecyparis lawsoniana cv.	34	2	54	3	64	3	66	3	66	3	33323	32
Cornus mas	63	3	48	2	68	3	64	3	42	2	33232	33
Corylus colurna	14	1	67	3	44	2	27	2	19	1	22311	21
Crataegus monogyna	42	2	5	1	5	1	38	2	57	3	12123	12
Fagus sylvatica	27	1	19	1	57	3	30	2	64	3	32113	31
Gingko biloba	43	2	51	2	28	2	2	1	6	1	21221	22
Gledistia triacanthos "Inermis"	7	1	43	2	13	1	3	1	26	2	11212	11
Gymnocladus dioica	6	1	44	2	36	2	10	1	1	1	21211	21
Juglans regia	39	2	28	2	35	2	17	1	3	1	21221	22
Koelreuteria paniculata	16	1	14	1	9	1	4	1	18	1	11111	11
Liquidambar styraciflua	22	1	52	3	54	3	50	3	4	1	33311	31
Liriodendron tulipifera	18	1	35	2	53	3	46	2	12	1	32211	31
Magnolia grandiflora	45	2	42	2	26	2	65	3	41	2	23222	22
Magnolia kobus	48	2	29	2	18	2	48	2	49	2	22222	22
Metasequoia glyptostroboides	33	2	27	2	59	3	59	3	53	3	33223	32
Morus alba	2	1	20	1	2	1	20	1	20	1	11111	11
Nyssa sylvatica	25	1	68	3	47	3	49	3	47	2	33312	31
Parrotica persica "Vanessa"	56	3	10	1	63	3	41	2	35	2	32132	33
Picea abies	65	3	11	1	67	3	39	2	67	3	32133	33
Pinus strobus	62	3	26	2	19	2	44	2	55	3	22233	23

	Foliage				**Crown**		**Wood**				**C-TAT**	
	Transluminescense		Porosity		Density		Zoning		Grain			
Species	*Ranking*	*Category*	*Ranking*	*Category*	*Ranking*	*Category*	*Ranking*	*Category*	*Ranking*	*Category*	*Weighted*	*Abbreviated*
Acer campestere	29	2	31	2	42	2	43	2	50	2	22222	22
Acer cappdadocium "Rubrum"	54	3	33	2	60	3	35	2	29	2	32232	33
Acer platanoides "Emerlad Queen"	57	3	49	2	65	3	25	2	8	1	32231	33
Acer pseudoplatanus	3	1	56	3	32	2	7	1	10	1	21311	21
Acer saccharinum	5	1	22	2	33	2	18	1	9	1	21211	21
Alnus x spaethii "Spaeth"	49	2	47	2	30	2	36	2	37	2	22222	22
Amelanchier lamarckii	17	1	25	2	24	2	42	2	44	2	22212	21
Betula nigra "BNTF" Dura Heat	4	1	15	1	15	1	24	2	65	3	12113	11
Betula pendula	20	1	24	2	20	2	19	1	56	3	21213	21
Betula pubescens	32	2	7	1	4	1	22	2	58	3	12123	12
Betula utilis "Jacquemontii"	19	1	4	1	8	1	31	2	59	3	12113	11
Carpinus betulus	13	1	61	3	61	3	34	2	54	3	32313	31
Castanea sativa	9	1	59	3	49	3	52	3	24	1	33311	31
Catalpa bignonioides	11	1	53	3	25	2	8	1	2	1	21311	21
Cedrus libani	68	3	62	3	11	1	1	1	11	1	11331	13
Celtis occdientalis	1	1	63	3	52	3	5	1	39	2	31312	31
Chamaecyparis lawsoniana cv.	34	2	54	3	64	3	66	3	66	3	33323	32
Cornus mas	63	3	48	2	68	3	64	3	42	2	33232	33
Corylus colurna	14	1	67	3	44	2	27	2	19	1	22311	21
Crataegus monogyna	42	2	5	1	5	1	38	2	57	3	12123	12
Fagus sylvatica	27	1	19	1	57	3	30	2	64	3	32113	31
Gingko biloba	43	2	51	2	28	2	2	1	6	1	21221	22
Gledistia triacanthos "Inermis"	7	1	43	2	13	1	3	1	26	2	11212	11
Gymnocladus dioica	6	1	44	2	36	2	10	1	1	1	21211	21
Juglans regia	39	2	28	2	35	2	17	1	3	1	21221	22
Koelreuteria paniculata	16	1	14	1	9	1	4	1	18	1	11111	11
Liquidambar styraciflua	22	1	52	3	54	3	50	3	4	1	33311	31
Liriodendron tulipifera	18	1	35	2	53	3	46	2	12	1	32211	31
Magnolia grandiflora	45	2	42	2	26	2	65	3	41	2	23222	22
Magnolia kobus	48	2	29	2	18	2	48	2	49	2	22222	22
Metasequoia glyptostroboides	33	2	27	2	59	3	59	3	53	3	33223	32
Morus alba	2	1	20	1	2	1	20	1	20	1	11111	11

Appendix 2. | Campaign Days measurement protocol for volunteers.

1. For the Campaign Day you should:

Wear a white t-shirt and a hat
Bring drinks and lunch
Install the Kestrel Link app on your phone LINK: https://play.google.com/store/apps/details?id=com.kestrelinstruments.kdex&hl=en&gl=US
Don't forget sunscreen!

2. Collect the campaign bag:

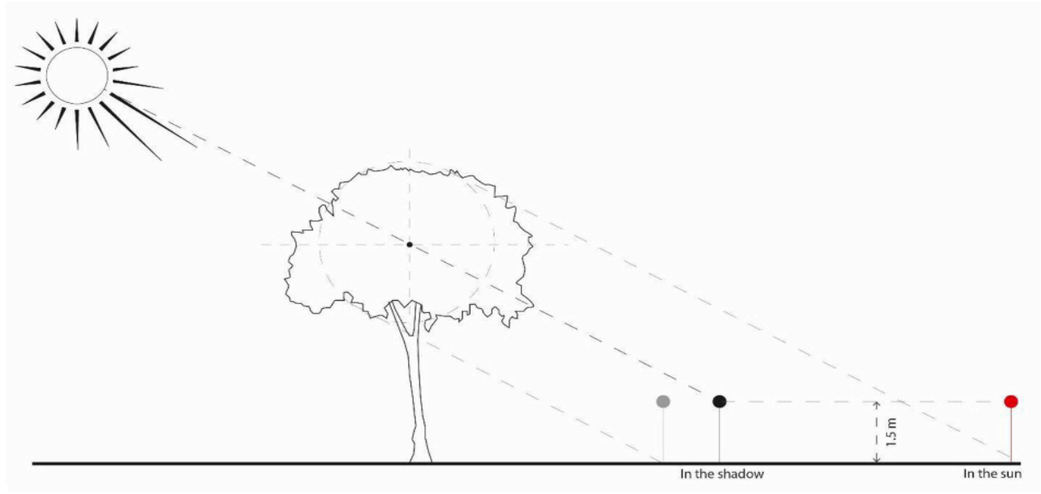
- The week manager will communicate when and where to meet the day before the campaign
- The bag should contain 1 kestrel + 1 tripod + 1 copy of the campaign diary + 1 copy of this protocol +1 extra battery

3. Install the kestrel at location:

- When you reach the location install the 2 kestrels on tripods
- Switch ON the Kestrels by pressing the power button
- Use the phone app Kestrel Link, and connect to the kestrels. If you do not see the kestrel number appearing on your screen check on kestrel if the Bluetooth is ON.
- Once the devices are connected the kestrel should automatically synchronize with the current date and time. If this doesn't happen change the time on kestrels going on System> Time and date
- Check to see if traffic cones are need to cordon off zone.

4. Place the kestrels in position:

- Ensure that the sensor is properly positioned. One sensor has to stay in the shade of the tree and one has to be in the sun. See image below for aligning the tree in the shade to the central point of the crown
- Make any necessary adjustments according to the condition of the ground.
- Open the wind cup
- Check the spirit level to get it completely level and adjust accordingly using the control knob



5. Allow sensor acclimatization:

- Wait minimum 10 minutes to allow the sensor to acclimatize to the surrounding environment. This step helps ensure accurate readings from the sensor.
- The campaign should start by 10.30

6. Report on C diary:

- After 10 minutes you can officially start the campaign.
- Use the Campaign diary (C diary) to report the starting time and the other details requested. This information will be used for reference and tracking purposes.

7. Activity during the campaign:

- Every 10 minutes check that the screen is on and the position of both kestrels in the shade and in the sun.
- Reposition the kestrel following the shade. Check the spirit level and adjust accordingly using the control knob
- Reposition the kestrel in the sun if needed. Check the spirit level and adjust accordingly using the control knob
- Report on the C diary if something happens during the campaign, for example if the kestrel switched off or if it fell or you change the battery
- During the day ask how the other volunteer feels and communicate how do you feel.
- At the first signs of thermal distress sit on the floor in the shade, eat something sweet and drink water. After it, call the week manager for instructions.
- Take turns with the other volunteer at the tree for going to the toilette. Never leave the kestrels unattended.

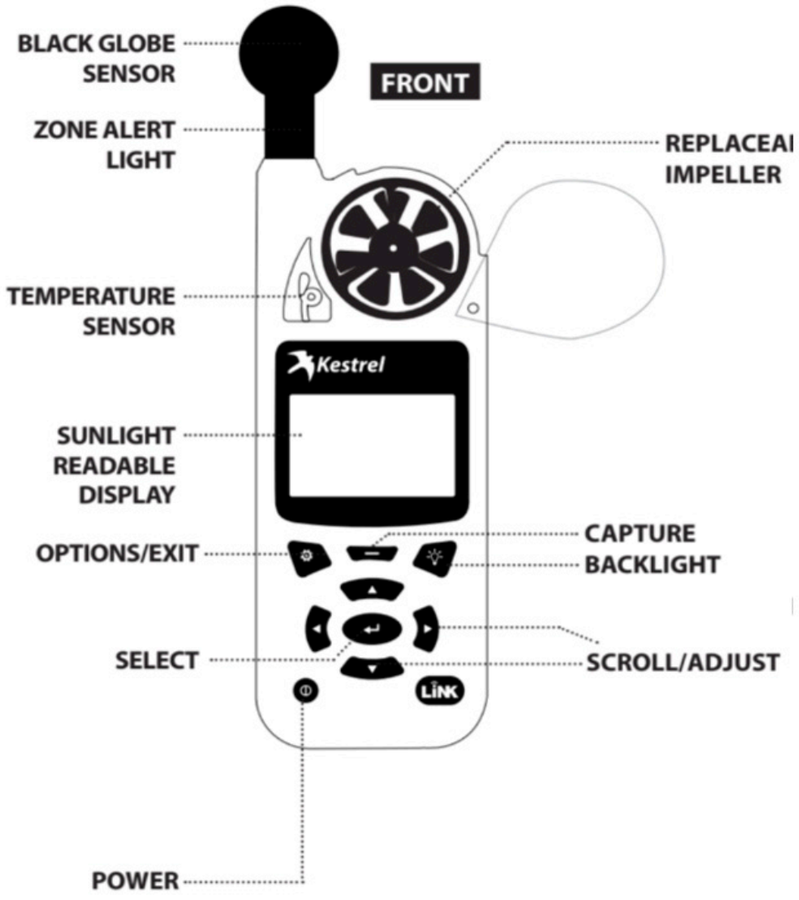
8. End of the campaign:

- At 17.00h switch off the kestrel and repack the instruments

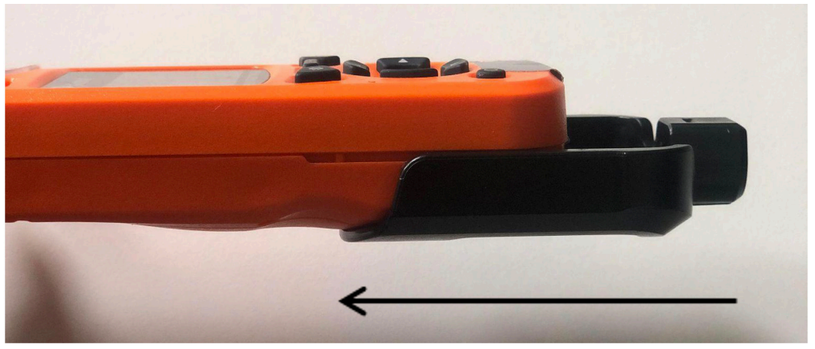
and tripods
- Meet the week manager at the meeting point previously communicated and return the bag with 1 kestrel + 1 tripod + 1 campaign diary

If you have doubts or questions reach the week managers by phone
A document will be shared the day before the campaign with the contact numbers and meeting points. You will also be added to a WhatsApp group for communicating with the other volunteers and week manager

Kestrel installation instructions

















Appendix 3. | Measurements of the cooling effects of a selection of mature trees in the i-Tree 2.0-NL project and the results of the data analysis.

1. Introduction

This addendum reports on the measurements of the cooling effects of a selection of mature trees in the i-Tree 2.0-NL project and the results of the data analysis.

2.1 Selection

The first step in the selection of mature trees for measurement was to inventory the tree species present in the municipalities, using the local databases. Species with a high number of specimens in all municipalities were prioritized. Based on this criterion, the species selected for measurement were Platanus × hispanica, Tilia × europaea, and Betula pendula (Fig 1).
Since this second phase of the research focused on the cooling performance of trees in adult stage, only the specimens meeting this requirement were included in the dataset.

Subsequently, specimens were selected according to three spatial criteria:

- The tree was required to be freestanding; its crown could not be in physical contact with adjacent crowns, and its projected shade could not intersect with that of neighboring trees.
- The tree could not be situated within close proximity to built structures.
- The tree could not be situated within close proximity to surface water bodies.

As a final step, consultation workshops were held with local tree experts to establish the final selection, which was subsequently confirmed through field inspections.
In each municipality, three trees – one of each species - were selected within a street canyon (east-west orientation) and three within a park, i.e., located on either pervious or impervious surfaces.



Figure 1 spatial distribution of the three selected species in the project municipalities

2.2 Equipment and Protocols for Measurements

The equipment and setup utilized for the measurements was the same as for the measurements in the climate arboretum (see technical report pp.47), except for the Davis Vantage Pro2, which was excluded (Fig. 2).

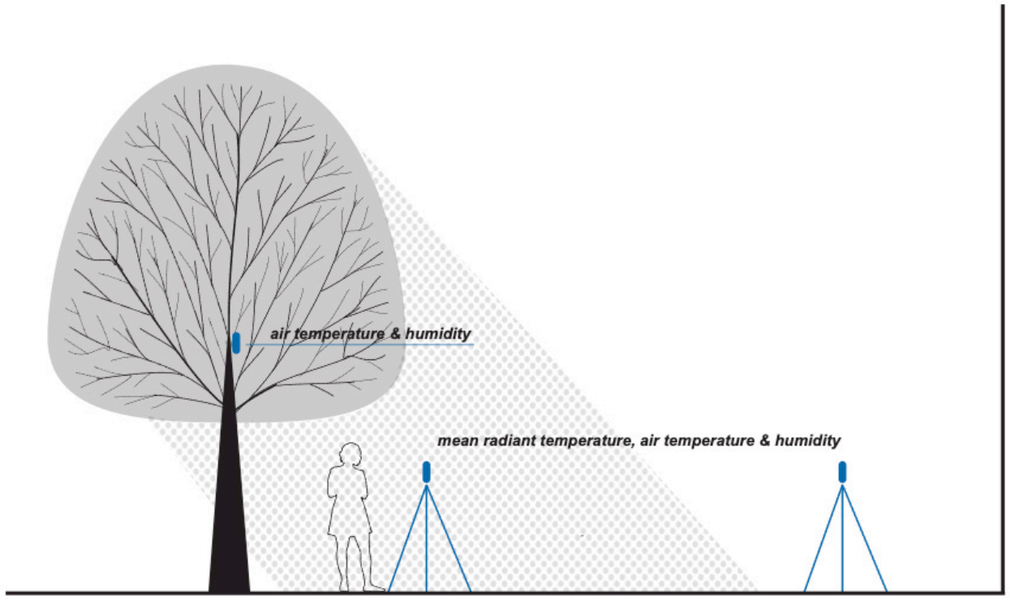


Figure 2 measurement setup

A HOBO Onset MX2301A Temperature/RH data logger encased by a TFA Dostmann 98.1114 radiation shield was installed on the widest part of the crown of each tree, facing north to minimize incident solar radiation to enter the casing. The loggers were set to a 3-minute measurement frequency. Data was stored locally in the logger. With this measurement frequency, the loggers had a capacity of approximately 60 days.

The protocol for measurements in the trees' shades was comparable to that of the trees in the climate arboretum (see technical report pp.48): for each tree, one Kestrel 5400 WGBT Heat Stress Tracker was placed in the middle of the canopy shade of the tree and one in the sun as a reference, both at 1.5 meters above ground level to reflect human exposure. The sensors in the canopy shade were repositioned every 10 minutes following the movement of the sun, logging data every 5 seconds.

Measurements were performed on warm cloudless days with an (expected) daily maximum air temperature of at least 22 degrees Celsius, between 10.30 and 17.00 hrs, in the period from June 21st until September 21st.

2.3 Measurement campaigns

Measurements using Kestrel devices were conducted in five of the eight participating municipalities during the summers of 2023 and 2024 (Table 1). For each tree, one TU Delft staff member was responsible for carrying out the measurements, assisted by a municipal volunteer. TU Delft staff were instructed on the installation and operation of the measurement equipment (see Appendix 2).

Each team was asked to complete a field diary for every measurement day, documenting the tree identity, the measurement instruments used, the exact start and end times, and any relevant observations or anomalies (e.g., nearby human activity, passing cloud cover).

Table 1. Measurement days for each city (Kestrels)

07/07/2023	21/08/2023	08/09/2023	19/07/2024	12/08/2024
Den Haag	Amsterdam	Utrecht	Groningen	Rotterdam

3. Methods for data processing

In order to analyse the results, the data collected during the campaigns were retrieved from local data storage, preprocessed, and corrected.
During the campaigns, data from Hobos and Kestrels were stored locally with different time intervals (3 minutes -Hobos, 5 seconds -Kestrels). As previously described in section 1.3.1.3 linear error functions were used for correcting air temperature and relative humidity values. Aggregation techniques in R environment were performed to average the values.

For data collected through Hobo loggers, values were selected in the interval 30/June – 31/September during the summers 2023 and 2024. Due to malfunctioning of the loggers or stolen instruments, data loss was reported for the Tilia in green (Amsterdam), and the Platanus in green (Groningen). A metadata file was generated with the start and end date of each hobo measurement. Median, maximum and minimum values were calculated for measured air temperature and relative humidity.

For data collected through Kestrels, values were aggregated at 20 minutes interval in the time range between 11.00h and 16.30h. In a second phase Mean Radiant Temperature was calculated. Finally statistical analyses and data plotting were carried out for the entire dataset.

4. Results

4.1 Tree canopies (HOBO's)

The measured maximum and minimum air temperatures in the tree crowns during the summer of 2024 are shown in Figures 3 and 4, respectively. With regard to maximum air temperatures, the results indicate that Betula specimens generally provide the least temperature reduction compared with Platanus and Tilia specimens within the same municipality and type of environment (i.e., street canyon or park). Exceptions to this trend were observed for the Betula in the canyon in Rotterdam and the Betula in the park in Dordrecht.
Moreover, in nearly all municipalities, the highest maximum air temperatures were recorded in canyon settings, confirming that paved/enclosed environments tend to be warmer than open vegetated areas.

The results for the minimum air temperatures indicate that city-level differences are larger than differences between the three species; minimum temperatures are broadly comparable within the same municipality. This suggests that local climatic conditions (geographic location, ventilation and/or regional scale climate characteristics) may play a more important role in nighttime (crown) temperatures.
Rotterdam exhibits the lowest minimum air temperatures, which may be explained through the peripheral location of the trees measured.

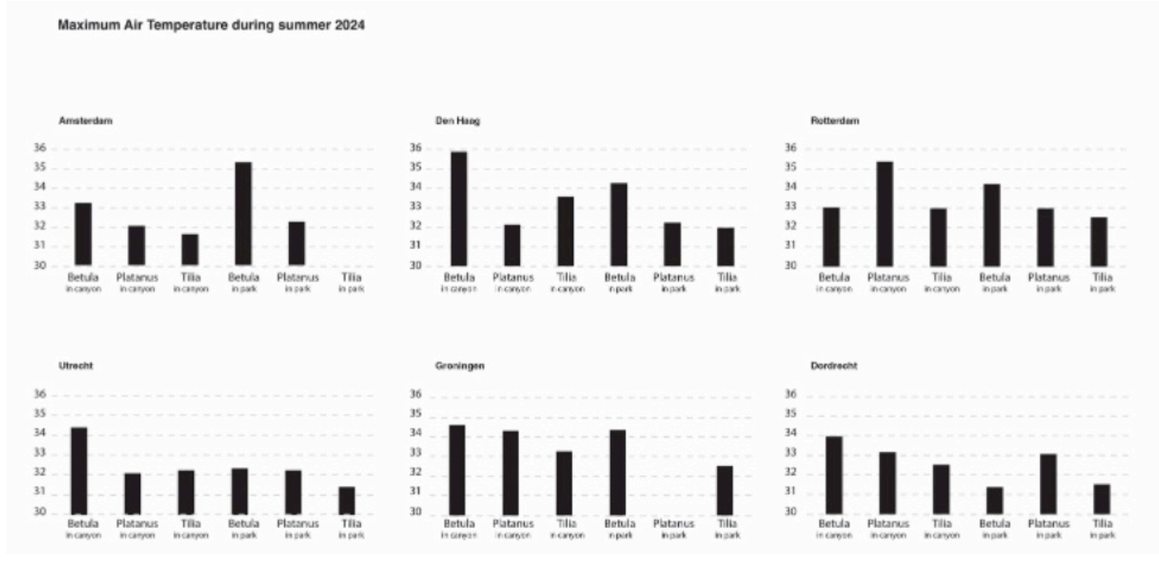


Figure 3 Maximum air temperature in tree crowns during the summer of 2024

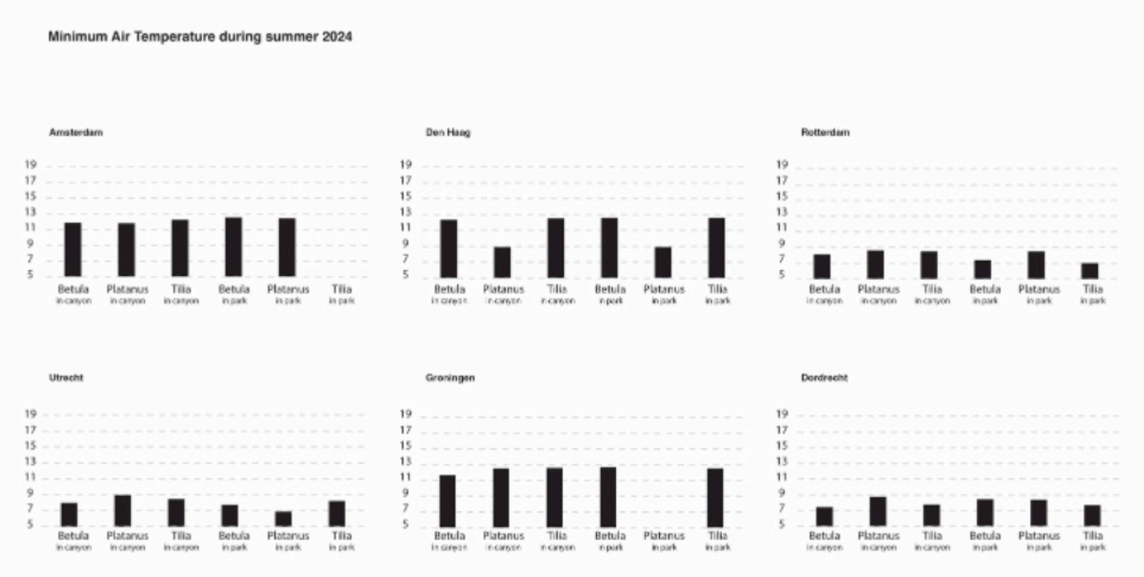


Figure 4 Minimum air temperature in tree crowns during the summer of 2024

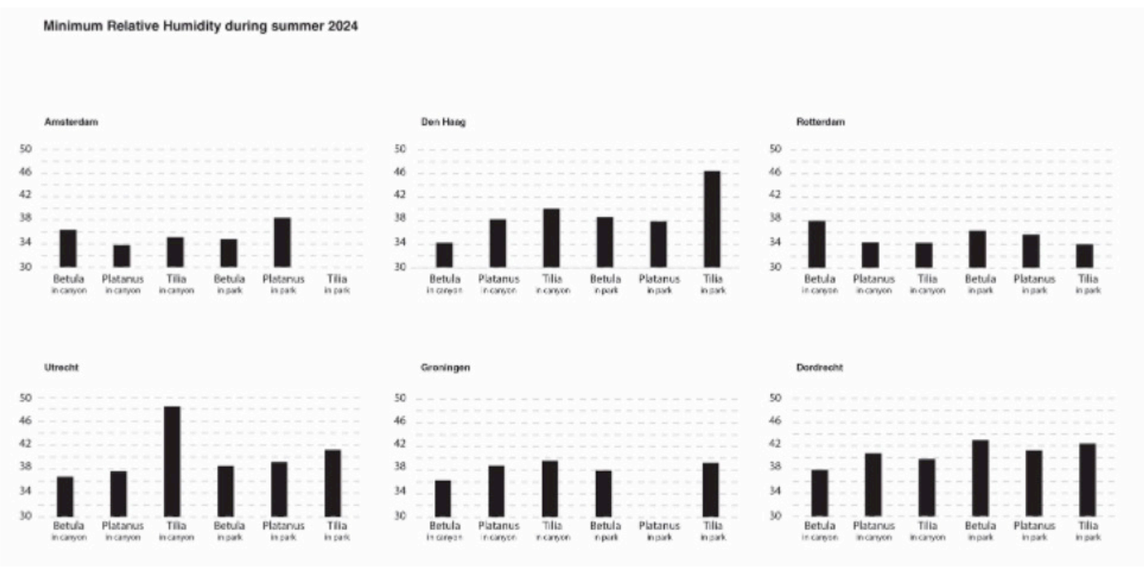


Figure 5 Minimum relative humidity in tree crowns during the summer of 2024

Figure 5 shows the minimum relative humidity measured in the tree crowns in the summer of 2024. Like for minimum air temperatures, the measurements suggest that regional scale climate conditions are dominant over tree species characteristics. Environment type only seems to have a marginal impact, differences between canyon and park environments are very small, with generally slightly higher minimum relative humidity in vegetated areas. This minor variation also suggests that cooling through evapotranspiration is reduced during hot periods, resulting in low relative humidity also within green areas and parks.

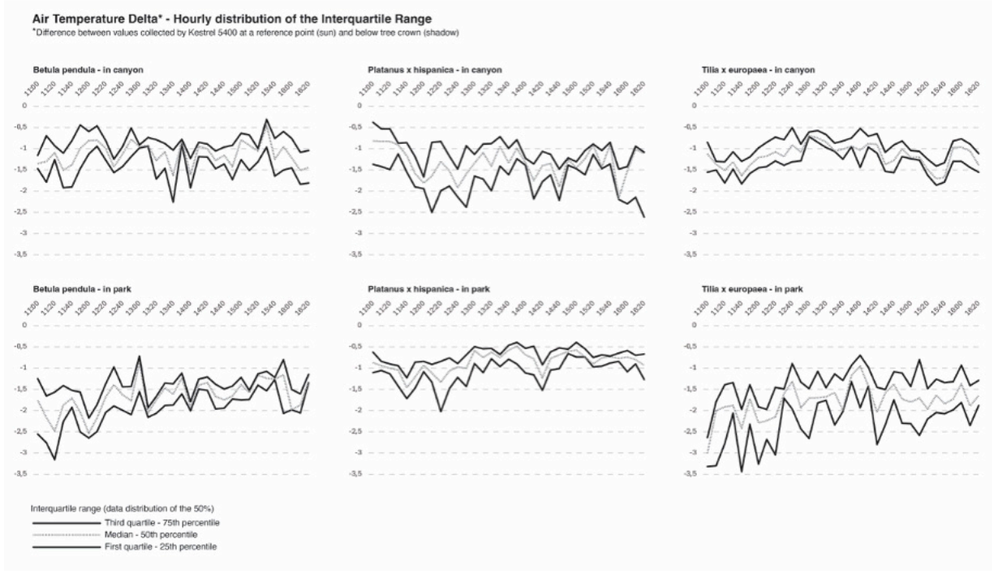
4.2 Tree shades (Kestrels)

The climate performance of trees was observed through measured and calculated variables.
Figures 6 and 7 report the 25-75 percentile of variation between values measured at a reference point in the sun and values measured in the shade of each tree crown with a 20 minute timestamp. Values are grouped for the three species and their location in canyon and in green areas.

The difference in air temperature between a reference point in direct sunlight and the shaded point beneath the tree canopies varied across monitored species and their location (figure 6). Overall, the air temperature delta ranged from -3.5°C to -0.3°C. These values below zero indicate that the air temperature in the shade of tree is lower than the one at the reference point, and thus the cooling potential of the tree during the day. The interquartile range shows the aggregated cooling pattern among cities. In East-west canyons the Tilia x europaea and the Betula pendula have an almost linear performance typically ranging between -2°C and -0.5°C, while the Platanus x hispanica reaches a 75th percentile cooling potential up to -2,5°C and shows an higher elasticity during the late morning hours.

In parks, the Platanus x hispanica maintains an almost linear cooling pattern with a lower elasticity between -2°C and -0.4°C, compared to in canyon location. At the opposite, the Betula pendula and the Tilia x europaea, show an overall higher cooling potential in parks than in canyons, but their capacity of reducing air temperature is ascendent, meaning that it tends to diminish progressively throughout the day. Despite this pattern, the Tilia x europaea demonstrate to provide the highest cooling potential by reaching air temperature reduction up to -3,5°C.

Figure 6 Hourly interquartile range of differences in air temperature between the reference measurement (in the sun) and the tree shade.



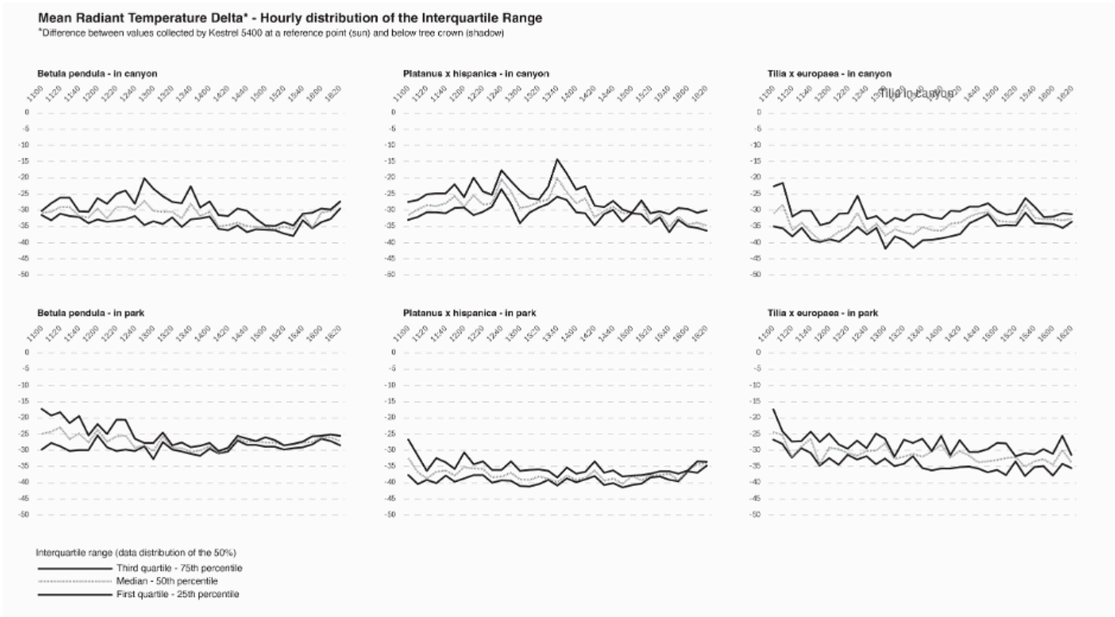


Figure 7 Hourly interquartile range of differences in mean radiant temperature between the reference measurement (in the sun) and the tree shade.

The Mean Radiant Temperature plots confirm the strong cooling effect of tree canopies, with interquartile values ranging from -42°C to -15°C (Figure 7). The substantial reduction in MRT under the tree canopy underscores the significant impact of trees in mitigating radiant heat, thereby enhancing thermal comfort in shaded areas compared to sun-exposed locations. Also in this case, the difference in MRT between a reference point in direct sunlight and the shaded point beneath the tree canopies varied across monitored species and their location.

In East-west canyons the Betula pendula and the Platanus x hispanica contribute to reduce MRT between -20°C to -38°C and -15°C and -36°C respectively. In canyons, the Tilia x europaea demonstrate the highest cooling performance in MRT terms by showing -42°C interquartile difference between reference point and shaded point. Differently the Platanus x hispanica shows the highest cooling potential in parks, by reaching MRT up to -41°C.

5. Limitations and future work

The selection of specimens to monitor based on multiple variables pose multiple challenges. Standalone trees are infrequent to find both in canyons and in parks, reducing sensibly the sample size for measurements. Additionally, distance from the building façade is calculated based on the crown diameter reported in the municipal datasets which are updated every 3-5 years and do not consider pruning activities. The information in the digital dataset therefore needs to be confirmed through repeated qualitative evaluations in the field during the selection process.

While specimens for the monitoring were chosen based on criteria of canyon orientation and distance from water bodies and buildings, the relative position in the city was not taken into consideration. As a result, trees located in the urban peripherical areas might be generally exposed to lower temperatures compared to those located in the denser city centers. Future monitoring protocols for adult trees in urban environments should include the selection of multiple specimens in different urban locations (morphologies and densities).

Appendix 4. | Calculated growth formulas at genus, species and cultivar level.

*Table B. Growth parameters to calculate crown diameter (CD) with the formula: CD = β0 + β1*age + β2*(age)².*

Growth parameters for crown diameter (CD)			CD = β0 + β1*age + β2*(age)²			
Genus	Species	Cultivar	Nr. of trees	β0	β1	β2
Acer			15689	1,93	1,29	0,02
Aesculus			5845	1,80	1,27	0,04
Ailanthus			2351	1,81	1,59	-0,09
Alnus			6552	2,05	1,95	-0,13
Betula			5816	0,85	2,53	-0,22
Carpinus			7838	2,56	-0,02	0,20
Corylus			4100	2,21	0,58	0,07
Crataegus			642	4,29	0,83	-0,04
Fagus			1029	2,23	1,54	0,11
Fraxinus			19374	0,98	1,88	-0,06
Ginkgo			2712	2,84	-0,22	0,13
Gleditsia			1873	1,50	2,26	-0,30
Liquidambar			5095	1,47	1,78	-0,24
Magnolia			1560	1,73	0,83	0,01
Metasequoia			2802	2,40	0,88	0,07
Pinus			658	3,69	0,08	0,15
Populus			1604	0,85	1,89	-0,09
Prunus			7733	1,43	1,65	-0,13
Pterocarya			804	0,13	4,73	-0,30
Pyrus			11068	0,99	1,29	-0,13
Quercus			15616	0,94	2,14	-0,03
Robinia			2826	2,71	1,79	-0,20
Salix			4710	3,25	0,57	0,14
Sorbus			2813	2,02	0,58	0,02
Styphnolobium			2833	2,94	0,69	0,06
Taxus			190	0,98	-0,22	-0,05
Tilia			13461	0,97	1,86	-0,12
Ulmus			17243	1,34	1,58	-0,18
Acer	*campestre*		4333	1,40	1,90	-0,06
Acer	*platanoides*		3144	0,79	1,74	-0,08
Acer	*pseudoplatanus*		6723	2,41	0,98	0,06
Acer	*saccharinum*		1489	3,78	0,38	0,21
Aesculus	*hippocastanum*		5845	1,80	1,27	0,04
Ailanthus	*altissima*		2351	1,81	1,59	-0,09
Alnus	*cordata*		3248	2,06	1,83	-0,13
Alnus	*glutinosa*		3304	1,98	2,16	-0,15
Betula	*pendula*		3695	1,01	2,75	-0,28
Betula	*pubescens*		651	1,09	2,85	-0,26
Betula	*utilis*		1470	1,88	0,85	0,08
Carpinus	*betulus*		7838	2,56	-0,02	0,20
Corylus	*colurna*		4100	2,21	0,58	0,07
Crataegus	*monogyna*		642	4,29	0,83	-0,04
Fagus	*sylvatica*		1029	2,23	1,54	0,11
Fraxinus	*angustifolia*		1870	-0,73	4,23	-0,46
Fraxinus	*excelsior*		17504	1,06	1,72	-0,03
Ginkgo	*biloba*		2712	2,84	-0,22	0,13
Gleditsia	*triacanthos*		1873	1,50	2,26	-0,30
Liquidambar	*styraciflua*		5095	1,47	1,78	-0,24
Magnolia	*kobus*		1560	1,73	0,83	0,01
Metasequoia	*glyptostroboides*		2802	2,40	0,88	0,07
Pinus	*nigra*		658	3,69	0,08	0,15
Populus	*nigra*		1604	0,85	1,89	-0,09
Prunus	*avium*		4387	0,66	2,49	-0,25
Prunus	*cerasifera*		1227	1,61	1,42	-0,10
Prunus	*serrulata*		2119	2,57	0,41	0,05
Pterocarya	*fraxinifolia*		804	0,13	4,73	-0,30
Pyrus	*calleryana*		11068	0,99	1,29	-0,13
Quercus	*cerris*		5103	2,02	0,56	0,26
Quercus	*palustris*		2296	2,60	0,91	0,07
Quercus	*robur*		8217	0,28	2,96	-0,16
Robinia	*pseudoacacia*		2826	2,71	1,79	-0,20
Salix	*alba*		4710	3,25	0,57	0,14
Sorbus	*aria*		1250	3,01	-0,23	0,16
Sorbus	*intermedia*		1563	1,31	1,16	-0,08
Styphnolobium	*japonicum*		2833	2,94	0,69	0,06
Taxus	*baccata*		190	9,84	-0,22	-0,05
Tilia	*americana*		1206	2,46	0,68	0,03
Tilia	*cordata*		3968	1,13	1,94	-0,16
Tilia	*platyphyllos*		1379	0,53	2,17	-0,15
Tilia	*tomentosa*		6908	1,06	1,64	-0,06
Acer	*campestre*	Elsrijk	1831	2,71	-0,02	0,23
Acer	*platanoides*	Globosum	1060	1,09	1,38	-0,13
Acer	*pseudoplatanus*	Erectum	866	1,17	2,08	-0,07
Acer	*pseudoplatanus*	Negenia	2056	4,46	-0,78	0,27
Aesculus	*hippocastanum*	Baumannii	3983	1,41	1,40	0,01
Betula	*utilis*	Doorenbos	1470	1,88	0,85	0,08
Carpinus	*betulus*	Fastigiata	3144	2,09	0,52	0,09
Carpinus	*betulus*	Frans Fontaine	3002	2,36	0,04	0,05
Fraxinus	*angustifolia*	Raywood	1870	-0,73	4,23	-0,46
Fraxinus	*excelsior*	Diversifolia	2049	-0,36	0,28	-0,24
Fraxinus	*excelsior*	Westhofs Glorie	5186	2,10	0,60	0,14
Populus	*nigra*	Italica	1604	0,85	1,89	-0,09
Prunus	*avium*	Plena	3169	1,03	1,97	-0,21
Prunus	*cerasifera*	Nigra	1227	1,61	1,42	-0,10
Prunus	*serrulata*	Kanzan	2119	2,57	0,41	0,05
Pyrus	*calleryana*	Chanticleer	11068	0,99	1,29	-0,13
Quercus	*robur*	Alpha	625	-1,05	5,11	-0,45
Robinia	*pseudoacacia*	Bessoniana	2184	2,84	2,21	-0,27

Robinia	*pseudoacacia*	Umbraculifera	642	2,15	0,90	-0,12
Tilia	*tomentosa*	Brabant	3558	1,69	0,92	0,05

*Table C. Growth parameters to calculate tree height (H) with the formula: H = β0 + β1*age + β2*(age)².*

Growth parameters for tree height (H)			H = β0 + β1*age + β2*(age)²			
Genus	Species	Cultivar	Nr. of trees	β0	β1	β2
Acer			15689	4,25	1,76	-0,02
Aesculus			5845	4,40	1,29	0,06
Ailanthus			2351	3,95	2,12	-0,10
Alnus			6552	3,84	3,83	-0,35
Betula			5816	2,96	4,05	-0,40
Carpinus			7838	5,26	0,97	0,04
Corylus			4100	4,78	1,07	-3,32
Crataegus			642	3,84	2,64	-0,25
Fagus			1029	4,61	1,63	0,13
Fraxinus			19374	3,74	2,57	-0,13
Ginkgo			2712	4,12	2,32	-0,18
Gleditsia			1873	3,00	3,89	-0,42
Liquidambar			5095	3,13	3,36	-0,42
Magnolia			1560	4,22	0,95	-0,07
Metasequoia			2802	4,91	2,50	-0,03
Pinus			658	1,68	3,79	-0,25
Populus			1604	4,45	7,38	-0,57
Prunus			7733	4,59	1,26	-0,10
Pterocarya			804	3,08	3,26	-0,18
Pyrus			11068	4,34	1,72	-0,18
Quercus			15616	3,30	3,14	-0,17
Robinia			2826	4,47	2,29	-0,16
Salix			4710	5,45	0,55	0,19
Sorbus			2813	4,68	0,54	0,00
Styphnolobium			2833	4,07	1,62	-0,02
Taxus			190	6,55	2,02	-0,28
Tilia			13461	3,78	2,03	-0,10
Ulmus			17243	3,95	4,10	-0,53
Acer	*campestre*		4333	3,82	1,95	-0,07
Acer	*platanoides*		3144	3,60	1,51	-0,03
Acer	*pseudoplatanus*		6723	5,41	1,31	0,04
Acer	*saccharinum*		1489	4,70	2,43	-0,05
Aesculus	*hippocastanum*		5845	4,40	1,29	0,06
Ailanthus	*altissima*		2351	3,95	2,12	-0,10
Alnus	*cordata*		3248	3,87	3,93	-0,34
Alnus	*glutinosa*		3304	3,89	3,61	-0,34
Betula	*pendula*		3695	3,54	4,55	-0,52
Betula	*pubescens*		651	4,15	3,29	-0,29
Betula	*utilis*		1470	4,46	1,24	0,00
Carpinus	*betulus*		7838	5,26	0,97	0,04
Corylus	*colurna*		4100	4,78	1,07	-3,32
Crataegus	*monogyna*		642	3,84	2,64	-0,25
Fagus	*sylvatica*		1029	4,61	1,63	0,13
Fraxinus	*angustifolia*		1870	2,84	3,89	-0,42
Fraxinus	*excelsior*		17504	3,83	2,44	-0,10
Ginkgo	*biloba*		2712	4,12	2,32	-0,18
Gleditsia	*triacanthos*		1873	3,00	3,89	-0,42
Liquidambar	*styraciflua*		5095	3,13	33,63	-0,42
Magnolia	*kobus*		1560	4,22	0,95	-0,07
Metasequoia	*glyptostroboides*		2802	4,91	2,50	-0,03
Pinus	*nigra*		658	1,68	3,79	-0,25
Populus	*nigra*		1604	4,45	7,38	-0,57
Prunus	*avium*		4387	4,01	2,20	-0,22
Prunus	*cerasifera*		1227	4,42	0,96	-0,05
Prunus	*serrulata*		2119	4,94	0,26	0,03
Pterocarya	*fraxinifolia*		804	3,08	0,33	-0,18
Pyrus	*calleryana*		11068	4,34	1,72	-0,18
Quercus	*cerris*		5103	5,03	1,53	0,12
Quercus	*palustris*		2296	3,72	2,86	-0,13
Quercus	*robur*		8217	2,21	3,92	-0,28
Robinia	*pseudoacacia*		2826	4,47	2,29	-0,16
Salix	*alba*		4710	5,45	0,55	0,19
Sorbus	*aria*		1250	5,49	-0,06	0,11
Sorbus	*intermedia*		1563	4,12	0,93	-0,07
Styphnolobium	*japonicum*		2833	4,07	1,62	-0,02
Taxus	*baccata*		190	6,55	2,02	-0,28
Tilia	*americana*		1206	5,45	0,96	0,03
Tilia	*cordata*		3968	3,70	2,33	-0,16
Tilia	*platyphyllos*		1379	3,31	2,23	-0,08
Tilia	*tomentosa*		6908	3,87	1,90	-0,09
Acer	*campestre*	Elsrijk	1831	5,28	-0,24	0,28
Acer	*platanoides*	Globosum	1060	2,42	1,26	-0,13
Acer	*pseudoplatanus*	Erectum	866	4,55	2,15	-0,12
Acer	*pseudoplatanus*	Negenia	2056	5,99	1,01	0,01
Aesculus	*hippocastanum*	Baumannii	3983	4,01	1,47	0,02
Betula	*utilis*	Doorenbos	1470	4,46	1,24	0,00
Carpinus	*betulus*	Fastigiata	3144	4,89	1,34	-0,03
Carpinus	*betulus*	Frans Fontaine	3002	5,52	0,75	-0,03
Fraxinus	*angustifolia*	Raywood	1870	2,84	3,89	-0,42
Fraxinus	*excelsior*	Diversifolia	2049	3,88	2,58	-0,08
Fraxinus	*excelsior*	Westhofs Glorie	5186	3,55	2,62	-0,17
Populus	*nigra*	Italica	1604	4,45	7,38	-0,57
Prunus	*avium*	Plena	3169	3,65	2,45	-0,31
Prunus	*cerasifera*	Nigra	1227	4,42	0,96	-0,05
Prunus	*serrulata*	Kanzan	2119	4,94	0,26	0,03
Pyrus	*calleryana*	Chanticleer	11068	4,34	1,72	-0,18
Quercus	*robur*	Alpha	625	2,96	3,58	-0,28
Robinia	*pseudoacacia*	Bessoniana	2184	4,59	3,06	-0,27

Robinia	*pseudoacacia*	Umbraculifera	642	3,75	0,76	-0,09
Tilia	*tomentosa*	Brabant	3558	4,25	1,41	0,00

Appendix 5. | Number of trees per city, genus, species and cultivar used to calculate growth curves.

Table D. Number of trees per city, genus, species and cultivar used to calculate growth curves.

	A'dam	Den Haag	Dordrecht	Groningen	Herhugowaard	R'dam	Utrecht	Total
Acer	**5319**	**2013**	**581**	**2073**	**1154**	**2583**	**1966**	**15689**
campestre	1489	326	63	707	536	789	423	4333
-	*847*	*136*	*63*	*573*	*232*	*303*	*348*	*2502*
Elsrijk	*642*	*190*	*0*	*134*	*304*	*486*	*75*	*1831*
platanoides	1058	508	88	448	147	467	428	3144
-	*687*	*186*	*70*	*384*	*67*	*314*	*376*	*2084*
Globosum	*371*	*322*	*18*	*64*	*80*	*153*	*52*	*1060*
pseudoplatanus	2281	1001	241	830	467	884	1019	6723
-	*1179*	*137*	*235*	*762*	*177*	*746*	*565*	*3801*
Erectum	*91*	*397*	*0*	*35*	*33*	*21*	*289*	*866*
Negenia	*1011*	*467*	*6*	*33*	*257*	*117*	*165*	*2056*
saccharinum	491	178	189	88	4	443	96	1489
Aesculus	**1693**	**1451**	**196**	**531**	**149**	**1275**	**550**	**5845**
hippocastanum	1693	1451	196	531	149	1275	550	5845
-	*541*	*123*	*128*	*378*	*65*	*433*	*194*	*1862*
Baumannii	*1152*	*1328*	*68*	*153*	*84*	*842*	*356*	*3983*
Ailanthus	**671**	**835**	**35**	**13**	**0**	**668**	**129**	**2351**
altissima	671	835	35	13	0	668	129	2351
Alnus	**1375**	**629**	**410**	**1431**	**658**	**1029**	**1020**	**6552**
cordata	577	323	287	608	458	638	357	3248
glutinosa	798	306	123	823	200	391	663	3304
Betula	**2036**	**780**	**192**	**1300**	**176**	**823**	**509**	**5816**
pendula	1098	537	168	1170	91	414	217	3695
pubescens	293	40	13	28	45	134	98	651
utilis	645	203	11	102	40	275	194	1470
Doorenbos	*645*	*203*	*11*	*102*	*40*	*275*	*194*	*1470*
Carpinus	**2710**	**901**	**474**	**707**	**465**	**1412**	**1169**	**7838**
betulus	2710	901	474	707	465	1412	1169	7838
-	*492*	*57*	*182*	*254*	*97*	*353*	*257*	*1692*
Fastigiata	*851*	*561*	*208*	*297*	*116*	*431*	*680*	*3144*
Frans Fontaine	*1367*	*283*	*84*	*156*	*252*	*628*	*232*	*3002*
Corylus	**767**	**1238**	**256**	**135**	**45**	**1261**	**398**	**4100**
colurna	767	1238	256	135	45	1261	398	4100
Crataegus	**255**	**56**	**33**	**163**	**27**	**72**	**36**	**642**
monogyna	255	56	33	163	27	72	36	642
Fagus	**192**	**235**	**50**	**213**	**31**	**127**	**181**	**1029**
sylvatica	192	235	50	213	31	127	181	1029
Fraxinus	**3650**	**2255**	**2634**	**3506**	**1393**	**2649**	**3287**	**19374**
angustifolia	208	523	162	170	26	455	326	1870
Raywood	*208*	*523*	*162*	*170*	*26*	*455*	*326*	*1870*

excelsior	3442	1732	2472	3336	1367	2194	2961	17504
-	*492*	*57*	*182*	*254*	*97*	*353*	*257*	*1692*
Diversifolia	*145*	*137*	*63*	*243*	*348*	*260*	*853*	*2049*
Westhofs Glorie	*1807*	*884*	*1109*	*271*	*221*	*442*	*452*	*5186*
Ginkgo	**1153**	**524**	**15**	**208**	**32**	**630**	**150**	**2712**
biloba	1153	524	15	208	32	630	150	2712
Gleditsia	**772**	**152**	**270**	**287**	**5**	**201**	**186**	**1873**
triacanthos	772	152	270	287	5	201	186	1873
Liquidambar	**1435**	**509**	**195**	**753**	**124**	**847**	**1232**	**5095**
styraciflua	1435	509	195	753	124	847	1232	5095
Magnolia	**467**	**309**	**57**	**79**	**6**	**272**	**370**	**1560**
kobus	467	309	57	79	6	272	370	1560
Metasequoia	**1379**	**239**	**217**	**194**	**451**	**204**	**118**	**2802**
glyptostroboides	1379	239	217	194	451	204	118	2802
Pinus	**196**	**161**	**3**	**103**	**24**	**134**	**37**	**658**
nigra	196	161	3	103	24	134	37	658
Populus	**478**	**178**	**72**	**154**	**8**	**278**	**436**	**1604**
nigra	478	178	72	154	8	278	436	1604
Italica	*478*	*178*	*72*	*154*	*8*	*278*	*436*	*1604*
Prunus	**2057**	**2560**	**169**	**381**	**98**	**1137**	**1331**	**7733**
avium	1167	1453	68	131	67	523	978	4387
-	*482*	*132*	*44*	*98*	*25*	*221*	*216*	*1218*
Plena	*685*	*1321*	*24*	*33*	*42*	*302*	*762*	*3169*
cerasifera	279	234	95	173	20	261	165	1227
Nigra	*279*	*234*	*95*	*173*	*20*	*261*	*165*	*1227*
serrulata	*611*	*873*	*6*	*77*	*11*	*353*	*188*	*2119*
Kanzan	*611*	*873*	*6*	*77*	*11*	*353*	*188*	*2119*
Pterocarya	**315**	**104**	**17**	**90**	**10**	**212**	**56**	**804**
fraxinifolia	315	104	17	90	10	212	56	804
Pyrus	**2533**	**3045**	**518**	**1068**	**622**	**1628**	**1654**	**11068**
calleryana	2533	3045	518	1068	622	1628	1654	11068
Chanticleer	*2533*	*3045*	*518*	*1068*	*622*	*1628*	*1654*	*11068*
Quercus	**3057**	**2404**	**460**	**2417**	**1206**	**2962**	**3110**	**15616**
cerris	1043	906	28	250	908	1843	125	5103
palustris	581	401	137	308	6	494	369	2296
robur	1433	1097	295	1859	292	625	2616	8217
-	*1433*	*1097*	*295*	*1859*	*292*	*0*	*2616*	*7592*
Alpha	*0*	*0*	*0*	*0*	*0*	*625*	*0*	*625*
Robinia	**843**	**874**	**34**	**90**	**10**	**789**	**186**	**2826**
pseudoacacia	843	874	34	90	10	789	186	2826
Bessoniana	*543*	*754*	*21*	*76*	*5*	*691*	*94*	*2184*
Umbraculifera	*300*	*120*	*13*	*14*	*5*	*98*	*92*	*642*
Salix	**1058**	**289**	**299**	**907**	**182**	**776**	**1199**	**4710**
alba	1058	289	299	907	182	776	1199	4710
Sorbus	**859**	**384**	**94**	**498**	**83**	**153**	**742**	**2813**
aria	410	153	61	247	57	111	211	1250
intermedia	449	231	33	251	26	42	531	1563

Styphnolobium	**812**	**231**	**28**	**52**	**29**	**986**	**695**	**2833**
japonicum	812	231	28	52	29	986	695	2833
Taxus	**56**	**38**	**15**	**21**	**0**	**21**	**39**	**190**
baccata	56	38	15	21	0	21	39	190
Tilia	**3762**	**968**	**1062**	**988**	**246**	**3379**	**3056**	**13461**
americana	898	112	12	0	0	60	124	1206
cordata	860	173	292	491	167	1301	684	3968
platyphyllos	600	76	39	300	15	265	84	1379
tomentosa	1404	607	719	197	64	1753	2164	6908
-	*633*	*80*	*461*	*126*	*43*	*938*	*1069*	*3350*
Brabant	*771*	*527*	*258*	*71*	*21*	*815*	*1095*	*3558*
Ulmus	**9533**	**3601**	**227**	**1078**	**800**	**1587**	**417**	**17243**
Clusius	*671*	*970*	*66*	*0*	*27*	*435*	*152*	*2321*
Columella	*2120*	*131*	*45*	*305*	*384*	*717*	*44*	*3746*
Dodoens	*3355*	*45*	*43*	*4*	*348*	*111*	*0*	*3906*
Lobel	*2253*	*2455*	*58*	*357*	*17*	*181*	*162*	*5483*
New Horizon	*1134*	*0*	*15*	*412*	*24*	*143*	*59*	*1787*
Total	**49433**	**26963**	**8613**	**19440**	**8034**	**28095**	**24259**	**164837**

Appendix 6. | Case-study: The Oranje Loper in Amsterdam.

Auteur: Wendy Batenburg, Terra Nostra

Meegewerkt aan het project:
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Maikel Nouws, Bomenwacht (dit wisselde nogal bij Bomenwacht, maar Maikel was de laatste)
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Figure 1. Project area of the Oranje Loper (credits Amsterdam.nl).

Introduction

The Oranje Loper project in Amsterdam consists of a trajectory from the Raadhuisstraat to the Mercatorplein (figure 1). In this route, 7 bridges will be restored and streets will be improved for bicycles, pedestrians, public transport and trees. Due to the redevelopment trees will be removed, some will be replanted elsewhere and new trees will be planted to compensate the loss of trees and its canopy. With climate change in mind Amsterdam focused on cooling down the streets of the Oranje Loper using the current and new trees. This entailed improving the subsoil conditions for the remaining trees and creating optimal conditions for the new trees. The goal is to create optimal tree cover and crown volume to lower the temperature in the city. In this case study growth curves from i-Tree Eco were used to get insight into the development over time of the trees and their ecosystem services under different growing conditions.
In this project 4 scenarios were developed, a situation where there is no change or redevelopment of the area. The quality of the growth site was investigated and the results were calculated over a timespan of 75 years. The 4 scenarios are visualized in table 1.

Starting situation	Development	Growth site	Future	Scenario
Original situation	No change	Standard	+25 years +50 years +75 years	Scenario 1 1.284 trees
	No change	Growth site improvement	+25 years +50 years +75 years	Scenario 2 1.284 trees
	Redevelopment	Standard	+25 years +50 years +75 years	Scenario 3 1.368 trees
	Redevelopment	Growth site improvement	+25 years +50 years +75 years	Scenario 4 1.368 trees

Table 1. Description of the 4 scenario's.

Methods

Growth equations

In i-Tree Eco, 3 growth formulas are used to calculate the growth of the diameter at breast height (DBH). They are calculated based on the species growth rate (slow, moderate, fast; i-Tree Database). The formulas are corrected for the competition between trees by calculation of the number of sides of the crown obtaining light (crown light exposure, CLE). The growth of DBH was adjusted to the length of the growing season (frost free days) since the growth rate was based on tree growth in Minnesota, United States. The base growth (formula 1 and 2) includes a correction for the number of frost free days in the Netherlands (315 frost free days, KNMI) (table 2). There is the option to standardize the formula for the condition of the tree, however in this project it was not used. Condition was used to simulate growth site improvement.

1. Base growth (BG) = standard growth x (number of frost free days/153)
2. Base growth (BG) = standard growth x 2,05

Street trees	Species standard growth rate	Tree competition correction factor	Maximum DBH (cm)
Slow growth rate	0,58 cm/year		
Moderate growth rate	0,84 cm/year		
Fast growth rate	1,09 cm/year		
CLE 0-1		BG x 0,44	
CLE 2-3		BG x 0,56	
CLE 4-5		BG x 1	
Height of maturity < 12,2m			38,1
Height of maturity 12,2 - 18,3 m			76,2
Height of maturity >18,3 m			114,3

Table 2. Description of the growth rate and corrections of the growth rate for tree competition (Nowak, Understanding i-Tree, 2021).

As a tree approaches maximum DBH growth rate decreases. The species growth rate as described were adjusted based on the ratio between the current DBH and the maximum DBH. When the DBH of a tree is more than 80% of its maximum DBH, the growth rate was proportionally reduced (table 2). The maximum DBH is based on height of maturity of a tree species (i-Tree Database).

Using this i-Tree Eco background the DBH was calculated over time (0-100 years with 10 year steps) for 2.834 species and cultivars. The species and cultivars were divided into first height of maturity (<6 meters in height), second height of maturity (6-12 meters in height) and third height of maturity (>12 meters in height) (Handboek Bomen). This was imported into i-Tree Eco and the output was used to create growth curves for tree height and crown diameter. These growth curves were used for the scenario's to get output for the timepoints +25, +50 and +75 years after redevelopment.

Simulation of growth site quality

The quality of the growth site was simulated using the condition input in i-Tree Eco. The condition of the current trees was collected and simulated in time according to the schedule in table 3. The condition of a new tree was simulated starting at condition 97%. The categories of percentage condition was based on the categories provided in i-Tree Eco.

The output of i-Tree Eco consists of (among others) leaf area (m2) and crown area (m2) and the ecosystem services: carbon storage (kg), carbon sequestration (kg/year), avoided water runoff (m3/year) and pollution removal (g/year). This data was imported into the Dashboard of workpackage 3.

Current condition (%)	Condition (%)					
	No GSI			With GSI		
	+25	+50	+75	+25	+50	+75
12	0	0	0	0	0	0
17	12	7	2	0	0	0
32	-	-	-	12	0	0
37	32	27	22	22	2	0
52	-	-	-	72	62	52
62	57	52	47	77	72	62
77	72	67	62	87	82	77
92	87	82	77	92	87	82
100	97	92	87	100	97	92

Table 3. Condition adjustment (in percentages) for the simulation of growth site quality. These values were input for i-Tree Eco. GSI = growth site improvement. Some conditions were not used in the category 'no GSI'.

Results

Growth formulas for DBH, tree height and crown diameter were constructed (table 4). The fit was exponential in most of the cases (formula 3) and linear for 1 type of tree (first height of maturity, slow growth rate, formula 4). The scenario's were calculated using these formulas.

3. $Yt = Ym-(Ym-Y0)*e(-k*X)$
4. $Yt = 0,67X + 7,992$

Yt = DBH, tree height or crown diameter, t years after planting
Ym = maximal theoretical value
Y0 = DBH, tree height or crown diameter at year of planting of year of calculation
k = constant
x = year after planting

	Tree size	Growth rate	YM	Y0	k
DBH	First height of maturity	Slow	NA	NA	NA
		Moderate	814,3	7,512	0,00126
		Fast	217,2	5,145	0,007524
	Second height of maturity	Slow	306,5	7,371	0,002447
		Moderate	117,4	5,844	0,01165
		Fast	209,7	7,138	0,00714
	Third height of maturity	Slow	111,3	7,865	0,007091
		Moderate	44,77	7,375	0,03882
		Fast	51,38	7,612	0,0401
Tree height	First height of maturity	Slow	28,09	6,728	0,01881
		Moderate	27,99	7,07	0,01785
		Fast	28,41	7,409	0,02895
	Second height of maturity	Slow	23,6	6,704	0,01556
		Moderate	19,72	6,154	0,03679
		Fast	21,47	5,962	0,0408
	Third height of maturity	Slow	12,19	5,718	0,03817
		Moderate	12,75	5,892	0,06409
		Fast	17,08	6,334	0,08361
Crown diameter	First height of maturity	Slow	18,21	3,714	0,01107
		Moderate	24,78	3,854	0,009081
		Fast	20,99	3,534	0,01531
	Second height of maturity	Slow	19,28	3,776	0,008936
		Moderate	15	3,455	0,02137
		Fast	14,55	3,211	0,03277
	Third height of maturity	Slow	9,526	3,638	0,02839
		Moderate	8,859	3,591	0,05507
		Fast	9,216	3,706	0,08284

Table 4. Overview of the variables of formula 3 for calculation of DBH, tree height and crown diameter.

The parameter values summarized in Table 4 indicate that growth dynamics vary substantially among species groups and height classes. Trees of the third height-of-maturity class generally exhibit higher growth constants (k) for both height and crown diameter, suggesting a faster relative growth in early life stages compared with smaller species.

Ecosystem services

Leaf area strongly influences the provision of ecosystem services such as cooling, rainfall interception (avoided runoff), and air-pollutant removal. Therefore, this variable was analyzed in greater detail.

All four scenarios demonstrated a notable increase in total leaf area within 25 years after the baseline year (Figure 2, left). Scenario 4 (redevelopment with growth-site improvement) produced the highest leaf area increase, while scenario 1 (no redevelopment, no growth-site improvement) resulted in the lowest. After approximately 25 years, the growth curves began to stabilize, and a slight decline in leaf area was observed between 50 and 75 years for scenarios 1 and 2. These findings indicate that maximum ecosystem service benefits are reached about 25 years after baseline or redevelopment, after which maintenance of site quality becomes increasingly important to sustain canopy performance.

In terms of carbon storage, which reflects the cumulative biomass of trees, all scenarios showed a steady increase throughout the 75-year simulation period (Figure 2, right). No stabilization or decline was detected, and scenarios 1 and 2, as well as 3 and 4, displayed similar trajectories. This suggests that the simulated carbon storage is relatively insensitive to growth-site quality within the current model structure. However, in reality, site constraints, competition, and age-related growth reduction are expected to affect long-term carbon accumulation. The discrepancy between modeled and empirical expectations highlights a limitation of the applied growth equations and emphasizes the need for further calibration and validation of growth models for urban tree species under Dutch environmental conditions.

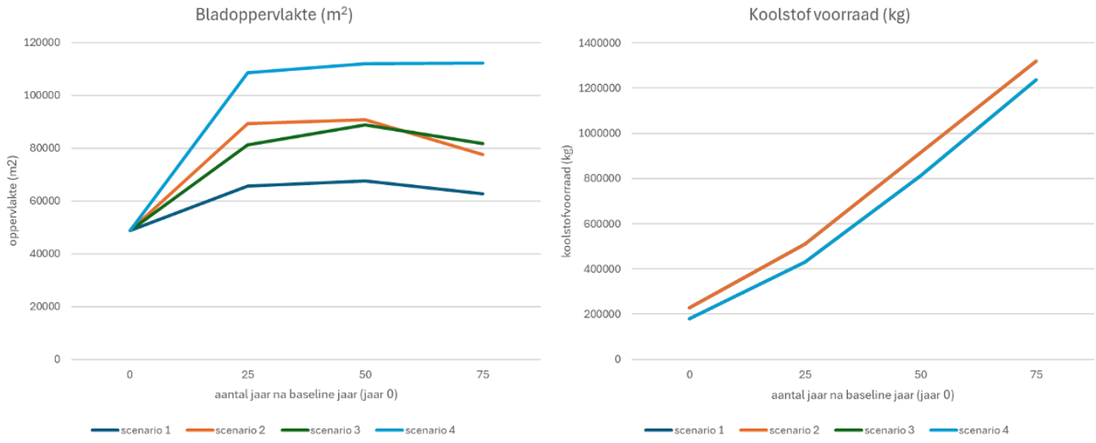


Figure 2. The effect of the growth equations on leaf area (left) and carbon storage (right) for the 4 scenarios.

Dashboard

The outcomes of the scenarios were visualized in the interactive Dashboard of WP3 (see Figure 3), allowing for exploration of tree growth trajectories and associated ecosystem services under varying management and redevelopment conditions.



Figure 3. Screenshots of Urban Forest Portfolio (Oranje Loper case)

Conclusions

The Oranje Loper project serves as a case study demonstrating the integration and visualization of tree growth equations within an urban redevelopment context. The growth equations for diameter at breast height (DBH), tree height, and crown diameter were parameterized based on species-specific growth rates and height of maturity, following the methodological framework of i-Tree Eco. Growth site quality was simulated through the condition parameter, enabling an assessment of its influence on long-term ecosystem service delivery.

The results indicate that ecosystem services such as leaf area development, and consequently cooling potential, avoided water runoff, and pollution removal, increase substantially within the first 25 years following redevelopment. After approximately 50 years, a stabilization and gradual decline are observed, reflecting the natural aging process of urban trees and potential site limitations. The simulations show that growth site quality exerts a clear influence on canopy development, whereas its effect on carbon storage appears less pronounced. This divergence may stem from the structural assumptions of the i-Tree Eco growth model, which simplifies age-related growth decline and site-specific stress factors.

The growth equations used in this study were derived from the i-Tree Eco framework, while parallel research activities in Work Package 2 produced growth equations specifically for Dutch urban tree species. A comparative analysis between these two sets of equations is essential to evaluate their predictive accuracy under local conditions. Integrating the Dutch growth equations into the i-Tree Eco platform could enhance its applicability for urban forestry planning in the Netherlands, supporting evidence-based decision-making on tree species selection, planting strategies, and ecosystem service optimization in future urban redevelopment projects.

i-Tree 2.0 NL