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WP3

Deliverable 3.1: Tree attributes version 1

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Table of content

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List of Acronyms

cm	Centimeter
CO2	Carbon dioxide
CPA	Canopy projection area
DBH	Diameter at breast height
DNA	Deoxyribonucleic acid
EC	European Commission
e.g.	Exempli gratia, Latin for "for example "
EAG	ElectroAntennoGraphy
GC	Gas Chromatography
HPLC	High Performance Liquid Chromatography
i.e.	Id est, Latin for "that is"
LAI	Leaf area index
LiDAR	Light Detection and Ranging
m	Meter
MS	Mass Spectrometry
NMR	Nuclear magnetic resonance
NO2	Nitrogen dioxide
O3	Ozone
PM10	Atmospheric particulate matter with a diameter of 10 µm or less
PM2,5	Atmospheric particulate matter with a diameter of 2,5 µm or less
spp.	Species (plural)
UV	Ultraviolet
VOC	Volatile Organic Compounds
WP	Work package

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Executive Summary

Deliverable 3.1 documents a science-based list of key tree attributes. These will be important in a later stage of the project for preparing an adequate definition of standard city tree types per demonstration site (Copenhagen and Sofia) considering their climatic characteristics.

This deliverable is the result of Task 3.1 (Analysis of the needed and existing data on tree attributes) and includes to some extent literature review from Task 3.3. In Deliverable 3.2 (Tree attributes final version), this document will be further expanded and completed with the work planned for Task 3.2 (Filling in missing data).

This first version document analyses the data availability and data gaps per key tree attribute, as well as the methods and data sources for filling the identified gaps. Both D3.2 – Tree Attributes – Final Version (submission: month 18) and this version will be published as OpenData.

After a short description of the document's purpose, audience and structure in chapter 1, chapter 2 is listing the most relevant tree attributes for estimation the ecosystem services by urban trees. Based on scientific literature as well as knowledge and experience of the authors, structured lists are prepared for each ecosystem service related to benefit modelling in WP4, namely:

- Urban Pluvial Flood Inundation and Damage Assessment,
- Air Pollution and $PM_{2.5}$, PM_{10} & NO_2 reduction,
- Tree Noise Absorption and Impact on Traffic Noise Distribution,
- Biodiversity and Carbon sequestration
- Urban Cooling Assessment.

Those attributes are then further explored in chapter 3, where their definition, measurement methods and standardization are discussed.

The first, preliminary data availability check in chapter 4 has led to the conclusion that some rather basic attributes on individual trees (tree species, size, and health) are highly available, but that solutions for filling the data gap for the other attributes are to be studied. The tree species level attributes have been partially well documented for the city of Sofia but seems to be absent for Copenhagen.

This deliverable serves as a basis for further work in T3.1, T3.2 and T3.3, which will lead to the publication and dissemination of D3.2. This first version serves internal purposes to get a good understanding of the relevant tree attributes and their links to modelling approaches (WP4). The second version (D3.2) will be the basis for the definition of standard city tree types (T3.4 and D3.3). It is also expected to impact WP5 and WP6, as the cost-benefit analysis of planting a tree strongly depends on the temporality of several of the attributes.

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1 Introduction

1.1 Purpose and audience of the document

It is important to state that this is the first of two deliverables related to tree attributes in the project. This early version, which is delivered in month 6 of the project serves mainly internal purposes and is shared with project partners and EC auditors to set a solid base for the upcoming tasks in WP3 and other project work packages; it will be made available publicly for transparency.

An extended and updated version of this report will be delivered in M18, which is foreseen to be shared with a broader audience and to be published as OpenData.

The information given in this report is science-based and validated with scientific resources listed in the references in chapter 6. Since not all partners in the 100kTREES project are experts in ecology and trees, this document is important to get a common understanding and a good knowledge on correlations of tree attributes, measuring approaches and data availability and data gaps.

Next to that, this deliverable serves as a starting point for the discussion on how data gaps in the two demo sites can be addressed and how to gather all needed data to feed into WP4. This discussion will be continued and finalized in the second version of this deliverable, D3.2, with the work planned in WP3.2 and WP3.3. It is during the work planned for the second version, that the ecological and dendrological information contained in this deliverable will be complemented with expert knowledge from remote sensing and modelling.

1.2 Structure of the document

After chapter 1 **Introduction**, a review of the available scientific literature is provided documenting the links between urban trees and the ecosystem services they provide (chapter **2 Listing the attributes for estimating the ecosystem services provided by urban trees)**. For each ecosystem service considered in the project 100kTrees, a list is constructed with the most important tree attributes useful for modelling the tree's contribution to the ecosystem service.

In chapter **3 Tree attributes as derived from previous chapter**, the tree attributes relevant for defining standard city tree types are retained from chapter 2. They are then described and methods and data sources for filling eventual gaps are listed. In chapter **4 Data availability**, the first conclusions of an analysis of the data available for these attributes within the urban tree databases for Copenhagen and Sofia is briefly discussed.

The document is then closed with chapters **5 Conclusions**, where the first challenges for developing deliverable 3.2 are proposed, and **6 References**, containing the information mentioned in its title.

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2 Listing the attributes for estimating the ecosystem services provided by urban trees

In this chapter, the scientific literature is reviewed and the links between urban trees and the ecosystem services they provide is documented. For each ecosystem service considered in the project 100kTrees, a list is constructed with the most important tree attributes useful for modelling the tree's contribution to the ecosystem service. The lists are then combined in the next chapter.

2.1 Air pollution reduction

Urban trees help to reduce air pollution by reducing air temperature and thus reducing energy use in buildings, and by directly removing pollutants (Nowak et al., 2006) mainly through dry deposition on the leaves, branches and trunk (Jim and Chen, 2008). In the latter case, the intercepted particle can be resuspended in the atmosphere, washed of by rain, or removed when the leaf or twig falls to the ground (Nowak, n.d.).

Annual pollutant removal is estimated at about 0.15, 0.42 and 0.79 g /m² tree cover /year for NO_2, O_3 and PM_{10}, respectively (Guidolotti et al., 2016). But on the other hand, some scientific papers mention trees to be suspected not to reduce air pollution in most **street designs** (Air pollution: outdoor air quality and health, 2023), e.g. as they can block air circulation in narrow streets.

Due to their large **leaf areas** and their physical properties, trees can act as biological filters (Depietri et al., 2012). The effectiveness of this ecosystem service varies according to **plant species**, **canopy area**, type and characteristics of air pollutants, **tree physiological status** (Guidolotti et al., 2016) and local meteorological environment. Larger trees (**tree size**) have a greater **leaf area,** which traps more air pollutants (Depietri et al., 2012), and hairy or otherwise rough leaves fixate more particles than leaves without hairs (Vigevani et al., 2022; Worsley and Champion, n.d.). Pollution removal rates are quite similar per m² of canopy cover (10-13 g/m²/yr) and fluctuate according to the amount of air pollution, length of in-leaf season, precipitation, and other meteorological variables (Nowak, n.d.). Some of the gaseous pollutants need an active photosynthesis (**tree irrigation status** and **tree health**) to be absorbed (Worsley and Champion, n.d.).

In urban areas, districts with more extensive urban trees capture more pollutants from the air, and this capacity is increased as trees gradually reach **final** dimensions (Depietri et al., 2012).

The **tree genus/species** has a strong effect on capturing aerial pollution, as deciduous leaves do not absorb in winter (when pollution is the highest), trees with needles (*Pinus* spp.) have a significantly higher absorption rate because of their larger **total surface area**, but trees with scales (*Cupressus* spp.) are less efficient (Depietri et al., 2012).

Interception of particles by vegetation seems also to be much greater for street trees, due to their location in **proximity to high road traffic** (Depietri et al., 2012). Trees situated close to a busy road capture significantly more material, especially larger particles, than those situated in a rural area (Beckett et al.1998) in (Depietri et al., 2012).

Trees also emit **volatile organic compounds** that can contribute to ozone formation. However, integrative studies have revealed that an increase in tree cover leads to reduced ozone formation (Nowak et al., 2006).

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One of the mechanisms behind this ozone reduction might be the temperature decrease linked with tree cover (Nowak, n.d.).

The impact of trees on building energy use can be positive (shade in summer, blocking winds in winter) but also negative (blocking winds in summer, shade in winter)(Nowak, n.d.). The (final) **size** of the trees and their **placement around the buildings** in relation to dominant winds and the sun, as well as the height of the building, and the overall impact of the tree on the **aerodynamics** of the environment, all are of importance for evaluating the impact of trees on building energy use.

But careful, trees don't always reduce air pollution: it depends on the street design, species, number and siting of trees, canopy density, time of year and wind direction relative to the street (Air pollution: outdoor air quality and health, 2023).

As a final comment on this ecosystem service, it is worth mentioning that the cooling effect, air pollution reduction and carbon mitigation of trees are strongly linked with potential trade-offs and co-benefits, and should not be analysed separately (Li and Wang, 2021).

Models describing air pollution reduction by trees (some examples):

- i-Tree,
    - i-Tree is a software suite from the USDA Forest Service that provides urban and rural forestry analysis and benefits assessment tools (*i-Tree website*, n.d.)
    - i-Tree Eco is an adaptation of the Urban Forest Effects (UFORE) model
- UFORE (Guidolotti et al., 2016; Nowak et al., 2006),
    - The Urban Forest Effects (UFORE) computer model was developed to help managers and researchers quantify urban forest structure and functions (UFORE model website, n.d.). The model quantifies species composition and diversity, diameter distribution, tree density and health, leaf area, leaf biomass, and other structural characteristics; hourly volatile organic compound emissions (emissions that contribute to ozone formation) throughout a year; total carbon stored and net carbon sequestered annually; and hourly pollution removal by the urban forest and associated percent improvement in air quality throughout a year.
    - The UFORE model has been absorbed in i-Tree (above)
- EMEP MSC-W (Guidolotti et al., 2016)
    - It estimates dry deposition, assuming the downfall of the particulate on a uniform canopy, not accounting for leaf area nor for physiological differences between species, LAI estimation is based on a spatialized grid (50 × 50 km) of land cover types (Guidolotti et al., 2016).

As a summary, the tree attributes linked with air pollution reduction are:

Attribute	Reference	To be obtained per	To be obtained by	Observation
Tree species	(Camarena et al., 2022)	Tree	Determination	VOC emissions per species, needles/ leaves/ scales
Crown diameter (canopy area)	(Depietri et al., 2012)	Tree	Remote sensing / observation	
Leaf area	(Depietri et al., 2012; Nowak, n.d.)	Species	Measuring / literature	Depends on season
Tree dimensions	(Depietri et al., 2012; Nowak, n.d.)	Tree	Remote sensing / observation	
Tree physiological status (health status of the tree)	(Guidolotti et al., 2016)	Tree	Observation	

Table 1. Tree attributes linked with air pollution reduction.

Other possibly interesting attributes are:

Attribute	Reference	To be obtained per	To be obtained by	Observation
Pollution concentrations	(Depietri et al., 2012; Nowak, n.d.)	Area studied	Meteorological services, proximity to pollution sources (remote sensing)	
Local meteorological conditions	(Depietri et al., 2012; Nowak, n.d.)	Area studied	Meteorological services	
Size and proximity of buildings to trees	(Nowak, n.d.)	Building or tree	Remote sensing (buildings) / Field observations (tree positions) / GIS (relative positions	
Aerodynamics and influence of trees on it	(Nowak, n.d.)	Area studied	Aerodynamic models	
Street design	(Air pollution: outdoor air quality and health, 2023)	Area studied	Observation	

Table 2. Other attributes linked with air pollution reduction.

2.2 Biodiversity improvement

Studies for the most part consider biodiversity in terms of taxonomic richness but also, to lesser extents, evenness of abundance, or the occurrence and abundance of groups of species classified by their threat status, ecological traits and functions (Norton et al., 2016). In a forest, the tree is the centre of the local ecosystem (Keizer, 2012), where it creates the right conditions for plants, fungi, insects and more that are dependent on the tree, and that the tree depends on. Trees are thus key for promoting biodiversity in their direct surroundings.

In an urban context, many of the influences of those trees are eliminated, because trees are managed, their fallen leaves are removed, the soil is compacted or sealed, and the local ecosystem is limited in its development. But there can still be a positive influence on the local biodiversity, through:

- Tree wounds, cavities, dead wood, and other **tree microhabitats** (Großmann et al., 2020), whose number increase with the tree's size (Moreira, n.d.)

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- Providing habitat and food to native fauna (insects, birds, etc.), where **native trees** are more effective than introduced species (Helden et al., 2012; Salisbury et al., 2017; Villarroya-Villalba et al., 2021; Worsley and Champion, n.d.), **bigger trees** are more effective than small plants (Helden et al., 2012; Salisbury et al., 2017; Worsley and Champion, n.d.), and trees with an undergrowth are more valuable than trees alone, trees with **allelopathic substances** diminish the diversity at their tree base (Omar et al., 2018)
- Providing connection (**connectivity**) between patches of vegetation (stepping-stones)(Norton et al., 2016)
- Adding **organic matter to the soil**, thus food for soil invertebrates (Kotze et al., 2022)
- Offering spots of more complex **vegetational structure** (vertical structure – combining smaller and taller plants)(Kotze et al., 2022), or places for spontaneous vegetation where such habitats are rare (at the tree base, also serving as stepping stones), an effect that increases with the **size of the tree base** (Omar et al., 2018), with the **size of the vegetation patch** (e.g. a park)(Dale and Frank, 2018) and with the **proximity of source populations** (e.g. parks and urban forests)(Omar et al., 2018)

On the other hand, many management practices strongly influence the effect of trees on the local urban biodiversity, such as:

- Intensive **pruning**, increasing the amount of tree microhabitats (Großmann et al., 2020)
- Allowing or not the tree base to be **trampled** by people (Omar et al., 2018)
- Allowing or not for dog **excrements** to be left at the tree bases (Omar et al., 2018)

Furthermore, biodiversity suffers with increasing light, noise and chemical pollution (but nitrogen pollution can have a positive effect on herbivore populations (Dale and Frank, 2018)), with the increased temperature in cities (but this can have a positive impact on herbivore fitness and abundance (Dale and Frank, 2018)), with habitat fragmentation, soil compaction or sealing, alkaline soil conditions (linked with the presence of cement), and much more (Dale and Frank, 2018; Kotze et al., 2022).

Urban **tree diversity** in itself also has a positive impact on the provision of ecosystem services and on ecosystem stability (Morgenroth et al., 2016).

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As a summary, the tree attributes linked with biodiversity improvement are:

Attribute	Reference	To be obtained per	To be obtained by	Observation
Tree microhabitats	(Großmann et al., 2020)	Tree	Observation	
Tree species	(Helden et al., 2012; Morgenroth et al., 2016; Norton et al., 2016; Salisbury et al., 2017; Villarroya-Villalba et al., 2021; Worsley and Champion, n.d.)	Tree, species	Determination, literature	Native/exotic, diversity, threat status, ecological traits, functions
Circumference of the trunk at breast height	(Helden et al., 2012; Salisbury et al., 2017; Worsley and Champion, n.d.)	Tree	Measurement	Proxy for tree size > tree microhabitats
Tree undergrowth and structure	(Kotze et al., 2022; Omar et al., 2018)	Tree	Observation	
Allelochemicals	(Omar et al., 2018)	Species	Literature	
Connectivity	(Norton et al., 2016)	Tree	GIS	
Soil organic matter (leaves, excrements) and compaction	(Kotze et al., 2022; Omar et al., 2018)	Tree	Observation	
Tree base size / tree patch size	(Dale and Frank, 2018; Omar et al., 2018)	Tree or tree group	Observation, GIS	
Tree management (intensive/extensive)	(Großmann et al., 2020)	Tree	Observation	Proxy for tree microhabitats

Table 3. Tree attributes linked with biodiversity improvement.

Other possibly interesting attributes are:

Attribute	Reference	To be obtained per	To be obtained by	Observation
Proximity of source populations	(Omar et al., 2018)	Area studies	GIS	

Table 4. Other attributes linked with biodiversity improvement.

2.3 Cooling effect

Trees are known to have a cooling effect on their surroundings. This is of special importance in cities, where structures such as buildings and roads, can capture the sun's heat more than more natural environments, such as forests. Trees can reduce this heat island-effect positively and even negatively in the next ways (Meili et al., 2021):

- Radiation (shade, reflexion, etc.),
- Transpiration, and
- Aerodynamic roughness.

Shading (radiation) is probably the most important factor (80% of the effect) in cooling (Depietri et al., 2012; Meili et al., 2021; Rahman et al., 2020a), and this depends on the structural characteristics, i.e. **tree height** variability, **Diameter at Breast Height (DBH)**, **leaf area index (LAI), crown diameter**, **canopy volume**, **canopy projection area (CPA)**(Rahman et al., 2020a), and **crown form** (Fini et al., 2022). Furthermore, the

albedo of the surface materials is also a factor (Czaja et al., 2020; Rahman et al., 2020a). LAI and CPA are statistically spoken the most important factors (Rahman et al., 2020a). Moreover, ecological characteristics such as the wood anatomy or the water use efficiency can also affect the boundary layer air-cooling (Rahman et al., 2020a). Trees with higher LAI can reflect incoming shortwave radiation and provide extensive shading at pedestrian level (Gupta et al., 2018; Kong et al., 2017). Larger trees (**tree size**) cast, of course, more shade (Depietri et al., 2012).

Planting arrangements can also influence shading, as cluster arrangements will improve the cooling benefits (Rahman et al., 2020a). The same counts for **undergrowth**, as high trees in combination with grass (grass has a very high transpiration, check (Meili et al., 2021)) would combine the best (Rahman et al., 2020a), as the wind circulation is less hindered. Having trees **higher than the buildings**, adding thusly to the urban roughness (Meili et al., 2021) also has a reducing effect on the temperature of their surroundings.

Transpiration is controversial. Most modelling happens apparently with trees without water stress, something that is improbable when the heat island effect is the highest (Meili et al., 2021; Rahman et al., 2020a). The effect seems to be nonsignificant during hot summer days but can be significant on mild summer days (Rahman et al., 2020a). A factor as the '**irrigation status'**, indicating the water stress level of the tree or the availability of water for the tree in the soil, would thus be interesting (Bensaoud et al., 2018). **Species specific transpiration** rates could also help calculating the effect of trees on the temperature of their surroundings (Gupta et al., 2018; Qiu et al., 2020), with isohydric or anisohydric behaviour (i.e. the capacity to decouple their leaf water potential from atmospheric demand, where anisohydric tree species would provide greater cooling in summer) being potentially interesting (Fini et al., n.d.) but controversial (Hochberg et al., 2018).

Wind circulation is essential. Trees lower than buildings in street canyons hinder air circulation and can increase the heat island effect (Meili et al., 2021). The value of adding street trees may vary with the specific urban topography, such as street orientation, surrounding environment such as geometry, building heights and density (Rahman et al., 2020a), but those factors are out of scope for WP3. The impact of trees on wind speeds in high density urban contexts seems to be small (Kong et al., 2017).

Aerodynamic modelling would thus be needed. The tree part of air circulation could be calculated with some of the models mentioned below.

Urban stresses, such as the lack of available soil water, pollution, higher temperatures, management practices, and more, limit the ability of trees to reduce temperatures in the environment (Bensaoud et al., 2018; Rahman et al., 2015).

As a final comment on this ecosystem service, it is worth mentioning that the cooling effect, air pollution reduction and carbon mitigation of trees are strongly linked with potential trade-offs and co-benefits, and should not be analysed separately (Li and Wang, 2021).

Mentioned models (some examples)**:**

- Interception of water on the vegetation canopy is modelled with a mass budget approach following **the Rutter model** (Meili et al., 2021),

- The mechanistic urban ecohydrological **model Urban Tethys-Chloris (UT&C)** is a combination of an urban canyon scheme and an ecohydrological model and it is solving the energy and water budget on a neighbourhood scale (Meili et al., 2021),
- In order to model the shading effect of different tree species, the Solar and Long Wave Environmental Irradiance Geometry (**SOLWEIG**) model can be used (Kong et al., 2017),
- **ENVI-met** (Simon et al., 2018), **the 3D-3T model** (Qiu et al., 2020) and **MAESTRO** (latest update in '01)(Bowden and Bauerle, 2008) are models that, using meteorological parameters and 3D tree models, a set of measured temperatures and radiation, or 3D models of trees, their leaf area distribution, meteorological variables and more, respectively, give an estimation of the tree transpiration rates,
- **LASER.T** (LAtente SEnsible Radiation & Trees) modelizes the interactions between the trees and their environment, using meteorological variables, material characteristics and physiological data on the vegetation.

As a summary, the tree attributes linked with the cooling effect of trees are:

Attribute	Reference	To be obtained per	To be obtained by	Observation
Tree height	(Rahman et al., 2020a)	Tree	Remote sensing - LiDAR / observation	
Circumference of the trunk at breast height	(Rahman et al., 2020a)	Tree	Measurement	
Leaf area index (LAI)	(Rahman et al., 2020a)	Species	Measuring / literature	Most important factor / Depends on season
Crown diameter	(Rahman et al., 2020a)	Tree	Remote sensing / observation	
Canopy volume	(Rahman et al., 2020a)	Tree	Remote sensing / observation	
Crown projection area	(Rahman et al., 2020a)	Tree	Measurement	Most important factor
Crown form	(Rahman et al., 2020a)	Species	Literature	
Planting arrangement	(Rahman et al., 2020a)	Tree	Observation	
Species specific transpiration	(Gupta et al., 2018)	Tree	Measurement	Depends on many factors, as water availability, wind speed, air temperature, etc.
Tree stress level (health status of the tree)	(Bensaoud et al., 2018; Rahman et al., 2015)	Tree	Observation	

Table 5. Tree attributes linked with the cooling effect of trees.

Other possibly interesting attributes are:

Attribute	Reference	To be obtained per	To be obtained by	Observation
Albedo of surface materials	(Czaja et al., 2020; Rahman et al., 2020a)	Area studied	Literature, remote sensing/GIS	
Tree undergrowth and structure	(Rahman et al., 2020a)	Tree	Observation	
Height of surrounding buildings	(Meili et al., 2021)	Area studies	LiDAR	
Irrigation status of trees	(Bensaoud et al., 2018)	Tree / Area studied	Meteorological services or measurement	Strongly dependent on season
Air and surface temperatures under or far from trees	(Rahman et al., 2020a)	Area studied	Meteorological services or measurement	Strongly dependent on weather

Table 6. Other attributes linked with the cooling effect of trees.

2.4 Flood risk and estimated damages

Their leaves, branches and trunks reduce runoff volume, soil erosion, and they also delay peak flooding through the interception process (Alves et al., 2018; Peper et al., 2007; Zabret and Šraj, 2015). Their growing roots and organic compounds improve the permeability of the soil, and they send a part of the rainwater back into the air through evapotranspiration (Alves et al., 2018). This capacity depends **on tree species** as tree canopy architecture, leaf and bark typologies influence tree interception capabilities (Alves et al., 2018).

The positive impact of trees is most effective in **areas with high proportions of impervious surfaces** (Zabret and Šraj, 2015). But there are negative effects, too, as **roots** as well as **fallen leaves** can block sewer systems (Cherqui et al., 2015).

An example of a model for calculating, amongst others, the effect of trees on flood risks is:

- the hydrological **model LEAFlood** (Landscape and vEgetAtion-dependent Flood model), which is based on the open source 'Catchment Modelling Framework' (CMF)(Camarena et al., 2022). This model needs:
  - **Canopy closure** (the quotient of the canopy area and cell area equals the canopy closure),
  - Throughfall (mm of water per minute when raining - Throughfall is measured through a tipping bucket rain gauge, which is mounted under the tree's canopy) and interception capacity, which both can be modelled using **LAI** and **meteorological data** (Ying, 2016),
  - **Tree number,**
  - And some more environmental parameters (not linked with the trees).

As a summary, the tree attributes linked with flood risk and estimated damages are:

Attribute	Reference	To be obtained per	To be obtained by	Observation
Tree species	(Camarena et al., 2022)	Tree	Determination	
Canopy closure	(Camarena et al., 2022)	Area studied	Canopy area (remote sensing) / cell area	
Tree number	(Camarena et al., 2022)	Area studied	LiDAR/remote sensing	
LAI	(Camarena et al., 2022)	Species	Measuring / literature	Depends on season

Table 7. Tree attributes linked with flood risk and estimated damages.

Other possibly interesting attributes are:

Attribute	Reference	To be obtained per	To be obtained by	Observation
Proportion of impervious surfaces	(Zabret and Šraj, 2015)	Area studied	Observation / remote sensing	
Precipitation	(Camarena et al., 2022)	Area studied	Pluviometer / meteorological services	

Table 8. Other attributes linked with flood risk and estimated damages.

2.5 Noise abatement

The forest floor seems to have a high effect on reducing noise in the surroundings, even more if the litter remains present and the soil is not compacted (Attenborough, 2019; Van Renterghem et al., 2021). **Ground porosity**, but even more, **flow resistivity** is a positive factor (Attenborough, 2019; Attenborough et al., 2011). Trunks will mainly lead to multiple scattering of sound, where the sound absorption by tree barks, although limited, is helpful. But only when **tree trunk density** is close to its biological maximum can significant effects be expected from the scattering process (Van Renterghem et al., 2021). Also leaves and branches reflect, refract, scatter, diffract and absorb sound waves (Fan et al., 2010; Maleki and Hosseini, 2011).

Tree bark reduces slightly sound pollution, with coniferous species leading the statistics, and the **presence of moss** on the tree adding to the absorption rate (Li et al., 2020). **Species**, **tree age** and **radial roughness index** (based on the thickness of the bark at 32 points, neglecting the influence of the shape of the trunk) seem the most decisive parameters (Fan et al., 2010; Huyghe and Verheyen, n.d.; Li et al., 2020).

Leaves have the ability to attenuate acoustic waves, and their **species**-specific properties influence the frequencies for which they are the most effective in attenuating (Fan et al., 2010). The higher the **density of greenery**, the total **surface** of the leaves (LAI) and **area** or **width** of the complex, the greater the damping value (Defrance et al., 2019; Jaszczak et al., 2021; Maleki and Hosseini, 2011). On the level of a tree stand, the **planting arrangements** and tree species mixture can also influence the capacity of the complete stand to attenuate noise pollution (Fan et al., 2010).

Subjective factors also count. **Nicely smelling trees** reduce perception of noise (Ba and Kang, 2019). If the perceiver does **not see the traffic** (thanks to the trees), the noise annoys less (Jaszczak et al., 2021). And

positive noises, such as whistling birds, softly blowing wind, gently flowing water, …, attenuate the effect of negative noises (Jaszczak et al., 2021).

In brief, a tree belt can serve as a type of acoustic barrier, and it can suppress sounds depending on the **density**, **height**, **width**, and **species** used (Jaszczak et al., 2021).

As a summary, the tree attributes linked with noise abatement are:

Attribute	Reference	To be obtained per	To be obtained by	Observation
Tree (trunk) density	(Jaszczak et al., 2021; Van Renterghem et al., 2021)	Area studied	Counting (GIS)	
Tree planting arrangement	(Fan et al., 2010)	Area studied	Observation	
Tree height	(Jaszczak et al., 2021)	Tree	Remote sensing (LiDAR) / observation	
Crown diameter	(Jaszczak et al., 2021)	Tree	Remote sensing / observation	
Tree species	(Huyghe and Verheyen, n.d.; Li et al., 2020)	Tree	Determination	Nice smell?
Presence of moss on trunk	(Li et al., 2020)	Tree	Observation	
Tree age	(Huyghe and Verheyen, n.d.; Li et al., 2020)	Tree	Observation	
Radial roughness	(Huyghe and Verheyen, n.d.; Li et al., 2020)	Species	Literature / Observation (based on the thickness of the bark at 32 points, neglecting the influence of the shape of the trunk)	Depends on age
LAI	(Jaszczak et al., 2021)	Species	Measuring / literature	Depends on season
Tree cover	(Jaszczak et al., 2021)	Area studied	Canopy area (remote sensing) / cell area	

Table 9. Tree attributes linked with noise abatement.

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Other possibly interesting attributes are:

Attribute	Reference	To be obtained per	To be obtained by	Observation
Ground porosity	(Attenborough, 2019)	Area studied	Literature(Attenborough et al., 2011; Kephalopoulos et al., 2012) and observation	
Flow resistivity	(Attenborough, 2019)	Area studied	Measuring (the ratio of the applied pressure gradient to the induced steady volume flow rate of air through the surface of the ground) / literature(Attenborough et al., 2011)	
Presence of positive noises	(Jaszczak et al., 2021)	Area studied	Observation (birds) or GIS (water noises) or GIS (tree species producing pleasant noises)	Depends on season
Visual screen to traffic	(Jaszczak et al., 2021)	Area studied	GIS	Depends on season
Intensity of negative noises	(Jaszczak et al., 2021)	Area studied	GIS	

Table 10. Other attributes linked with noise abatement.

2.6 Potential carbon mitigation

The potential carbon mitigation impact of urban trees can come from different sources:

- Carbon absorption by the tree,
- Carbon leakage to the soil by the roots,
- Use of aboveground biomass when tree is removed (the different end-of-life scenarios) (Nowak and Crane, 2002; Speak et al., 2020),
- Increase (decrease) in the total number of trees (or planting pits) in an area,
- Use of carbon-rich materials for soil improvement when planting or maintaining the, such as biochar, mulch, fallen leaves or organic rich growth medium tree (Ariluoma et al., 2021; Havu et al., 2022; Riikonen et al., 2017; Tammeorg et al., 2021),
- Fuel used for pruning equipment and transport vehicles (Nowak et al., 2002; Speak et al., 2020).

The first one, the carbon absorption by the tree, can be calculated using the next attributes:

- Tree trunk, branches, and roots volume,
    - **Trunk circumference** (Speak et al., 2020)
    - **Tree height** (Speak et al., 2020)
    - Stem profile (species dependent) = allometric equations (Henry et al., 2013; Jucker et al., 2022; Nowak and Crane, 2002) or volume equations (Henry et al., 2013; McPherson et al., 2016)
    - Expansion coefficients (Longuetaud et al., 2018; Nowak and Crane, 2002)
        - **Pruning regime** (Speak and Salbitano, 2023)
        - Root-to-shoot ratio of 0.26 (Nowak and Crane, 2002) or 0.28 (Rahman et al., 2015)
- Density of wood for tree species,
    - **Tree species** (Speak et al., 2020)
    - Species-specific wood density (Donegan et al., 2014)

  - Fresh to dry biomass (Nowak and Crane, 2002)
  - Conversion statistics from forest trees to urban trees (Nowak and Crane, 2002)
- Carbon content of wood (Thomas and Martin, 2012),
- Increase in wood volume per year
  - **Average diameter and height growth** (Nowak and Crane, 2002; Smith et al., 2019), and
  - **Health status of tree** (Nowak and Crane, 2002; Speak et al., 2020)
- Life expectancy of urban trees
  - **Tree removal rate** (Speak et al., 2020)**,** or
  - **Averages of tree mortality** (Nowak and Crane, 2002; Smith et al., 2019)

Larger trees (**tree size**) extract and store more CO_2 from the atmosphere (Depietri et al., 2012).

When taking into account that the carbon sequestered and stored in trees, gets released after the tree's death (if not disposed of in a landfill), and that the tree management needs fossil fuels, many, if not most trees have a negative carbon balance (Nowak et al., 2002; Speak et al., 2020).

As a final comment on this ecosystem service, it is worth mentioning that the cooling effect, air pollution reduction and carbon mitigation of trees are strongly linked with potential trade-offs and co-benefits, and should not be analysed separately (Li and Wang, 2021).

Models (some examples):

- I-Tree (Havu et al., 2022; Speak et al., 2020)
  - i-Tree software uses data on tree characteristics and estimates carbon sequestration and storage using biomass equations developed for urban trees based on US urban tree data.
- UCM-CO_2 (Li and Wang, 2021)
  - The UCM-CO2 model integrates the urban thermal and hydrological processes using a single-layer urban canopy model (UCM) with the carbon exchange in the built environment.
- Tree Prune Model(Speak and Salbitano, 2023)
  - Models the changes in tree biomass considering pruning rates, pruning frequencies and mortality rates.
- SUEWS and Yasso
  - Estimate the carbon cycle dynamics in urban nature (Havu et al., 2022).

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As a summary, the tree attributes linked with potential carbon mitigation are:

Attribute	Reference	To be obtained per	To be obtained by	Observation
Circumference of the trunk at breast height	(Speak et al., 2020)	Tree	Measurement	
Tree height	(Speak et al., 2020)	Tree	Remote sensing - LiDAR / observation	
Tree species	(Speak et al., 2020)	Tree	Determination	
Health status of the tree	(Nowak and Crane, 2002; Speak et al., 2020)	Tree	Observation	
Pruning regime	(Nowak et al., 2002; Speak and Salbitano, 2023)	Tree	Observation	
Fuel used for tree management	(Nowak et al., 2002; Speak et al., 2020, 2020)	City	Questionnaire	
End-of-life scenario for trees and pruned materials	(Nowak et al., 2002; Speak and Salbitano, 2023)	City	Questionnaire	
Average diameter and height growth	(Nowak and Crane, 2002)	City	Measurement or database analyses	
Tree removal rate	(Speak et al., 2020)	City	Questionnaire or database analysis	
Averages of tree mortality	(Nowak and Crane, 2002)	City	Questionnaire or database analysis	

Table 11. Tree attributes linked with potential carbon mitigation.

Other possibly interesting attributes are:

Attribute	Reference	To be obtained per	To be obtained by	Observation
Soil carbon content and carbon content change	(Ariluoma et al., 2021; Tammeorg et al., 2021)	Tree	Measurement, or averaged in literature	
Soil management practices	(Ariluoma et al., 2021; Tammeorg et al., 2021)	City	Questionnaire	

Table 12. Other attributes linked with potential carbon mitigation.

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3 Tree attributes as derived from previous chapter

In the previous chapter, the ecosystem services important for the 100kTrees project have been described, the possible contribution of urban trees has been discussed and a list of tree attributes has been constructed, with which those contributions can be modelled.

The overall goal of this document is *to establish a list of existing data (tree data, scientific data) and missing data to get to a decent definition of 4 to 6 standard city tree types per climatic situation (Copenhagen, Sofia) using a set of key attributes*. At this stage, only the attributes relevant for defining those standard city tree types are considered, so the irrelevant attributes have been omitted (see 7 Appendix 1: Eliminated attributes). This reduces the list to the next tree-related attributes:

Attribute	Ecosystem service
Crown diameter (~canopy projection area)	Air pollution reduction, Cooling effect, Noise abatement
Tree dimensions	Air pollution reduction
Tree species	Air pollution reduction, Biodiversity improvement, Flood risk and estimated damages, Noise abatement, Potential carbon mitigation
Leaf area	Air pollution reduction
Tree physiological status (health status of the tree)	Air pollution reduction, Cooling effect¸ Potential carbon mitigation
Circumference of the trunk at breast height	Biodiversity improvement, Cooling effect, Potential carbon mitigation
Tree management (intensive/extensive)	Biodiversity improvement
Allelochemicals	Biodiversity improvement
Tree microhabitats	Biodiversity improvement
Canopy volume	Cooling effect
Tree height	Cooling effect, Noise abatement, Potential carbon mitigation
Crown form	Cooling effect
Species specific transpiration	Cooling effect
LAI	Cooling effect, Flood risk and estimated damages, Noise abatement
Radial roughness	Noise abatement
Presence of moss on trunk	Noise abatement
Tree age	Noise abatement
Average diameter and height growth	Potential carbon mitigation
Pruning regime	Biodiversity improvement, Potential carbon mitigation

Table 13. Attributes that help in describing ecosystem services provided by urban trees, and that are useful for defining standard city tree types.

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Some of those attributes are calculated through one or more other attributes or can be obtained by a proxy.

Attribute	Calculated through or proxy used
Tree dimensions	Circumference of the trunk at breast height, Crown diameter, Tree height
Leaf area	LAI, Canopy projection area (~Crown diameter)
Tree management (intensive/extensive)	Pruning regime
Tree microhabitats	Circumference of the trunk at breast height
Canopy projection area	Crown diameter
Canopy volume	Crown diameter, Tree height, Clearance height, Crown form
Tree age	Tree planting date
Average diameter and height growth	Circumference of the trunk at breast height, Tree height, Tree planting date

Table 14. Attributes of the previous list that can be calculated through other attributes or replaced by a proxy.

This allows the list of retained tree attributes to be reduced to the next:

Attribute	Ecosystem service
Allelochemicals	Biodiversity improvement
Clearance height*	Cooling effect
Crown diameter (canopy projection area)	Air pollution reduction, Cooling effect, Noise abatement
Crown form	Cooling effect
Diameter / circumference of the trunk at breast height	Air pollution reduction, Biodiversity improvement, Cooling effect, Noise abatement, Potential carbon mitigation
Leaf Area Index (LAI)	Air pollution reduction, Cooling effect, Flood risk and estimated damages, Noise abatement
Presence of moss on trunk	Noise abatement
Pruning regime	Biodiversity improvement, Potential carbon mitigation
Radial roughness	Noise abatement
Species specific transpiration	Cooling effect
Tree height	Air pollution reduction, Cooling effect, Noise abatement, Potential carbon mitigation
Tree physiological status (health status of the tree)	Air pollution reduction, Cooling effect, Potential carbon mitigation
Tree planting date*	Noise abatement, Potential carbon mitigation
Tree species	Air pollution reduction, Biodiversity improvement, Flood risk and estimated damages, Noise abatement, Potential carbon mitigation

**This attribute has been added to the list.*

Table 15. Final list of attributes for defining standard city tree types.

The **temporality** of most of these attributes is also to be considered, apart from the few attributes that remain the same during the complete life cycle of an urban tree (such as the attribute "species" or some species-dependent attributes). Indeed, all dendrometric attributes (diameter, height, clearance height, diameter at breast height) and season, size or age-dependent attributes (e.g. LAI, crown form, radial roughness) evolve greatly over the lifespan of a tree, as do their impact on the ecosystem services the tree provides.

There are several existing tree growth models, allowing for taking this temporality into account, like:

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- i-Tree,
    - www.itreetools.org
    - i-Tree Eco is an adaptation of the Urban Forest Effects (UFORE) model
- UFORE,
    - Has been absorbed in i-Tree (above)
- L-Peach,
    - L-PEACH is a computer-based model that simulates the growth of peach [Prunus persica (L.) Batsch] trees. The model integrates important concepts related to carbon assimilation, distribution, and use in peach trees. It also includes modeling of the responses to horticultural practices such as tree pruning and fruit thinning. While running L-PEACH, three-dimensional (3D) depictions of simulated growing trees can be displayed on the computer screen and the user can easily interact with the model. L-PEACH is a powerful tool for understanding how peach trees function in the field environment, and it can be used as an innovative method for dissemination of knowledge related with carbohydrate assimilation and partitioning (Lopez et al., 2008). This model explains quite correctly the form of a tree, but not the correlation between age and size (i.e. the growth curve).
- UrbTree
    - The developed tree growth model uses species specific tree characteristics like shape (column, round or ellipse), size classification (big, regular, small), growth speed (slow, regular or fast-growing tree), life phase (young, mature, old) in combination with influences caused by the stand characteristics of the nearby surface coverings (paved, open or vegetated). The UrbTree model is a spatial driven growth model and can model differences in tree growth caused by the nature of the surface covering of the neighbouring area of the location of the trees by using spatial analyses techniques (Kramer and Oldengarm, 2010).

But careful, the tree height and crown form, and density of the crown (leaves) are strongly influenced by competition by neighbouring trees (MacFarlane and Kane, 2017) (see reference for formula).

The attributes of the last list are treated individually in the rest of this chapter. Their definition and link with the ecosystem services are discussed in detail, a standardized method is proposed for measuring or obtaining the data, and their temporality is documented.

3.1 Allelochemicals

Some authors in the scientific literature refer to allelopathy as the mechanism that some plants use to release chemical compounds that inhibit or stimulate the growth of different plant species (Omar et al., 2018). Other authors suggest that the use of the term allelopathy is misleading and reductive of complex interactions involving plant chemical communication and advise not to use the term any longer (Schenk and Seabloom in (Baluška et al., 2010)). For example, some recent studies show that these substances are not only involved in direct competition but can also represent a source of information that is used to adapt to upcoming events, a process called *allelobiosis* (Ninkovic in (Baluška et al., 2010)). Nevertheless, all authors seem to agree on the term allelochemicals to identify interspecific substances that can constitute an advantage for the emitter (allomone), for the receiver (kairomone) or for both the emitter and the receiver (synomone) (Kost et al., 2008). At least several hundreds of these substances are known in plants (Ninkovic in (Baluška et al., 2010)). They can be released through different paths, e.g. volatilisation, leaching, root exudation and residue decomposition, and influenced by factors such as plant UV exposure, temperature,

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drought and presence of soil microorganisms that mediate changes in the local ecosystem (Kumar and Bais in (Baluška et al., 2010)).

Allelochemicals are usually expressed in nanogram per litre or kilogram (ng/L or ng/kg) and can be measured with different analytical techniques according to the type of matrix where they are found. For example, Volatile Organic Compounds (VOCs) can be collected in small air chambers using porous polymeric materials (a technique called Dynamic Headspace Collection) or directly on small fibres coated with adsorbent material (a technique called Solid Phase Micro Extraction) (Birkett in (Baluška et al., 2010)). The VOCs are then desorbed thermically or with the use of a solvent, followed by separation with Gas Chromatography (GC) and detection with e.g. Mass Spectrometry (MS) or ElectroAntennoGraphy (EAG) (Birkett in (Baluška et al., 2010)). When the allelochemicals need to be extracted from plant tissues, soil or water samples, Liquid-Liquid extraction, Solid Phase Extraction or Stir Bar Sorptive Extraction can be used for sample preparation and High Performance Liquid Chromatography (HPLC) can be used for separation before detection with e.g. MS or EAG (Birkett in (Baluška et al., 2010)). Recently, also Nuclear magnetic resonance (NMR) spectroscopy has been used in plant communication studies (Birkett in (Baluška et al., 2010)).

Allelochemicals released by some urban trees can decrease the biodiversity at the tree base: *Robinia pseudoacacia* leaves contain robinetin, myricetin and quercitin that inhibit shoot and root growth (Omar et al., 2018); chemical inhibitors released by *Platanus* trees impair the growth of herbaceous species under the canopy cover, albeit they do not seem to be the driving factor explaining the number of species surrounding the trees, maybe because the fallen leaves are removed as soon as they fall on the pavement (Omar et al., 2018).

VOCs can be used to monitor crop health and their temporality is connected to biotic and abiotic stressors such as herbivore infestation, fungal/bacterial/viral infection, low nutrition, drought, high ozone or CO_2 concentration, temperature increase, pruning as well as to life cycle events such as budding, flowering, fruit setting and picking (Wildt et al. in (Baluška et al., 2010)). Similar temporality for allelochemicals is to be expected in trees and can tell something about the tree physiological status (see section 3.11).

Type of data that would be useful to define this tree attribute:

- chemical analyses of soil, water and/or air samples collected in the proximity of urban trees,
- chemical analyses of plant and/or animal tissues collected from urban trees or from nearby flora and fauna,
- plant diversity underneath trees suspected or not for releasing allelochemicals.

These analyses should report the presence/absence of allelochemicals, eventually their chemical nature and concentration, and their effects on the same species and/or on other species of flora and fauna.

Eventual data gaps could be filled by using lists of tree species known to release allelochemicals (Coder, 1999), along with the effects that these allelochemicals have on the same species and/or on other species of flora and fauna.

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3.2 Clearance height

Clearance height, also known as stem extent, “bole extent”, tree bole height, or trunk height to the first branch, is a tree attribute that describes the vertical distance from the ground to the point where the crown of a tree begins (Nowak and Dwyer, 2007). It is, amongst others, used to calculate crown volume together with tree height and crown diameter.

In urban landscapes, ecosystems, parks, and gardens, clearance height plays a crucial role in understanding tree growth patterns, aesthetics, and the various ecosystem services provided by trees, such as cooling effect, potential carbon mitigation, and flood risk reduction (Konijnendijk et al., 2006), and even air pollution reduction and biodiversity improvement.

Higher clearance heights can lead to increased light penetration, thus supporting the growth of understory vegetation like shrubs, grass and smaller trees and therefore enhancing biodiversity (Lindenmayer et al., 2012). Additionally, trees with greater clearance heights may have larger trunk biomass, contributing to carbon storage and mitigating climate change (Chave et al., 2005) Trees with varying clearance heights can be strategically utilized in urban planning and architecture to provide wind protection in cities. By incorporating trees with different heights and crown structures, urban planners can create a diverse vegetation profile that helps in reducing wind speed, turbulence, and the overall impact of wind on urban environments (Sternberg et al., 2010).

Taller trees with higher clearance heights can act as a windbreak, shielding buildings and pedestrians from strong winds, while trees with lower clearance heights may help in dispersing and redirecting wind flow at the ground level (Rudnicki et al., 2004). This combination of tree heights can significantly improve outdoor thermal and wind comfort, reducing energy consumption for heating and cooling in adjacent buildings (McPherson, 2005).

Moreover, integrating trees with various clearance heights into urban design can create microclimates that offer protection from wind and improve air quality by trapping pollutants, thus enhancing the overall liveability of urban spaces (Gromke and Ruck, 2007).

Clearance height is typically measured in meters (m) and can be obtained through field measurements or by remote sensing, combining LiDAR (Light Detection and Ranging) and multispectral data (Popescu et al., 2004; Popescu and Wynne, 2004). Indeed, LiDAR data analysed for forest stands, as the mentioned literature proposes, gives robust data on tree height, and the use of windows for smoothing LiDAR data helps in extracting tree crown sizes, thusly supporting the extraction of the right LiDAR point for representing the tree height. Multispectral data, in this model, are used for differentiating between forest types (and it might help in urban tree stands to differentiate between tree species or families). Standardizing this attribute involves measuring the height from the ground level to the base of the lowest live branch, ensuring consistency across different tree species and forest types (Asner et al., 2009).

In the context of urban tree development, clearance height is a dynamic attribute that changes as a tree matures and its crown structure evolves. Regular monitoring of clearance height data is essential for accurately representing urban tree populations and tracking changes in the ecosystem services they provide (Roman et al., 2017).

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3.3 Crown diameter

Tree crown is the part of the tree above its major branches and the crown diameter is the length between two opposite edges of the tree crown. The crown diameter is measured in meters (m), it is part of the key information gathered during field data collection or by an automated process, using LiDAR (and multispectral data) analysis, and it is used, together with crown height, to define the crown shape (McPherson et al., 2016).

While Diameter at Breast Height (DBH) can be used to estimate crown diameter, the latter is used to estimate the DBH in remote sensing applications via the creation of allometric relations (McPherson et al., 2016). Crown diameter can also be used to derive canopy projection area, canopy volume and Leaf Area Index (LAI), which are connected to air pollution reduction (Depietri et al., 2012), cooling effect (Rahman et al., 2020a) and noise abatement of trees (Jaszczak et al., 2021).

Crown dimensions (diameter, height and volume) depend on tree species and age, and are affected by climate and tree management practices, in particular pruning (McPherson et al., 2016). Also planting arrangement and density can play a role in defining the crown diameter.

Eventual data gaps can be filled by estimating the tree height using the tree DBH (see section 3.5 and (Understanding i-Tree - Appendix 13, n.d.)), or by LiDAR and multispectral data (Popescu et al., 2004; Popescu and Wynne, 2004).

3.4 Crown form

Tree crown form refers to the overall shape, structure, and branching pattern of a tree's crown, which is the upper part of the tree where branches and leaves are found. Crown form can vary widely among tree species, and it can be influenced by factors such as genetics (i.e. certain varieties have a crown form that is very different from the reference shape for that species (Hermy, 2021)), environmental conditions, competition for resources, management practices (see 3.8 Pruning regime) and age.

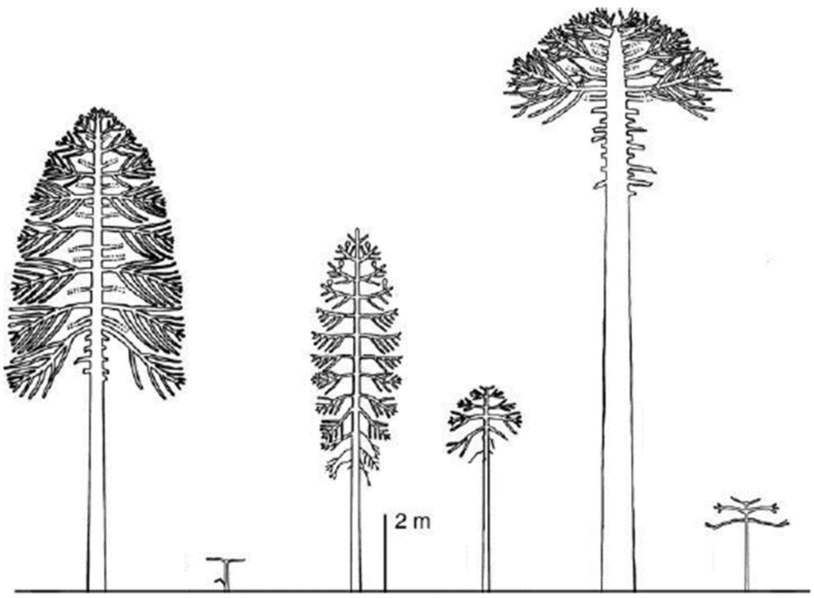
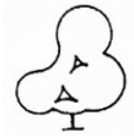
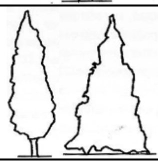
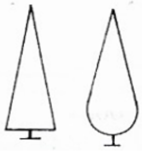
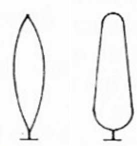
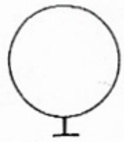
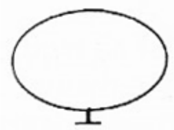
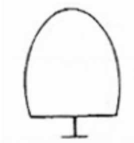
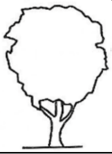
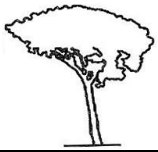
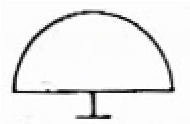


Figure 1. Architectural variations of Araucaria araucana *in its natural habitat (Grosfeld et al., 1999).*

The crown form is documented in scientific literature for a free-growing or lightly pruned tree, grown in optimal circumstances (Navés Viñas and Riudor i Carol, 2003). The most frequent crown forms are documented in the next table.

From: (Вакаралеов and Анисимова, 2010) *Translated from Bulgarian*	From: (Navés Viñas and Riudor i Carol, 2003) *Translated from Spanish*	From: (Hermy, 2021) *Translated from Dutch*
Spreading (irregular) 	Irregular 	
Conical (Pyramidal) ¬ narrow ¬ broad 	Conical / Flame 	Pyramidal 
Columnar (cylindrical, fastigiate, column-like) ¬ narrow ¬ broad 	Narrow fusiform column Broad column 	Columnar or cylindrical 
Spherical 	Spherical / Round 	Round 
Elliptical 	Ovoid 	Oval 
	Elliptical 	
Ovate 	Semi-ovoid / half-ellipsoid 	
Inverted ovate (obovate) 		
Umbrella-shaped 	Parasol 	Vase 

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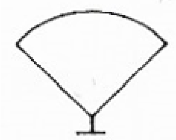
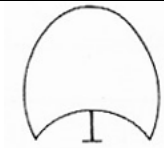
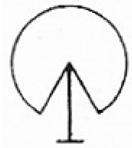
From: (Вакаралеов and Анисимова, 2010) *Translated from Bulgarian*	From: (Navés Viñas and Riudor i Carol, 2003) *Translated from Spanish*	From: (Hermy, 2021) *Translated from Dutch*
	Fan-shaped 	
Weeping 	Weeping 	Weeping 
	Palm-shaped 	

Table 16. Comparison of proposed crown form from 3 different sources.

The crown forms from Table 16 are described as follows:

- **Spreading (irregular)**
  Spreading or irregular crowns are characterized by irregular branching patterns that don't conform to a specific shape. This crown form can be seen in species such as *Quercus robur* and *Fraxinus excelsior*.
- **Conical / Pyramidal / Flame**
  Conical crowns have a broad base that tapers to a point at the top, resembling a cone (or a pyramid). Conifers like *Picea abies* often exhibit this crown form. This crown form can be divided into two sub-forms dependant of the ratio between crown height and the crown diameter:
  - **narrow**
  - **broad**
- **Columnar / Cylindrical / Fastigiate / Fusiform**
  Columnar crowns have a straight, cylindrical shape with relatively uniform width throughout. This form is found in trees like *Quercus robur* 'Fastigiata' and *Fagus sylvatica* 'Dawyck'. *Carpinus betulus* ‘Fastigiata’ has a similar cylindrical shape when young, but its crown grows strongly in lateral direction later on, and those trees will get as broad as they get high when old (Joye et al., 2008). This crown form can also be divided into two sub-forms dependant of the ratio between crown height and the crown diameter:
  - **narrow**
  - **broad**
- **Spherical / Round**
  Spherical crowns are characterized by their rounded, symmetrical shape. Trees with spherical crowns include some cultivars of ornamental cherry (*Prunus spp.*), hawthorn (*Crataegus spp.*), and dwarf varieties of certain tree species.
- **Elliptical**
  Elliptical crowns have an elongated, oval shape with a consistent width. Trees with elliptical crowns

include species such as American elm (*Ulmus americana*) and some maple (*Acer spp.*) and linden (*Tilia spp.*) cultivars.

- **Ovate / Oval / Elliptical / Ovoid**
  Ovate crowns are egg-shaped, with a narrow base, very broad in the middle and tapering towards the top. Trees with ovate crowns include species like *Liriodendron tulipifera*.
- **Semi-ovoid / Half-ellipsoid**
  Ovate crowns are also egg-shaped, with a wider base that tapers towards the top. Trees with ovate crowns include species like *Aesculus hippocastanum*.
- **Inverted ovate**
  Inverted ovate crowns have an egg-shaped form with a narrower base that widens towards the top. This crown form can be seen in species like *Fagus sylvatica*.
- **Oval**
  Oval crowns have an elliptical shape with a more rounded, symmetrical appearance. Trees with oval crowns include species such as sugar maple (*Acer saccharum*) and American basswood (*Tilia americana*).
- **Umbrella-shaped / Parasol / Fan-shaped / Vase**
  Umbrella-shaped crowns have a broad, flattened top with branches that sprout from the centre and spread out more or less horizontally, resembling an open umbrella. Trees with this crown form include species like *Pinus pinea, Cornus alternifolia, Albizia julibrissin* and *Zelkova serrata*.
- **Weeping**
  Weeping crowns have branches that droop or hang downward, creating a cascading or "weeping" effect. This crown form is often seen in *Salix babylonica* and some cultivars of weeping birch (*Betula pendula*) and cherry (*Prunus spp.*).
- **Palm-shaped**
  Palm-shaped trees have typically a straight bole ending in a fan of big leaves. As the name indicates, this form is frequent amongst palm trees, such as *Trachycarpus fortunei.*

The most common crown shapes seem to be Conical / Pyramidal / Flame, Columnar / Cylindrical / Fastigiate / Fusiform, Ovate / Oval / Elliptical / Ovoid, Semi-ovoid / Half-ellipsoid, and Spherical / Round (Franceschi et al., 2022).

As it is written - “A tree’s crown shape has a great influence on the crown volume and thus on the ecosystem service provision of a tree such as the shade area or the shade density.” (Franceschi et al., 2022). Crown volume can be used as an element to estimate leaf area, transpiration and filtration of fine particles. For this project, the ecosystem service potentially the most impacted by the crown form, is the cooling effect, as shade provisioning is probably the most important factor.

The crown form is generally fixed per tree species/variety. Eventual missing data can be completed using the information present in scientific literature (Hermy, 2021; Navés Viñas and Riudor i Carol, 2003; Вакаралеов and Анисимова, 2010).

3.5 Diameter / circumference at breast height

Tree Diameter at Breast Height (DBH or d.b.h.) is measured in meters (m) with callipers and/or tapes on the trunk of the tree at a height of 1.3 - 1.4 m from the ground (Nowak et al., 2006; Rahman et al., 2020a; Speak et al., 2020). However, some tree inventory manuals propose that this measurement is to be taken at a different height, e.g. at a height of 1 m from the ground (Speak et al., 2020). Of course, in the field, many trees are not conform the standards, so several special cases have been identified (i-Tree Eco Users Manual, n.d.):

- If a tree is growing on a slope, the breast height is measured from the upper side,
- For multi-stemmed trees, all trunks are measured,
- If the tree is swollen at breast height, measure DBH at least 45cm above the swell,
- If the tree has irregularities at breast height, measure DBH immediately above the irregularity,
- If a tree leans, breast height is measured along the underside face of the bole,
- If a tree has been windblown but lives, breast height is measured from the top of the root collar along the length of the bole.

For saplings, the diameter is usually measured just above the root collar/neck.

Circumference is also measured in meters (m) with tapes on the trunk of the tree at similar heights. The two parameters are related by the formula $C = \pi d$ where C is the circumference and d the diameter.

DBH is used as a proxy for tree size, which in turn defines the potential for microhabitats and biodiversity improvement (Helden et al., 2012; Salisbury et al., 2017). DBH can also be used to derive the sapwood depth and the tree age to estimate the tree cooling effect (Rahman et al., 2020b), as well as to derive the tree growth and size to estimate the carbon sequestration and storage (Nowak et al., 2006, 2008).

Tree diameter and circumference depend on tree species and age, and are affected by climate, type of soil and availability of nutrients.

Eventual data gaps can be filled using forestry yield tables to estimate the tree DBH or circumference from the tree age (see section 3.5).

3.6 Leaf Area Index (LAI)

The Leaf Area Index (LAI) is a dimensionless quantity that expresses the amount of leaves (in m^2) above a square meter or ground. So (Watson, 1947):

$$LAI = \frac{Leaf\ area\ (m^2)}{Ground\ area\ (m^2)}$$

Where:

- Leaf area: one-sided leaf area for leaves or half of the needle surface area above a certain ground area, in m^2,
- Ground area: the ground area above which the leaf area has been measured, in m^2.

So, in brief, LAI is an indicator for the quantity of leaf surface in a certain area. Logically, it has a strong impact on the ecosystem services where the leaves play an important role in, such as:

- Air pollution reduction (through adherence or absorption of pollution by leaves (Depietri et al., 2012)),
- Cooling effect (through shadow casted by leaves and, to a lesser extent, by transpiration (Rahman et al., 2020a)),
- Flood risk and estimated damages (by reducing the volume of water reaching the ground, as it *sticks* to the leaves and evaporates (Alves et al., 2018; Peper et al., 2007; Zabret and Šraj, 2015)), and
- Noise abatement (by leaves absorbing or reflecting sound waves (Jaszczak et al., 2021)).

LAI depends on the age of the tree and is, for deciduous species, seasonal.

LAI can be measured directly by removing all the leaves and measuring their surface in a certain plot. It can also be measured indirectly, e.g. by hemispherical photography (even by the camera of any mobile phone, complemented with a fisheye lens (Wang et al., 2018)) or normal photography of the underside of the canopy (Degerickx et al., 2018; Peper and McPherson, 2003) (also available as an app (Confalonieri, 2014)), by measuring above and below canopy light and calculating the LAI (Rahman et al., 2015), by using LiDAR data (Degerickx et al., 2018), or by using a terrestrial laser scanner and a path length distribution model (Hu et al., 2018). It is also possible to calculate the LAI using regressing equations for open-grown deciduous urban species (Nowak, 1996; Nowak et al., 2008), or to use known average LAI for the species in urban environments (McPherson et al., 1994; Ying, 2016).

3.7 Presence of moss on trunk

The surface of the tree trunks, mostly by their roughness (see 3.9 Radial roughness) and by the presence of moss, has a strong influence on their capacity to suppress sound (Li et al., 2020). Moss tends to grow in damp, shaded places, with a good access to water (Keating, 2020), so it can be expected to find moss more in the next circumstances:

- Close to the ground,
- In tree bark irregularities, such as crevasses,
- On the north side of trees,
- On shaded tree trunks,
- On trees in dense plantations or under full crown coverage.

Very few scientific references mention their method for measuring the presence of moss on tree trunks, but it seems that it has been observed visually and described in a binary scale (present / not present) for the tree trunk sections where sound absorption was measured.

As we consider the whole tree when defining the standard tree types, it is proposed to consider the whole tree trunk, and to refine this attribute by adding some categories. The proposition is the next:

- Moss absent on the tree trunk,
- 1-25% of moss coverage on the tree trunk,
- 25-50% of moss coverage on the tree trunk,
- 50-75% of moss coverage on the tree trunk,
- 75-100% of moss coverage on the tree trunk.

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It is unlikely that it is possible to replace this tree attribute by a proxy, or that a method for remote detection of moss presence on tree trunks can be sufficiently accurate. It is, though, a good attribute to include in a citizen science application, as it can easily be observed and quantified by lay people. A classification via artificial intelligence based on high resolution mobile mapping images might be an option to explore.

3.8 Pruning regime

Tree pruning consists in the removal of tree branches or limbs. It is a common practice in tree maintenance, especially for trees growing near human infrastructures such as buildings and electrical lines (Großmann et al., 2020; Suchocka et al., 2021). Different pruning techniques exist: reduction cuts, removal cut, heading/topping cut when a singular branch or limb is considered (Fini et al., 2015); young tree training, crown cleaning, crown thinning, crown raising, crown reduction, crown shaping (trimming, pollarding, topping), espalier pruning, vista pruning and restorative pruning when the whole tree is considered (Joye et al., 2008; Kolařík et al., 2021). Two very specific pruning techniques mimicking natural fractures in trees are also worth mentioning, the coronet cut and the rip cut, which creates uneven pruning surfaces as habitats for fauna and flora (Fay, n.d.; Kolařík et al., 2021). While proper pruning is helpful to reduce conflicts between trees and human presence and activities, improper pruning leads to problems in tree health, appearance and safety (Suchocka et al., 2021).

A recent study reflected on the fact that pruning can often result in large tree wounds and other microhabitats not found in unpruned trees (Großmann et al., 2020). The study found that intensive pruning increases the number of microhabitats in urban trees, albeit the abundance and diversity of these microhabitats remain lower than in trees in natural unmanaged forests (Großmann et al., 2020). The coronet cut and the rip cut are particularly useful for creating these microhabitats (Fay, n.d.; Kolařík et al., 2021). However, large tree wounds, i.e. wounds of more than 5-10 cm diameter (depending on the tree species compartmentalisation capacity) have also been linked to significant stem discoloration, cavities and decay associated to tree infections from parasitic fungi that can decrease tree stability (e.g. *Fomes fomentarius*) or vigour (e.g. *Armillaria* ssp.) (Suchocka et al., 2021). Recent studies on *Acer pseudoplatanus* and *Tilia cordata* also showed that heading/topping cuts, i.e. where the primary axis is suppressed without providing a substitute, induce harmful morpho-physiological changes in trees that are not observed when using other pruning techniques (Fini et al., 2015; Suchocka et al., 2021). These changes include (1) increase of sprouting, in particular adventitious water sprouts and root suckers, (2) decrease of stem diameter growth, (3) increase of leaf area with an associated decrease of leaf mass per area, (4) increase in chlorophyl content and photosynthetic activity without higher CO_2 assimilation, (5) increase of the occurrence of wounds, necrosis and dieback (Fini et al., 2015; Suchocka et al., 2021). These results confirm what has been previously reported in the technical and scientific literature for several tree species (Shigo, 1991). Therefore, pruning techniques must be applied with prudence.

Pruning regime reflects also the importance of finding a good trade-off between different ecosystem services. A very recent study showed that ecosystem services provided by urban trees can be simulated using pruning and mortality rates (Speak and Salbitano, 2023). The resulting model estimated that eight tree species in two different cities, pruned every 6 years and with a mortality rate of 1%, provide around

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93% of the maximum potential ecosystem services (Speak and Salbitano, 2023). The recovery period after the pruning was observed to be around 3-4 years without considering the severe local effects due to heavy pruning (Speak and Salbitano, 2023). Cuts removing more than 50% of the crown cause the destruction of the crown shape (see section 3.4) and the deformation of the alley structure (Fini et al., 2015; Suchocka et al., 2021).

In brief, tree pruning in urban environments is to be organized and executed carefully towards a desired future tree shape, preferably by pruning the tree lightly but frequently, thusly limiting the number and size of pruning wounds. If this is neglected, it is possible that the desired future tree shape is unattainable (see Figure 2).

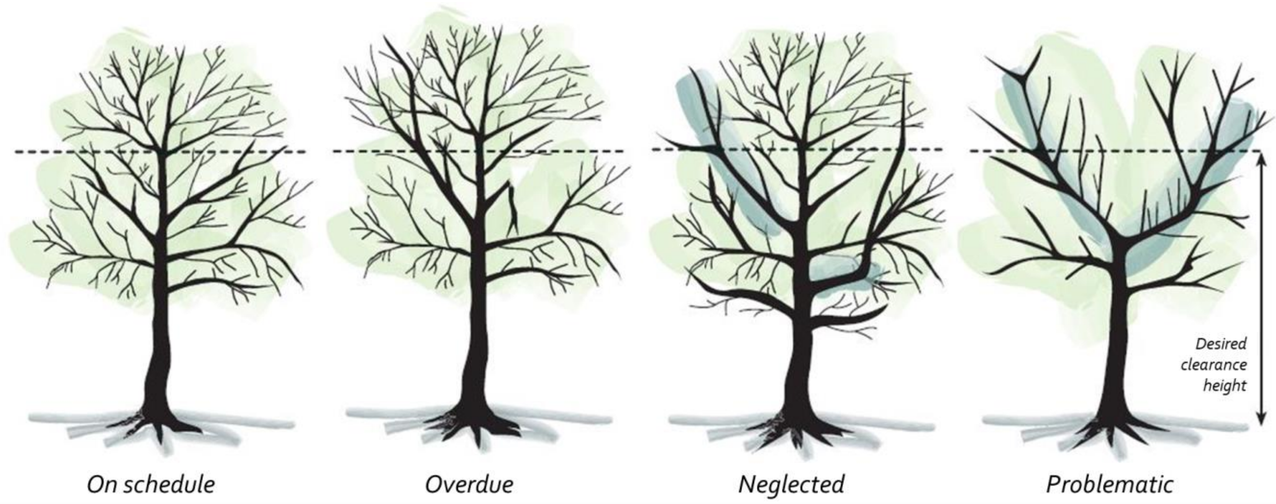

Figure 2. Tree pruning situations in relation with the desired clearance height (adapted from (Joye et al., 2008)).

Data that would be useful to define this tree attribute:

- Number of pruning events (per tree)
- Date of each pruning event
- Percentage of photosynthetic surface that has been removed during each pruning event
- Pruning technique(s) used for each pruning event: young tree training, crown cleaning, crown thinning, crown raising, crown reduction, crown shaping (trimming, pollarding, topping), espalier pruning, vista pruning, restorative pruning, coronet cut and rip cut.

These data will be useful to estimate the Potential carbon mitigation (Nowak et al., 2002; Speak et al., 2020; Speak and Salbitano, 2023) and the biodiversity improvement (Fay, n.d.; Großmann et al., 2020; Kolařík et al., 2021).

Eventual data gaps can be filled with tree assessments carried out by experts.

3.9 Radial roughness

Radial roughness is an attribute expressing the unevenness of the surface, based on measurements of the bark thickness without considering the shape of the tree trunk. The formula for calculating it is (Li et al., 2020):

$$R = \sum_{i=1}^{n} \left(\frac{ri}{\sum_{i=1}^{n} ri} \right) * 100 - \frac{100}{n}$$

Where:

- R: radial roughness
- ri: thickness of bark
- n: number of measurements on one tree trunk section

This attribute, together with tree age (see 3.13 Tree planting date), are significant factors with a positive correlation to noise abatement (Li et al., 2020).

Tree trunk radial roughness typically augments with increased age and varies according to the height or radial roughness measurement (Sioma et al., 2018).

It is unlikely that it is possible to replace this tree attribute by a proxy, or that a method for remote detection of radial roughness on tree trunks can be sufficiently accurate. Bertrand *et al.* proposes a visual method for classifying bark roughness with the next classes (Bertrand et al., 2017):

- Smooth,
- Lenticels,
- Furrows,
- Ridges,
- Cracks,
- Scales, and
- Strips.

But the relationship between this classification and noise abatement has not been documented in the available scientific literature.

An instrument for measuring the relief of bark has been developed by a University of Delaware doctoral student, LaserBark™ (Diane, 2009), but it does not seem to be available. A classification via artificial intelligence based on high resolution mobile mapping images might be an option to explore.

3.10 Species specific transpiration

Species specific transpiration rates, expressed in liters of water evaporated per unit of time (e.g. per hour) by a tree, help calculating the cooling effect of trees on the temperature of their surroundings. It is measured directly on the tree's leaves, e.g. with the portable Photosynthesis System 6400-XT (LI-COR , Lincon , NE)(Gupta et al., 2018) or using a set of temperature and radiation measurements and the 3D-3T model (Qiu et al., 2020), or directly measuring the sap flow (Qiu et al., 2020; Simon et al., 2018). It can also be estimated using meteorological parameters, 3D tree models and the ENVI-met model (which takes into account probable hydric stresses)(Simon et al., 2018). It depends strongly on the wind speed and radiation load (sunshine), so those parameters should also be measured or controlled in order to be able to analyse the data (Gupta et al., 2018).

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The measurement methods as well as the models consider the strong impact of water stress on tree transpiration rates.

As transpiration is done by leaves and under influence of solar radiation and temperature (and wind), this attribute depends strongly on the season and meteorological conditions (absence/presence of leaves, temperature, sunshine, available water) and the age and physiological status of the tree (amount and well-functioning of leaves) as well as species-specific water needs. For the same reason, this attribute is also strongly linked with LAI.

If you remove all the time- and environment specific factors, only the species-specific water need remains (Costello et al., 2000; Litvak et al., 2017). Indeed, the landscape coefficient formula states that:

$$K_L = k_s * k_d * k_{mc}$$

Where:

- K_L = Landscape coefficient
- k_s = Species factor
- k_d = Density factor
- k_{mc} = Microclimate factor

And the species factor is a value ranging from 0,1 to 0,9, where:

- < 0,1 (meaning <10% of the ET_0[1] value) = Very low water needs
- 0,1 – 0,3 = Low water needs
- 0,4 – 0,6 = Moderate water needs
- 0,6 – 0,9 = High water needs

These values are based on water use studies for landscape species (Costello et al., 2000), where values are given as the minimum fraction of reference evapotranspiration needed to maintain acceptable appearance, health, and reasonable growth for the species. They can be found on the WUCOLS database website (*WUCOLS DB*, n.d.) and although the database has been written for California, USA, it is possible to use it for similar climate zones, too (Rambhia et al., 2023).

Data gaps could be remedied by using remote sensing spectral indices, e.g. TVWSI (Temperature Vegetation Water Stress Index)(Joshi et al., 2021), NDWI (Normalized Difference Water Index)(Miller et al., 2020) and others (Yu et al., 2018), for comparing water stress resilience of species with a known species factor, with species without a known species factor, and approximating thusly theirs.

3.11 Tree height

Tree height is expressed in meters (m) and can be measured with a hypsometer (Speak et al., 2020). Both average height and height to crown base are crucial for modelling purposes (Weiskittel et al., 2011). In this document, height to crown base is referred to as clearance height (see section 3.2).

[1] ET_o represents the evapotranspiration rate from a reference surface, not short of water. A large uniform grass field is considered worldwide as the reference surface. The reference crop completely covers the soil, is kept short, well watered and is actively growing under optimal agronomic conditions. (FAO, n.d.)

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Although the collection of field data on tree height is time consuming and prone to errors, the availability of handled laser hypsometers has increased the speed and accuracy of these measurements (Weiskittel et al., 2011). Tree height can also be measured via tree climbing and tape drop to further minimize the errors due to the use of hypsometers from the ground. Recently, LiDAR datasets have been used to derive tree heights (Speak et al., 2020). For example, field measurements could be used to develop and/or validate a continuous Canopy Height Model derived from LiDAR.

Tree height is used to estimate the cooling effect (Rahman et al., 2020b) and the noise abatement (Jaszczak et al., 2021) and it is fundamental to calculate the carbon storage (Speak et al., 2020).

Tree height depends on tree species and age, and is affected by planting arrangement and density, climate, type of soil and availability of nutrients.

Eventual data gaps can be filled by estimating the tree height using the tree DBH (see section 3.4 or (Understanding i-Tree - Appendix 13, n.d.)), or by LiDAR and multispectral data (Popescu et al., 2004; Popescu and Wynne, 2004). Indeed, LiDAR data analysed for forest stands, as the mentioned literature proposes, gives robust data on tree height, and the use of windows for smoothing LiDAR data helps in extracting tree crown sizes, thusly supporting the extraction of the right LiDAR point for representing the tree height. Multispectral data, in this model, are used for differentiating between forest types (and it might help in urban tree stands to differentiate between tree species or families).

3.12 Tree physiological status (health status of the tree)

The physiological status, or the health status of a tree, describes by a simple indicator if the tree is healthy, stressed, dying or dead, sometimes allowing for pinpointing the tree's status on a gradient (e.g. how stressed or how dying is the tree?).

This attribute has an impact on the provision of ecosystem services, as unhealthy or stressed trees are less able to provide them (Czaja et al., 2020). At least three of the ecosystem services treated in 100kTrees are affected, more precisely:

- Air pollution reduction, as some of the gaseous pollutants need an active photosynthesis to be absorbed (Worsley and Champion, n.d.),
- Cooling effect, as urban stresses reduce the ability of trees to reduce temperatures in the environment (Bensaoud et al., 2018; Rahman et al., 2015), and on
- Potential carbon mitigation, as the health status of the tree influences the increase in wood volume per year (Nowak and Crane, 2002; Speak et al., 2020).

This attribute depends on a wide set of variables, such as the age, the soil, eventual disturbances, the species and its adaptation to the climate zone, the urban environment and management stresses, water availability, and a lot more. The attribute should take into account a set of relatively easily observable and relevant characteristics of the tree and its surroundings, such as leaf cover, the size of the leaves, the presence of dead wood, and the presence of diseases or pests (Hermy et al., 2005).

Some examples are available in the literature, such as:

- The 'sanitary state' or '*état sanitaire'* used in the Brussels Region, which uses a scale of 11 choices, going from perfectly healthy (1), to having some malformations or growth difficulties (0,9 – 0,6), to declining possibly dying in the next 2 to 6 years (0,5 – 0,2), to final limit before death (0,1) and finally dead (0) (Gailly, 2016),

- A similar tree condition is proposed with 7 choices, based on the crown leaf dieback, namely excellent (less than 1% dieback), good (1% to 10% dieback), fair (11% to 25% dieback), poor (26% to 50% dieback), critical (51% to 75% dieback), dying (76% to 99% dieback), and dead (100% dieback)(Nowak et al., 2008),
- The ARCHI-method, that combines the development stage of the tree with the physiological state in 5 choices, going from healthy, to stressed (but recoverable), to resilient (recovering), or to irreversible decline and early death (Drénou, 2019),
- By combining easily observable variables, like the trunk condition, the growth rate, the tree structure, the presence of pests, the development of the crown and the life expectancy, the condition class can be calculated, going from excellent to very poor, with 5 classes in total (Scharenbroch and Catania, 2012; Webster, 1978),
- Leaf chlorophyll fluorescence and leaf chlorophyll analysis can be used for detecting and quantifying environmental stress and senescence (Rahman et al., 2015),
- The degree of defoliation and of discoloration of leaves or needles is proposed by FAO of monitoring the condition of trees in forests (Manual for Visual Assessment of Forest Crown Condition, n.d.), and a proposal has been made to automate this procedure, using LiDAR and hyperspectral imagery, but this method neglects the existence of possible root damage, soil compaction, trunk deformation, and other aspects of tree health that are hard to assess using airborne remote sensing data (Degerickx et al., 2018),
- Another set of automated spectral indices for evaluating tree physiological status, is proposed by Yu *et al.*: PRI was the best performing spectral index in differentiating planting conditions as well as for capturing the phenology changes, for detecting soil sealing stress, mSR705, mND705 and the water spectral indices using SWIR bands, MDWI and WI2, are recommended, and SIPI is recommended for detecting leaf phenology change (Yu et al., 2018).

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The first four indices can be tentatively joined as follows:

<table>
<tr><th>The ‘sanitary state’ (Brussels Region) (Gailly, 2016)</th><th>The tree condition (Nowak et al., 2008)</th><th>The ARCHI-method (Drénou, 2019)</th><th>The condition classes (Webster, 1978)</th></tr>
<tr><td>1: perfectly healthy</td><td>Excellent (less than 1% dieback)</td><td>Healthy</td><td>Excellent</td></tr>
<tr><td>0,9: having some malformations or growth difficulties</td><td rowspan="2">Good (1% to 10% dieback)</td><td rowspan="4">Stressed (but recoverable) or resilient (recovering)</td><td rowspan="2">Good</td></tr>
<tr><td>0,8: having some malformations or growth difficulties</td></tr>
<tr><td>0,7: having some malformations or growth difficulties</td><td rowspan="2">Fair (11% to 25% dieback)</td><td rowspan="2">Fair</td></tr>
<tr><td>0,6: having some malformations or growth difficulties</td></tr>
<tr><td>0,5: declining possibly dying in the next 2 to 6 years</td><td rowspan="2">Poor (26% to 50% dieback)</td><td rowspan="5">Irreversible decline</td><td rowspan="2">Poor</td></tr>
<tr><td>0,4: declining possibly dying in the next 2 to 6 years</td></tr>
<tr><td>0,3: declining possibly dying in the next 2 to 6 years</td><td rowspan="2">Critical (51% to 75% dieback)</td><td rowspan="3">Very poor</td></tr>
<tr><td>0,2: declining possibly dying in the next 2 to 6 years</td></tr>
<tr><td>0,1: final limit before death</td><td>Dying (76% to 99% dieback)</td></tr>
<tr><td>0: dead</td><td>Dead (100% dieback)</td><td>Early death</td><td>(Dead is not included)</td></tr>
</table>

Table 17. A comparison of 4 tree physiological status indicators.

Many of the indicators of bad health appear naturally when a tree enters the development stage of senescence and are thus linked with the (advanced) age of a tree (Drénou, 2019), but no other time-dependencies have been identified.

Eventual data gaps could be filled with the use of automated spectral indices, as proposed in the last two elements of the examples above.

3.13 Tree planting date

The tree planting date is the most precise attribute available to calculate the age of a tree, by subtracting it from the current date. This is used for calculating the CO_2 capture (Speak et al., 2020) (Potential carbon mitigation) and estimating the noise abatement capacity (Li et al., 2020) of a tree.

The next data formats are allowed (in order of diminishing precision):

- Exact date (day, month, year),
- Month (month, year),
- Planting season (year the season starts – year the season ends).

As urban trees are most frequently planted outside of the growing season (autumn or winter)(Joye et al., 2008), there is a difference of one planting season between a tree planted in the beginning of the year and one at the end of it. If only the planting year is known, the tree age should thus be corrected by removing half a year (or growing season), for compensating this uncertainty.

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If the tree planting date is not known, it can be estimated by the next methods (in order of diminishing accuracy):

- Adopt the tree planting date of a similar tree (species and diameter at breast height),
- Estimate the tree planting date by comparing historical aerial images, and using the tree planting year resulting from the next formula: (year the first picture with the tree has been taken) + (year the last picture without the tree has been taken)/2,
- Estimate the tree age by applying the growth tables of the tree species in urban environments for the climatic zone,
- Estimate the tree age by dividing the circumference at breast height in centimetres by a coefficient calculated for the climatic zone (e.g. this coefficient is approximately 2,5 for Brussels, Belgium (Stassen, 2003)),
- Expert knowledge, when reference persons remember when the tree has been planted.

3.14 Tree species

The species name is the most basic and widely used attribute when working with trees, whether in a natural or urban environment. The species name is used as a key identifier, which links to rich information about the specific characteristics of the tree, its distribution range, requirements and tolerance to environmental conditions, guidance for expected development, its life rhythm and cycle, potential benefits for the urban environment, its impact on living organisms, and more (Donegan et al., 2014; McPherson et al., 2016; Navés Viñas and Riudor i Carol, 2003; Rambhia et al., 2023; Understanding i-Tree - Appendix 3, n.d.; Understanding i-Tree - Appendix 13, n.d.).

Tree types can be understood through their related groupings (taxa) and shared characteristics within these groups. Living things are classified hierarchically based on common traits. Carl Linnaeus developed the modern taxonomy method in the 1700s, which has evolved with advancing knowledge and tools. DNA analysis, chromosome numbers, isozymes, and nucleic acid sequences are some contemporary techniques. As different taxonomists may have varying conclusions, taxonomies from distinct sources might not align in terminology (Virginia Cooperative Extension Master Gardener Program, 2021).

Numerous sources provide comprehensive taxonomic information in the scientific community. The following list comprises some of the most prevalent resources utilized in both theoretical and practical applications:

- Global Biodiversity Information Facility (*Global Biodiversity Information Facility*, n.d.)
- World Flora Online (*An Online Flora of All Known Plants*, n.d.)
- Integrated Taxonomic Information System (*Integrated Taxonomic Information System*, n.d.)
- Plants of the World Online (*Plants of the World Online*, n.d.)
- The Catalogue Of Life (*The Catalogue of Life*, n.d.)

Similar to these resources, but with a narrower focus on urban trees, are projects such as OpenTreeMap (*OpenTreeMap*, n.d.) and The Global Urban Tree Inventory (Ossola, Hoeppner, Hugh Munro Burley, et al., 2020).

Based on the taxonomic species name, trees are divided into two main groups - native and non-native. In many cases, some non-native tree species are more resilient, effective, and provide more ecosystem benefits for the environment and human health when used in urban greening than some native tree species (Schlaepfer et al., 2020). This is due to the harsher conditions in cities and the specific characteristics of urban ecosystems that often differ drastically from natural ones (Ossola, Hoeppner, Hugh M. Burley, et al., 2020).

Lastly, the significance of taxonomic species names for urban trees is further demonstrated by their incorporation into widely recognized standards, such as CityGML (City Geography Markup Language) and IFC (Industry Foundation Classes). Both standards are designed to facilitate the representation, storage, and exchange of information related to the planning and design of populated areas and their constituent elements (Kolbe et al., 2021; *buildingSMART*, n.d.). While the development of attributes pertaining to urban trees as environmental components within these standards remains relatively underdeveloped, the tree species name continues to be featured as a fundamental attribute.

The species name of a tree is crucial attribute for maintaining and enhancing biodiversity. Different tree species provide habitats and food sources for various flora and fauna (Stagoll et al., 2012). Knowing the species name allows for the strategic planting of diverse plant communities, supporting a richer and more resilient urban ecosystems (Mullaney et al., 2015).

The attribute "tree species name" plays a critical role in urban ecosystem mapping and analysis. This attribute serves as an essential indicator for evaluating various categories of ecosystem services (Baró et al., 2014) and is widely utilized in the acquisition, storage, and dissemination of fundamental tree data at the taxonomic level (Davies et al., 2011). Focusing specifically on tree species allows for a more accurate representation of the unique contributions that individual species make to urban ecosystems and their associated ecosystem services (Livesley et al., 2016). Below are some examples of tree attributes gathered at the taxonomic level that are connected to the corresponding ecosystem services:

- Reduction of air pollution — Leaf area index; Tree species-specific pollutant uptake rates
- Cooling effect — Crown size, density and shape; Transpiration rates
- Reduction of flood risk and estimated damages — Root system architecture
- Noise abatement — Canopy density; Leaf size and shape; Bark texture
- Potential carbon mitigation — Growth rate; Wood density

Tree species nomenclature adheres to established taxonomic principles, as outlined in various scholarly publications (*Scientific Plant Names (Binomial Nomenclature) | Landscape Plants |*, n.d.). However, numerous factors contribute to inaccuracies and errors in existing inventory data, encompassing spelling and typographical errors, non-adherence to taxonomic guidelines, and incorrect arrangement of individual taxa within the scientific name of a specific tree (Stuessy, 2009). To facilitate accurate indexing and unambiguous identification of tree species, strict compliance with globally recognized rules for the scientific naming of woody vegetation is imperative (May et al., 2019).

The availability of multiple officially recognized sources of taxonomic data, in conjunction with advanced data processing tools, substantially streamlines the normalization of existing tree data (Chapman, 2005). A prime example of this is the development of the Global Urban Tree Inventory (GUTI), as detailed in the associated scientific literature (Ossola, Hoeppner, Hugh M. Burley, et al., 2020). One significant obstacle in semi-automatic normalization of scientific tree names is the vast diversity of existing cultivars and the dearth of comprehensive databases for these varieties. This issue is particularly concerning since numerous cultivars exhibit varying degrees of deviation from the distinctive specific features of the corresponding taxonomic tree species, genera, and families.

Contrary to the perception that taxonomy is a static science, it continually evolves in response to advances in human understanding of living organisms. It is not uncommon for botanical species to undergo reclassification within different taxonomic genera or even families, consequently altering their scientific names (May et al., 2019). In some instances, specific epithets are modified to accentuate a distinguishing feature of the trees they represent. This progressive development gives rise to an extensive database of taxonomic synonyms, with tree experts occasionally referring to particular trees by their previous names (Mabberley, 2017). Owing to these factors, it is crucial to perform routine checks and updates on species names in inventory databases to guarantee their maintenance and dissemination in a consistent, standardized format (Chapman, 2005).

4 Data availability

It is now clear which data will be needed for defining 4 to 6 standard city tree types per climatic situation (Copenhagen, Sofia). Indeed, the 15 most important attributes (see chapter 3) for describing the potential impact of a tree on its surroundings (i.e. the ecosystem services, see chapter 2) have been described in detail.

As the overall goal of this document is *to establish a list of existing data (tree data, scientific data) and missing data to get to a decent definition of 4 to 6 standard city tree types per climatic situation (Copenhagen, Sofia) using a set of key attributes*, this chapter will be dedicated to a first analysis of the available data from both reference cities of the 100kTree project as well as from scientific literature.

At this moment, the next tree databases are available to the 100kTree project:

- (Sofia) OneTree ('ЕдноДърво') Initiative urban tree database (OneTree database, n.d.), which has data input coming from tree experts as well as from citizen scientists through the mobile application,
- (Sofia) Sofiaplan ('Софияплан') tree map obtained by automated analysis of remote sensing data (Trees index, n.d.),
- (Copenhagen) Municipal tree database (Kommunale traeer, n.d.) which has input coming from tree experts.

During a first analysis of those databases, the presence of information on the attributes that are needed at the individual tree level, has been verified and documented in the next table. This analysis did not yet include the quality of the data but concentrated firstly on the availability of it.

Attribute at individual tree level	Section	Sofia - Experts	Sofia - Citizens	Sofia - automated	Copenhagen - Experts
Individual trees in total		14848 (total)	9544 (total)	5532297 (total)	63410 (total)
Clearance height	3.2	359 (2% of total)	0 (0% of total)	0 (0% of total)	278 (0% of total)
Crown diameter	3.3	9432 (64% of total)	7634 (80% of total)	5532297 (100% of total)	63407 (100% of total)
Diameter or circumference at BH	3.5	9218 (62% of total)	1941 (20% of total)	0 (0% of total)	63410 (100% of total)
Presence of moss on trunk	3.7	185 (1% of total)	34 (0% of total)	0 (0% of total)	0 (0% of total)
Pruning regime	3.8	0 (0% of total)	0 (0% of total)	0 (0% of total)	0 (0% of total)
Tree height	3.11	9452 (64% of total)	2239 (23% of total)	0 (0% of total)	0 (0% of total)
Tree physiological status	3.12	3821 (26% of total)	111 (1% of total)	0 (0% of total)	63410 (100% of total)
Tree planting date	3.13	0 (0% of total)	0 (0% of total)	0 (0% of total)	0 (0% of total)
planting year[2]		0 (0% of total)	0 (0% of total)	0 (0% of total)	36428 (57% of total)
planted half year[3]		0 (0% of total)	0 (0% of total)	0 (0% of total)	63410 (100% of total)
Tree species	3.14	4082 (27% of total)	1390 (15% of total)	0 (0% of total)	63408 (100% of total)

Table 18. Data availability for attributes on individual tree level.

At a first glance, both tree databases contain several thousands of trees, even millions in the case of the Sofiaplan database. Most of the traditional tree attributes (species, DBH, height, crown diameter and tree physiological status) have information on several thousand trees, albeit not always on all the trees in the database. Nevertheless, far from all attributes are covered by the data present in those databases, so data analysis and data gap filling will prove to be important (planned in WP3.2 in preparation for the next version of this deliverable, D3.2).

The map of automatically indexed trees contains basic information with a high degree of reliability (around 80% accuracy) for almost all trees located within the territory of the SO. For the needs of automatic indexing, a set of 3671 high-resolution (10 cm^2/px) georeferenced orthophoto images, captured in the fall of 2020, is used. In order to index the trees from the images, the DeepForest algorithm is adapted and additionally trained, which in turn is a variant of RetinaNet (an architecture for object detection). To train the algorithm, over 500 trees are manually indexed. Once trained, the algorithm is run on the entire set of orthophoto images, recognizing the outlines of the tree canopies in 95% of them. The main shortcomings of the algorithm are related to the presence of long shadows in the orthophoto images, which complicate both manual and automatic indexing of trees that fall in areas shaded by buildings. Based on the contours

[2] Planting year:

[3] Planted half year:

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of the tree canopies recognized by the algorithm, information is extracted about the average canopy diameter (measured in meters) and the assumed location of the planting site (centroid) for each tree.

Comparative analyses are carried out between the result of the automatic indexing and data resulting from expert field studies for 6873 existing trees. From the analyses, it becomes clear that the algorithm manages the task with over 80% accuracy. From all the recognized trees, those with a suspiciously large canopy size (diameter larger than 20 m) are singled out for additional verification.

The tree species is determined based on the systematic spatial interception of the indexing result with the data for the tree vegetation from Copernicus. Given the resolution of these data, it is advisable to use the "type" attribute with trust mainly for tree groups and masses.

The OneTree Initiative urban tree database (Sofia) also contains information on several attributes on species level, known as the 'knowledge database'. This has been completed with data from a set of scientific references on the tree species present in Sofia. The data availability of the species level attributes described in chapter 3 is shown in the next table:

Attribute at tree species level	Section	Sofia	Copenhagen
Different species present in database		190 (100%)	Database not yet identified
Allelochemicals	3.1	0 (0%)	-
Crown form	3.4	149 (78%)	-
Leaf Area Index (LAI)	3.6	0 (0%)	-
Radial roughness	3.9	132 (69%) - bark_type 120 (63%) - bark_depth 115 (61%) - bark_form	-
Species specific transpiration	3.10	0 (0%)	-

Table 19. Data availability for attributes on species level.

But there hasn't been such a knowledge database identified yet for the city of Copenhagen. Of course, contacts will be made again with the tree managers of Copenhagen to check if this database is available or not. In any case, this data gap can be solved by the work planned in WP3.3 and the results will be documented in the next version of this deliverable, D3.2.

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5 Conclusions

Urban trees provide a set of ecosystem services, which can help to tackle some of the major challenges linked to life in an urban environment. The ecosystem services deemed the most important to consider within the 100kTrees project, and the contributions of urban trees to them, have been briefly discussed in this document (see chapter 2). In order to be able to quantify those contributions, a set of tree attributes (on the individual tree level or on the species level) have been identified and documented (see chapter 3). This has allowed for a first evaluation of data availability on those attributes (see chapter 4).

The first, preliminary data availability check has led to the conclusion that some rather basic attributes on individual trees (tree species, size, and health) are highly available, but that solutions for filling the data gap for the other attributes are to be studied. The tree species level attributes have been partially well documented for the city of Sofia but seems to be absent for Copenhagen. The spatial distribution of documented trees in Sofia and Copenhagen in the available databases is sufficient.

The result of T3.1 'Analysis of the needed and existing data on tree attributes', documented in this deliverable, lays a good, scientifically based foundation for further work in T3.1 'Analysis of the needed and existing data on tree attributes', for T3.2 'Filling in missing data' as well as for T3.3 'Literature review'. This will lead to a good understanding of the tree and species attributes needed for estimating the trees' contributions to the ecosystem services important for the 100kTrees project (deliverable 3.2 in month 18), which eventually will lead to the definition of 4 to 6 standard city tree types per climatic situation (deliverable 3.3 in month 18).

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7 Appendix 1: Eliminated attributes

Attribute	Ecosystem service
Aerodynamics and influence of trees on it	Air pollution reduction
Street design	Air pollution reduction
Local meteorological conditions	Air pollution reduction
Pollution concentrations	Air pollution reduction
Size and proximity of buildings to trees	Air pollution reduction
Connectivity	Biodiversity improvement
Proximity of source populations	Biodiversity improvement
Tree undergrowth and structure	Biodiversity improvement
Soil organic matter (leaves, excrements) and compaction	Biodiversity improvement
Tree base size / tree patch size	Biodiversity improvement
Albedo of surface materials	Cooling effect
Height of surrounding buildings	Cooling effect
Irrigation status of trees	Cooling effect
Tree undergrowth and structure	Cooling effect
Planting arrangement	Cooling effect
Proportion of impervious surfaces	Flood risk and estimated damages
Canopy closure	Flood risk and estimated damages
Tree number	Flood risk and estimated damages
Precipitation	Flood risk and estimated damages
Intensity of negative noises	Noise abatement
Visual screen to traffic	Noise abatement
Presence of positive noises	Noise abatement
Tree (trunk) density	Noise abatement
Ground porosity	Noise abatement
Tree cover	Noise abatement
Flow resistivity	Noise abatement
Tree planting arrangement	Noise abatement
End-of-life scenario for trees and pruned materials	Potential carbon mitigation
Fuel used for tree management	Potential carbon mitigation
Soil management practices	Potential carbon mitigation
Soil carbon content and carbon content change	Potential carbon mitigation
Averages of tree mortality	Potential carbon mitigation
Tree removal rate	Potential carbon mitigation

Table 20. Attributes that help in describing ecosystem services provided by urban trees, but not directly useful for defining standard city tree types.

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