Master thesis in the project „City Trees – Stadtbäume im Klimawandel"

Bayreuth's Next Top Tree – Comparing Four Common City Tree Species under Climate Change

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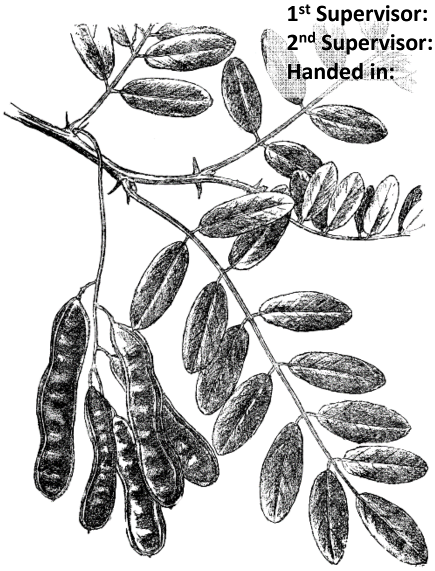

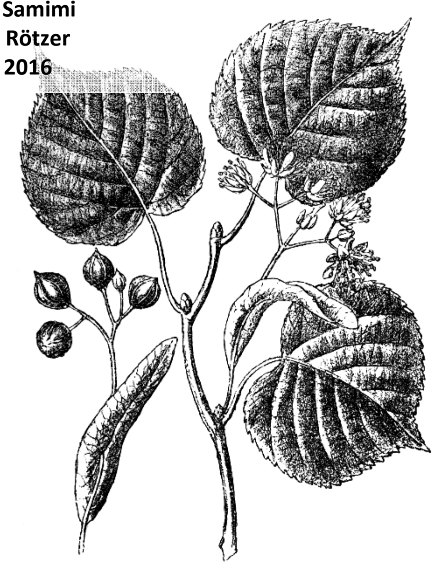

Abstract

There are several studies on the growth and ecosystem services of trees in North America and in forests. However, European urban trees are poorly studied, despite the usefulness of urban trees in climate change adaptation and mitigation. Tree data of 413 trees of the species *Tilia cordata*, *Robinia pseudoacacia*, *Platanus x acerifolia* and *Aesculus hippocastanum* was collected in the city of Bayreuth, Germany from March - June 2016. This data includes trunk diameter at breast height (DBH), tree height, crown dimensions, leaf area index and vitality. Allometric logistic regressions were calculated with the statistical software *R* to find formulas describing the connection of DBH and age and tree dimensions, to be able to describe the species-specific tree growth over time. In the next step, this growth data was processed using the environmentally sensitive process based individual tree growth model by Rötzer et al. (2010) to calculate the ecosystem services over tree age under three different climate scenarios: the reference period (1982 to 2011) and the two future climate scenarios (2021-2050) of the WETTREG A1B and B1. Additionally, the influence of the tree location (street, park, square) was evaluated statistically and a literature research was conducted to evaluate the practical value of the different species (for example allergy and safety risks, tree diseases, maintenance required).

It could not be clearly determined if the site type (street, square, park) had an influence tree growth, since the effects of age and growth could not be clearly distinguished. However, it was confirmed that tree growth and the associated delivery of the ecosystem services shading, cooling by evapotranspiration and carbon storage was species-specific, even though, the differences were not statistically relevant in all cases. This study found that the responses of tree ecosystem services delivery (of shading, cooling by evapotranspiration and carbon storage) to climate change were are species-specific but only cooling by evapotranspiration showed statistical differences. Finally, finding the single most suitable tree species for Bayreuth, according to the “good urban tree” criteria established in this study was not possible. There was not one single kind of tree better than all others, but the best species depends on the reason for planting the tree(s). If an undemanding or climate prove tree is desired, it should be *R. pseudoacacia*. If it is about aesthetic and cultural value, the choice is *A. hippocastanum*. If a robust tree is desired, the choice is *T. cordata*. For climate adaptation, *P. acerifolia* is best suited, for climate mitigation*, A. hippocastanum*.

The knowledge gained in this study can aid the planning authorities in making such choices, as they provide insight on the space and site requirements and the ecosystem services of the four studied species. The allometric equations may be used to estimate the growth of horse chestnut, London plane, black locust and small-leaved lime populations in Bayreuth and areas with similar climate, soil, and planting and management environments.

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I would like to thank my supervisors Prof. Dr. Cyrus Samimi, Dr. PD Thomas Rötzer and Astrid Moser for their professional support. The invariably quick replies to my e-mails and phone conversations, even from places as far away as Asia or the urban forest of Nuremberg, helped me progress with my work quickly. Also, I would like to thank Julia for persistently measuring hundreds of trees with me in the infamous pouring rain of Bayreuth, and for informing me about the CityTrees project that represented everything I had desired from a master thesis topic. The provision of helpful hints on where more London planes may be hiding in Bayreuth by Arnd Sesselmann of the Stadtgartenamt Bayreuth was greatly appreciated. I also want to include Henni and Hanna in this list, as I do not know what I would have done during the long, bleak university days without their humour and often necessary pinch of irony, which all too often made my day. Furthermore, I want to thank Sophie for taking over Julia’s job for at least a few trees and, of course, her mental support. Lastly, I would like to thank Dr. Joachim Rathmann for encouraging me to apply for GCE at all, and my parents for giving me the great opportunity to attend university to understand the world at least a little better.

Go raibh maith agaibh!

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Terms & abbreviations

AIC	Akaike Information Criterion
ANOVA	analysis of variance
AWB	aboveground woody biomass
CPA	crown projection area
cb	crown base height (where the tree has the first major branch)
cl	crown length (from crown base height until tree top)
cr	crown radius
cd	crown diameter
CF	bias correction of Baskerville (1971) and Sprugel (1983)
cv	crown volume
DBH	trunk **d**iameter at **b**reast **h**eight (1.3m)
DWD	Deutscher Wetterdienst (German weather service)
GALK	Deutsche Gartenamtsleiterkonferenz (German association of communal green space administrations)
GAM	generalized additive model
h	tree height
IPCC	Intergovernmental Panel on Climate Change
KLAM	KlimaArtenMatrix (climate species matrix).
LAI	leaf area index
n	sample size
r, r^2	coefficients of determination
RMSE	root-mean-square error
SD	standard deviation
SE	standard error
STMuV	Bayerisches Staatsministerium für Umwelt und Verbraucherschutz
UHI	urban heat island effect
USDA	United States Department of Agriculture
V	aboveground volume

1. Introduction and theoretical foundation

1.1 Background and aim

Climate change is one of the biggest challenges which humanity faces in the 21st century. Its current and future consequences, for example longer dry spells and more severe extreme weather events in some regions of the world, demand adequate responses from policy, economy and civil society. As most human activity is concentrated in cities and more than half the world's population lives in them, they carry a great potential for climate change adaptation and mitigation. At the same time, they are very vulnerable to climate change due to their high centrality. Furthermore, the large amount of sealed surfaces and the use of building material with a high heat storage capacity leads to the so-called urban heat island effect (UHI) which exacerbates the effects of raised temperatures and thus adds to vulnerability even more (Oke, 1987; Revi et al., 2014).

With recent crises in mind, for example the heat wave in Europe in 2003 that caused many thousand casualties especially in urban areas (Fouillet, 2006), the need for cities to provision for such extreme events becomes evident. One way to counteract urban heat is by planting trees (Gago et al., 2013). They provide multiple benefits, known as ecosystem services, which contribute to climate change adaptation and mitigation: carbon sequestration, shading, cooling by evapotranspiration and the reduction of stormwater runoff (Pretzsch et al., 2015a; Fryd et al., 2011; Klemm et al., 2015). Additionally, they serve as a habitat for birds, insects and other animals, absorb air pollutants, provide aesthetic value to the city and may even provide cultural services. Especially parks carry great recreational value. In summary, planting more trees can be an effective way to counteract climate change in cities (Bolund et al., 1999; UK National Ecosystem Assessment, 2011).

However, the right choice of tree is important, as planting and maintaining trees requires investment of labour and money. A street tree costs 1450€ on average in Germany, including tree and site preparation (Pauleit et. al, 2002). Urban trees face many specific challenges, such as reduced rooting and crowning space, heat stress, shading by buildings, and physical damage by cars and construction. In the future, climate change will make extreme events, such as heat stress, drought stress and extreme rainfall, even more urgent challenges which an urban tree needs to be able to stand up to. The main challenges for urban trees in Germany are considered poor or insufficient amounts of soil, de-icing salt, elevated temperatures in summer and frost damage (Pauleit et. al, 2002).

For this reason, the project CityTrees – "Urban trees under climate change: their growth, environmental performance, and perspectives" was conceived. The overall goal of CityTrees is to further validate the model and to collect comprehensive data on the growth and ecosystem services of a diversity of tree species in different cities, under current and changing climate. Within the project, the growth behaviour and ecosystem services of trees in Bavarian cities are examined, and an eco-physiological single-tree growth model is being developed. The first studies took place in Munich and Wurzburg, targeting the small-leaved lime (*Tilia cordata* Mill.) and black locust (*Robinia pseudoacacia* L.). In a second step, the study was expanded to more cities (Bayreuth, Hof, Kempten im Allgäu, Nuremberg) and the species horse chestnut (*Aesculus hippocastanum* L.) and London plane (*Platanus acerifolia)* were added to include a larger variety of common urban trees in Bavaria. This knowledge can then be used to give practice-oriented advice to urban planners and authorities.

This thesis was part of the research in Bayreuth and aims to find out which of four trees species popular in Germany is most suitable in the future. This evaluation is based on three broad criteria. Firstly, which tree species is more suitable for a city depends on how the different species grow, as space is a limited resource in urban areas and planners need to be able to predict how big a tree is at a certain age. Secondly, ecosystem services provided vary over the lifespan of a tree. In the context of climate change, it will be preferable to choose tree species consistently delivering ecosystem services that aid climate change mitigation and adaptation. Thirdly, the practical value of a tree is important. For example, urban trees should not cause health problems or threaten road safety.

Therefore, *T. cordata*, *R. pseudoacacia*, *P. acerifolia* and *A. hippocastanum* were compared for:

- growth over time
- influence of tree site on growth
- ecosystem services:
  - carbon storage
  - cooling by evapotranspiration
  - shading
- practical value

To this end, tree data of 413 trees across the study city Bayreuth was collected for about 100 trees of each species. This data includes the tree dimensions, its location (street, park, square), leaf area index (LAI) and vitality. In a further step, this data was put into an environmentally sensitive, process-based, individual tree growth model developed by Rötzer et al. (2010) to calculate the expected ecosystem services per age category and species under three different climatic scenarios (reference period, WETTREG A1B, B1). Finally, a literature research was conducted to evaluate the practical value of each species. The final goal of this study is to give a recommendation as to which of the four species is best suited as a city tree for the current and future climate of Bayreuth and other cities with a similar climate.

The study is divided into four parts. Chapter 1 gives a general introduction to the topic, chapter 2 explains the methods used. In chapter 3, the results are presented and discussed. Chapter 4 provides concluding thoughts and chapter 5 gives an outlook on how the research on urban trees in Bayreuth and Bavaria may be continued.

1.2 Climate change in Bavaria and characteristics of the study area

Evidence of the warming of the climate system is unequivocal and caused by both the variability of the natural system and anthropogenic forcing (Intergovernmental Panel on Climate Change (IPCC), 2013). The consequences attending this change are threats for health, livelihood and assets of people, economies and ecosystems. Climate change related risks include sea level rise, storm surges, heat stress, drought, inland and coastal flooding, extreme precipitation, landslides, increased aridity, water scarcity, and air pollution (Revi et al., 2014).

For Bavaria and especially Franconia, where Bayreuth is located, the expected consequences of climate change are: frequent dry periods in the summer, drier and wetter winters, more frequent heavy precipitation events, reduced snow cover and a shift of the phenological phases. Table 1 lists some of the consequences of climate change in Bavaria: The current yearly average temperature is 7.8 °C and already rose by +1.4 °C in the years 1881 to 2014. In the near future, the average annual temperature is expected to rise between another +1 and +2 °C. In the remote future, the rise compared to now is expected to be between +2 and +4.5 °C. Generally, the rise in winter temperatures is more pronounced than in summer. Frost days (T_{min} <0°C) will becomes less numerous: A decrease from 109 days by -12 to -36 and -36 to -60 days is expected. The number of annual ice days (T_{max} <0°C) will decrease by 9-21 days in the near future and up to 33 in the far future. Accordingly, snow cover is decreasing. There already has been a significant decrease in the number of snow days between 1951/52– 2010/11. In the low mountain ranges and the Alpine foothills, 40% of the weather stations reported negative trends, in the Alps even 55%. The duration of the vegetation period has already increased by 26 days from 1961-2010. Additionally, the number of hot days (T_{max} >30°C) will increase to up to 14 days per year, or even up to 30 in the distant future and the number of summer days (T_{max} ≥ 25°C) (STMuV), 2015).

Table 1: Consequences of climate change in Bavaria (adapted from STMuV, 2015). *Min./max. 1951-2014.

	Current (1971-2000)	Near future (2021-2050)	Far future (2051-2100)
Temperature [°C]	7.8	+1 to +2	+2 to +4.5
Frost days per year [d]	109 *(76-138)	-12 to -36	-36 to -60
Ice days per year [d]	30 (9-68)	-9 to -21	up to -33

Summer days per year [d]	32	(17-76)	+3 to + 21	+9 to + 51
Hot days per year [d]	5	(0-24)	up to 14	up to 30

A heat warning system is in place in Bavaria, as heat waves pose a threat to risk groups (especially people with high blood pressure and cardiovascular diseases). If the ambient temperature increases by more than 5 °C from one day to the other, the risk of heart attack rises by 60% for patients affected by the aforementioned health conditions (STMuV, 2015).

As the study aims to cover a climatological gradient, the city of Bayreuth was selected for the CityTrees project because its climate is relatively cooler than that of the original study cities of Munich and Wurzburg. Average precipitation is lower than in Munich, but higher than in Wurzburg (cf. table 2).

Table 2: Current climate of Bayreuth, averaged over the period 1982-2011 (DWD, 2016) and the original study cities of CityTrees Munich/Wurzburg, averaged over the period 1981-2010 (Pretzsch et al., 2015a).

City	**Temperature, yearly average [°C]**			**Precipitation, yearly sum [mm]**		
	Min	Max	Total	Min	Max	Total
Bayreuth	6.9	9.8	8.5	499	993	755
Munich	8.3	11.2	9.6	656	1191	942
Wurzburg	8.0	10.7	9.6	393	807	598

In the following, core geographical features of Bayreuth will be illustrated. The city is located between the Fichtel Mountains and Franconian Switzerland (49 ° 56′ 46″ N, 11° 34′ 44″ E). Measured at the central train station the city is 345 m above sea level. However, as it is surrounded by small mountain ranges, the highest elevation of the urban area is 527 m above sea level at the so called Oschenberg. The principal river is the Red Main, whilst the largest water body in the area is the artificial pond Röhrensee. There is no larger natural lake in the area. The total urban area covers 6 692 ha. Land use within the area is: 38.7% agricultural land, 26.9% buildings and open space, 18.3% forest, 10.1% traffic area, 4.6% recreational areas, 0.8% water surface, 0.4% other land and 0.2% operating areas. The considerable amount of forest and agricultural land surrounding the urban core area can be explained by villages incorporated into the municipal area (Bayreuth.de, 2016).

1.3 Climate and climate change in urban areas

Generally, urban areas are especially vulnerable to climate change, owing to the fact that economic and political activities, built assets and large numbers of people are concentrated in them. In fact, more than half of the population of the planet lives in cities and rapid urbanisation will further increase this number in the future (Revi et al., 2014). Beside their high centrality, urban areas are characterised by certain features that lead to a distinct urban climate. Among these, most important are high building density and building mass, sealed surfaces, a small amount of vegetation, the emission of heat by what, an increased amount of aerosols and pollutants, and the often small proportion of water surfaces (Henninger, 2011; Rötzer, et al. 2000). These characteristics lead to a special urban climatic phenomenon, the urban heat island (UHI). It is defined as the difference in temperature between urban areas and their rural surroundings (Bowler et al., 2010). The temperature difference caused by the UHI varies from 0.4°C to 11°C (Santamoutis, 2015). In Moscow, it has been reported to be as high as 14°C (Lokoshchenko, 2014). As figure 1 shows, the average difference between downtown and the surrounding areas is around 5°C. However, the magnitude of the UHI varies and is influenced by the size of the city, the time of the day, presence of clouds, and wind. Typically, the UHI effect is especially pronounced at night (Oke, 1987). Judging purely by city size, the effect of the UHI is expected to be present in Bayreuth, but less pronounced than in Wurzburg and Munich. The cities have around 72,000, 124,000 and 1,450,000 inhabitants respectively (Bayerisches Landesamt für Statistik, 2016), making Bayreuth the smallest city when population is used as a surrogate of city size (as suggested by Oke, 1987).

Extreme events exacerbate the vulnerability of cities. For example, extremely hot temperatures (like on so-called "hot days") cause a severe UHI and raised energy demands (Akbari et al., 2001), and extreme precipitation events can overwhelm the current sewer infrastructure in many cities. One way of climate-proofing cities is by establishing more urban green spaces and planting trees. These measures moderate urban climate and aid stormwater management, through which they contribute to climate change adaptation (Fryd et al., 2011). Additionally, urban green areas and trees reduce air pollution and serve as carbon sinks (Klemm et al., 2015).

Moreover, the urban climate has an influence on the local vegetation. For example, the phenophases of urban plants differ from their rural counterparts, as the warmer city climate can lead to earlier flowering (Rötzer et al., 2000). Also, plants potentially face high temperatures (Akbari et al., 2001; Kjelgren & Clark, 1992) and a reduced water availability (Beatty & Heckman, 1981; Whitlow & Bassuk, 1987). When selecting tree species for urban use, these climatic factors need to be kept in mind, along with the fact that climate change may lead to changed or exacerbated conditions in the future.

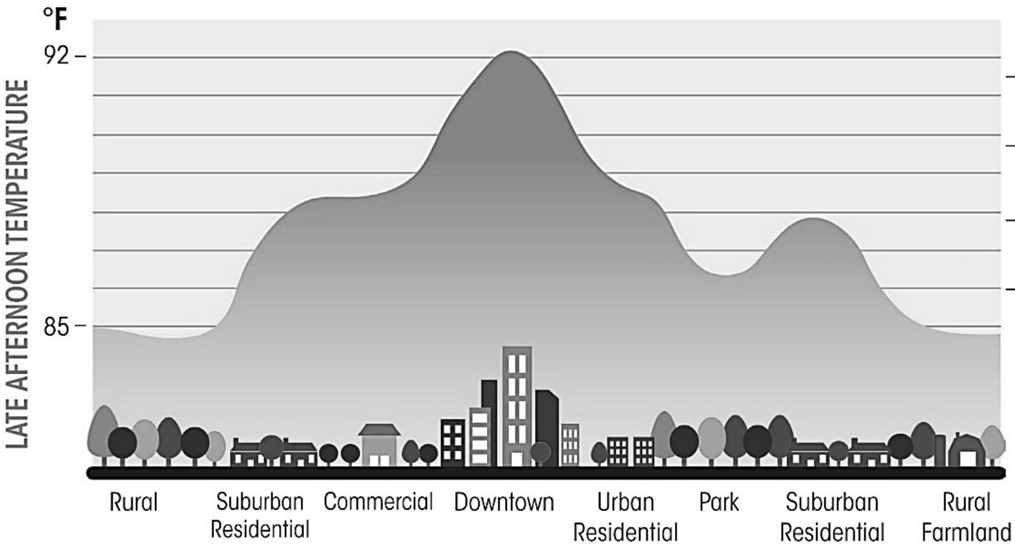


Figure 1: Schematic depiction of the urban heat island (Rosser, 2016).

1.4 Growth and ecosystem services of urban trees

Trees provide multiple benefits, known as ecosystem services, of which some are beneficial to climate change adaptation and mitigation (Akbari et al., 2001; UK National Ecosystem Assessment, 2011). In exact terms, ecosystem services are "the conditions and processes through which natural ecosystems, and the species that make them up sustain and fulfill human life. They maintain biodiversity and the production of ecosystem goods, such as seafood, forage, timber, biomass fuels, natural fiber, and many pharmaceuticals, industrial products, and their precursors" (Daily, 1997, p. 3).

The services provided by trees include carbon sequestration, micro-climate regulation (shading, cooling by evapotranspiration) and reduction of stormwater runoff. Additionally, they reduce noise, serve as a habitat for birds, insects and other animals, absorb air pollutants, and provide aesthetic value to the city, as well as cultural services (Bolund et al., 1999; UK National Ecosystem Assessment, 2011).

The ecosystem services of trees depend on their structural parameters (Binkley et al., 2013; Pretzsch et al., 2015b; Scott et al., 1998; Stoffberg et al., 2008; Troxel et al., 2013). Carbon storage, for example, is directly related to tree biomass (Yoon et al., 2013). This can be explained by the pipe model theory (Shinozaki et al., 1964ab) and the functional balance theory (Mäkelä, 1990), according to which carbon allocation, stem cross-section and biomass are closely connected. This fact makes it possible to calculate crown structure from other tree dimensions, which is why tree dimensions are often under research. Knowing a tree dimension, i.e. the commonly used diameter at breast height (DBH, Pretzsch et al., 2015a), allows to draw inferences on parameters which are harder to measure, e.g. biomass, which requires felling the tree (Shinozaki et al., 1964 ab).

A tree does not provide an equal amount of ecosystem services at every age, but its contribution varies over time. This is the reason why not DBH but age will be used as a proxy to make predictions about the ecosystem services (as by Peper et al., 2014; Rust, 2014). Chapter 2.3 explains how age was calculated from the tree parameters DBH and height. The three ecosystem services that will be further examined in this study are shading, carbon storage and cooling by evapotranspiration. As figure 2 shows, the shading ability of trees peaks between 30 to 35 years of age (Var1), carbon storage rises gradually (Var 2) and the leaf area index (LAI, Var 3, as a proxy for evapotranspiration; McPherson & Peper, 2012) is highest when the trees are young and then decreases. This development over time can be of interest for example when there is a debate whether an old tree stand should be replaced by young trees or not.

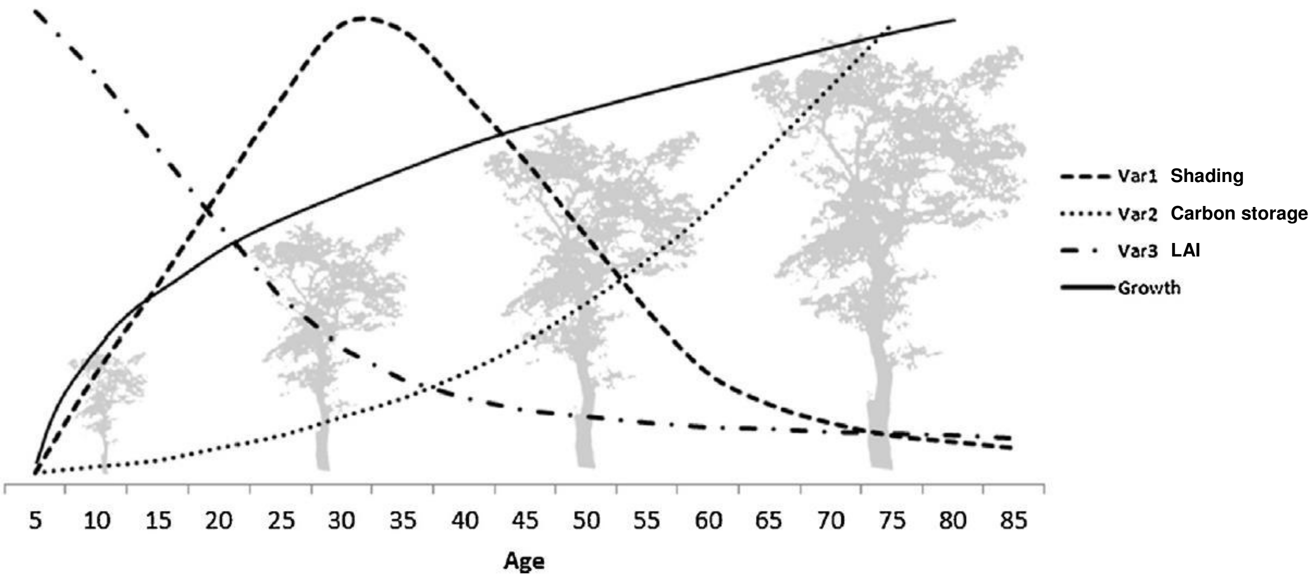


Figure 2: Ecosystem services of an urban tree over time. Var1, shading ,Var2 carbon storage, and Var3, LAI, represent exemplary ecosystem services. Growth represents the development of the tree over time (Moser, 2015).

In order to be able to model tree growth and subsequently, ecosystem services, it is necessary to know the allometric relations between age and other tree variables. These relations can be explained mathematically by allometric equations. Allometry is

> "the relative change of one plant dimension, dy/y (e.g., the relative height growth) in relation to the relative change of a second plant dimension dx/x (e.g., the relative diameter growth). The allometric exponent a can be understood as a distribution coefficient for the growth resources between organs y and x: when x increases by 1%, y increases by a%." (Pretzsch & Dieler, 2012)

When evaluating the future suitability of urban trees based on their ecosystem services, it will be relevant to keep in mind whether they should serve mitigation or adaptation goals. While carbon storage constitutes a mitigation goal, shading and cooling are first and foremost adaptation strategies (unless their cumulated effects were so large that they had a regional or even global cooling effect).

In summary, in order to calculate the structural development of trees over time (growth), it is necessary to measure at least some tree dimension and to establish what the relations between different tree dimensions are. As ecosystem services depend on structural parameters, they can then be calculated from the tree dimensions at a certain growth stage (age). Finally, knowing the structural parameters and ecosystem services of trees serves as the base for planning and management of urban tree inventories (Pretzsch et al., 2015a), climate change adaptation and mitigation, and of course, further research.

1.5 Species

Four tree species were examined in this study: *Aesculus hippocastanum* L. (horse chestnut), *Platanus x acerifolia* (London plane), *Robinia pseudoacacia* L. (black locust) and *Tilia cordata* Mill. (small-leaved lime). The choice of species was predetermined. *T. cordata* and *R. pseudoacacia* were the principal trees in the first step of the CityTrees study. They were selected because of their different ecological requirements: *R. pseudoacacia* requires a lot of light, while *T. cordata* is a shade-tolerant species. Additionally, they both represent common urban trees in Germany (Pretzsch et al., 2015a). In 2016, the study was expanded to include *A. hippocastanum* and *P. acerifolia* to add other common and ecologically different trees to the study. *P. acerifolia* is fast growing and requires large quantities of light, while *A. hippocastanum* only grows fast when young and can tolerate more shade (Roloff, 2013).

To be able to judge the relevance of the studied species in Bayreuth, the total number of trees under the administration of the Stadtgartenamt is presented in table 3. The total number of trees administered by the Stadtgartenamt is 20,528 trees, mainly on streets (Sesselmann, 2016). These numbers do not include trees on private land and in areas under the administration of the Bavarian Administration of State-Owned Palaces, Gardens and Lakes which includes the large central park “Hofgarten”. Consequently, Bayreuth has many trees compared to the European standard, as the average is 50-80 street trees per 1000 inhabitants, while Bayreuth has about 285 (Pauleit et al., 2002). As the tree inventory was counted by genus and not species, it was not possible to give exact species numbers. However, the administration nearly exclusively plants the studied species, and only few other species of the genera (for example, some individuals of *A. carnea*). *Tilia* is the second most common genus in the city. The only genus that is even more numerous is *Acer*, which makes up 19.42% of the tree inventory. The third most common genus is *Quercus* (12.65%). All other genera, including *Aesculus*, *Platanus* and *Robinia,* range between 6.76% and 1.21% of the total tree inventory (cf. appendix 2 for full list). Had the goal of this study been to examine the most common genera in Bayreuth, the choice would have been *Acer*, *Tilia*, *Quercus* and *Carpinus*. However, as CityTrees is conducted throughout the federal state of Bavaria, the relative importance of the species in the individual study cities may vary.

Table 3: Number of trees per genus examined in this study in Bayreuth (Sesselmann, 2016, cf. appendix 2 for full list).

Genus	Number of individuals	% of total trees
Aesculus	885	4.31%
Platanus	252	1.23%
Robinia	684	3.33%
Tilia spp.	3,846	18.74%

For each species, information on vegetative and generative features; distribution; soil, habitat and ecology; and potential diseases was collected. This includes information on the habitus, habitat preferences and climatic demands. The lists of diseases only include the most relevant ones.

Aesculus hippocastanum L. (horse chestnut)

Vegetative and generative features

This is a mesophytic, broad-leaved tree which grows up to 39 m tall (Ravazzi et al., 2016), but is 20 -25 m tall on average. The crown diameter can reach 20 meters (Van den Berk, 2004). 5-7 leaflets compose its palmate leaves (Ravazzi et al., 2016). The round to oval, very dense crown has a high potential for shading (Ravazzi et al., 2016; Van den Berk, 2004). It reproduces via large, spiky burs that contain 1-3 seeds known as “conkers”. Its hermaphrodite flowers are white and grow on a pyramidal inflorescence (Ravazzi et al., 2016).

Distribution

A. hippocastanum originated from mountain ranges on the Balkan Peninsula. It was imported to Prague in 1557 and has since been cultivated in Europe, where it is a widespread urban tree, common in parks, gardens and at roadways. At the same time, it has become rare in its native range (less than 2500 mature individuals) (Ravazzi et al., 2016).

Soil, habitat and ecology

The species prefers moist, warm-temperate climate (Ravazzi et al., 2016). It has low soil requirements and can tolerate solid soil. Furthermore, the tree is sensible to road salt (Van den Berk, 2004).

Diseases

The most prominent pest that befalls horse chestnuts is the nocturnal moth *Cameraria ochridella* (horse chestnut leaf miner). It feeds on the leaves, causing midsummer defoliation and exhaustion of the trees. The Asian longhorn beetle (*Anoplophora glabripennis*), a large wood-boring beetle, also targets the species (Ravazzi et al., 2016). Additionally, the bacterium *Pseudomonas syringae* may attack the living bark tissue and the cambium of horse chestnuts, causing a vitality reduction, the death of crown parts or even the entire tree (Roloff, 2013).

Platanus x acerifolia (London plane tree)

Vegetative and generative features

Sometimes also referred to as *Platanus hispanica* or *Platanus hybrida*. This fast growing tree reaches heights of 20 – 30 meters, sometimes even 35 m (Van den Berk, 2004). The crown shape of the London plane is very broad and round and semi-permeable to light. The heavy, robust stem and branches tolerate pruning and hence are often pollarded. Another specific feature of the species is that parts of the bark chip off, giving it a distinct pattern. The leaves are large (12-25 cm) with 3-5 toothed lobes and take long to decay. Its fruits are large, spherical clusters of seeds, about 2.5 cm in diameter (Van den Berk, 2004).

Distribution

P. acerifolia is likely a hybrid of *Platanus orientalis* (oriental plane) and *Platanus occidentalis* (American sycamore) (GALK 2012). It is a widespread urban tree, especially in Paris and London (hence the name) (Van den Berk, 2004).

Soil, habitat and ecology

The species can tolerate most soil conditions, but prefers less chalky soil. *P. acerifolia* can tolerate compacted soils, air pollution and paving, making it a very suitable tree for urban areas. As the tree forms surface roots, it can cause an uplift of pavement (Van den Berk, 2004).

Diseases

After cold and wet springs, the tree can suffer leaf necrosis, leaf fall and the death of buds caused by anthracnose of sycamore (*Apiognomia veneta*). The sycamore lace bug *Corythucha ciliate* also damages the leaves and can lead to the secretion of honeydew. The fungus *Splanchnonema platani*, known as "Massaria" can lead to the partial or complete die-off of branches and soft rot. It usually occurs after chronic or acute drought. Lastly, the fungus *Ceratocystis fimbriata* f. sp. *platani* can be deadly and occurs in the neighbouring countries of Germany, especially in the south (Roloff 2013).

Robinia pseudoacacia L. (black locust)

Vegetative and generative features

R. pseudoacacia is a deciduous, broadleaved, medium-sized, thorny tree. It reproduces mainly via suckers, but its hermaphrodite, white fragrant flowers also turn into 5-10 cm long dark brown pods containing seeds. Trees 6 to 30 – 40 years of age fruit twice per year. As a single tree, *R. pseudoacacia* reaches heights of about 20 m, in stands up 30 m. It often grows bent-stemmed (Sitzia et al., 2016). Especially at a young age, the species is fast-growing. Additionally, it has a well-developed shallow root system, a large capacity for vegetative propagation and seeds that stay viable for long periods of time (Wojda et al., 2015). The leaves are 10-30 cm long, composed and pinnate. One leaf has 2-12 pairs of leaflets and one additional leave at the rachis. A pair of spines grows at the end of the shoots (Sitzia et al., 2016).

Distribution

The species was the first North American tree to be introduced to Europe in 1601, as a decorative park tree (Wojda et al., 2015). It occurs in 42 European countries and is naturalised in 32 (Sitzia et al., 2016). The tree originally comes from the east and centre of the United States (Van den Berk, 2004).

Soil, habitat and ecology

The black locust is a pioneer species which colonises grassland, semi-natural woodlands and urban habitats (Sitzia et al., 2016). It can grow on poor, degraded and dry soils, but it avoids wet and compacted soils and prefers light, chalky soils (Wojda et al., 2015; Sitzia et al., 2016, Van den Berk, 2004). *R. pseudoacacia* fixes nitrogen with the help of symbiotic rhizobia in its root nodules. Consequently, the tree adds nitrogen to soils, which also becomes available to other plants (Sitzia et al., 2016). In this process, it can transform nutrient-poor habitats into larger, monospecific patches of *R. pseudoacacia* which have a negative allelopathic influence on the understory and ground covering plants (Wojda et al., 2015). Lastly, *R. pseudoacacia* is a light-demanding species, prefers sub-Mediterranean to warm continental climates and requires high heat-sums (Sitzia et al., 2016).

Diseases

In its natural habitat, black locust is the target of many diseases (Wojda et al., 2015). In Europe, the moths *Phyllonorycter robiniella* and *Parectopa robiniella*, one gall midge (*Obolodiplosis robiniae*) and several lignicolous fungal species are known to infest *R. pseudoacacia.* In Germany, eleven mildews and leaf-spot diseases have been recorded (Sitzia et al., 2016).

Tilia cordata Mill. (small-leaved lime)

Vegetative and generative features

T. cordata is a widespread, deciduous tree species, native to Europe (Aas, 2016; Van den Berk, 2004). The tree can grow up to 30-40 m tall in forests (Eaton 2016) and up to 30 m in cities (Roloff, 2013). At a young age, small-leaved lime grows slowly (Van den Berk, 2004). In order to absorb the maximum amount of light, the tree has a regular two-rowed leaf arrangement and bifurcation (Aas, 2016). The leaves are approximately heart-shaped and measure 4-9 cm (Van den Berk, 2004). Additionally, the tree forms a dense, egg-shaped to round crown (Aas, 2016; Van den Berk, 2004).

Distribution

It has been present in European woods for more than 10,000 years and has been a popular street tree in Europe for a long time, for example along “Unter den Linden” (beneath the limes) in Berlin (Eaton, 2016). Generally, it is one of the most common urban trees in Germany (Aas, 2016).

Soil, habitat and ecology

The species is quite drought-tolerant, prefers warmer temperatures (Eaton, 2016) and can tolerate dry air; it mostly occurs in temperate continental climate (Aas 2016). Therefore, *T. cordata* may increase its range in a warming climate (Eaton, 2016). Spring or autumn frosts do not have a large effect on the species as it flushes late and the buds set early (Eaton, 2016). The tree has low requirements when it comes to soil water content and soil nutrients, but can also tolerate waterlogging, the proximity of groundwater, flooding (Aas, 2016) and dry soils (Van den Berk, 2004). The fragrant blossoms of the species are pollinated by insects (honey bees, bumblebees, hoverflies, and moths) (Aas, 2016). Small-leaved lime commonly grows below other, more light demanding species as it is shade-tolerant (Aas, 2016).

Diseases

T. cordata generally is resistant to diseases. Nonetheless, the tree may suffer from bleeding stem cankers caused by *Phytophthora cactorum* and *Phytophthora citricola*. Other pests include *Phytophthora plurivora*, aphids and the gypsy moth (*Lymantria dispar*) (Eaton 2016). In dry, inner cities sites and during warm and arid spells the leaves are often infested by the lime mite *Eotetranychus tiliarius* which cause damage to the leaves and early leaf fall (Roloff 2013).

1.6 Current knowledge on urban trees in Europe and the studied species

Most tree research to date has focused on areas that are classically associated with trees, i.e., forests. However, on account of the rising importance and rapid expansion of urban areas, interest in understanding the so called "urban forest" has grown. However, as it is not possible to transfer the insights from forest research par from far into cities (Peper et al., 2014), urban tree research is necessary. One of the reasons urban trees are not easily to comparable to forest trees are the many unique environmental challenges they are facing. These challenges include the effects of high urban temperatures (Akbari et al., 2001; Kjelgren & Clark, 1992), reduced water availability (Beatty & Heckman, 1981; Whitlow & Bassuk, 1987), compacted soils (Beatty & Heckman, 1981; Day et al., 1995), limited root volume (Day et al., 1995; Grabosky & Bassuk, 1995), and mechanical injury (Beatty & Heckman, 1981; Foster & Blaine, 1978).

While urban tree research has been a topic in the United States for longer, for example in a study of the urban forest of Chicago by McPherson et al. (1994, 1997), it only recently arrived in Europe and elsewhere (Pretzsch et al., 2015a). Subsequently, there is not a large database on European urban trees and urban forest ecology.Apart from Chicago, urban tree research has been carried out in other cities in North America (McPherson, 1998; Peper et al., 2001a; Peper et al., 2001b; Peper et al., 2014; Rijal et al., 2012; Roman & Scatena (2011); Troxel et al., 2013; Scott et al., 1998). Also, transregional studies were conducted (Nowak & Crane, 2002).

Other researchers aimed to quantify the ecosystem services provided by trees, for instance carbon storage (McPherson, 1998; Nowak & Crane, 2002; Russo et al., 2015; Yoon et al., 2013), how the UHI (Akbari et al., 2001; Pretzsch et al., 2015b) and runoff (Xiao et al., 2000a; Xiao et al., 2000b) can be reduced, how urban trees contribute to pollutant filtering (McPherson et al., 1997; Pretzsch et al., 2015b), their shading and cooling effects (Akbari et al., 2001; Dimoudi & Nikolopoulou, 2003; Shashua-Bar & Hoffman, 2003) and general studies on urban tree benefits (Roy et al., 2012; Tyrväinen et al., 2005).

As ecosystem services are strongly related to the structural parameters of trees Binkley et al. (2013), Lukaszkiewicz et. al (2005), Lukaszkiewicz & Kosmala (2008), Pretzsch (2014), Scott et al. (1998), Stoffberg et al. (2008) and Troxel et al. (2013) tried to establish the exact nature of these relations, while the structural dynamics across the lifespan of trees were investigated by McPherson et al., (2000) Peper et al. (2001b) and Semenzato et al. (2011).

Currently, the growth equations of urban trees are only based on few species with small age and size ranges (Rust, 2014; Troxel et al. 2013), but new research is trying to broaden this range and to establish more knowledge on European trees (Hasenauer, 1997; Larsen & Kristoffersen, 2002; Moser et al., 2015; Lukaszkiewicz & Kosmala, 2008; Pauleit et al., 2012; Pretzsch et al., 2015ab; Rust, 2014; Russo et al., 2015; Semenzato et al., 2011).

The present study contributes to the knowledge on the growth and ecosystem services of urban trees in Europe in general, and on urban trees in climates similar to the one of Bayreuth in particular. Additionally, more knowledge on the growth and ecosystem services provided by four studied species as urban trees is acquired. Lastly, the range of trees in the CityTrees database improves from currently 414 individuals of *R. pseudoacacia* and *T. cordata* (Moser et al., 2015) to 827 trees and adds *A. hippocastanum* and *P. acerifolia* and Bayreuth as a new study city to the scope, providing information on more different species and the influence of the urban climate on them.

1.7 Hypotheses

The right choice of an urban tree is important, as planting and maintaining trees requires investment of labour and money. Furthermore, benefits derived from urban trees, like ecosystem services, can be larger or smaller depending on the species.

In the context of climate change and urbanization, a "good urban tree" will be defined by four criteria for the purposes of this study:

1) Habitat demands – a good future city tree will require little water and nutrients, and thrive on a wide range of soils;

2) Climate endurance – good city trees will withstand current and future urban climatic conditions

3) Ecosystem service delivery – a good city tree will deliver a range of ecosystem services (across its lifespan and in a range of climatic conditions)

4) Practical and added value – a good future city tree will have high safety and low maintenance requirements, a high aesthetic value and as many other benefits (such as cultural relevance) as possible.

The four species in the study *Tilia cordata*, *Robinia pseudoacacia*, *Platanus x acerifolia* and *Aesculus hippocastanum*, referred to as "studied species", will be evaluated following these criteria.

An urban tree well-suited to Bayreuth has low demands, can withstand extreme events, has a large practical value, is adapted to the local climate and provides a large amount of ecosystem services across its lifespan. This will make certain species more suitable city trees than others, both at present and in the future. Additionally, it has to be considered that an urban area is not a uniform terrain offering the same site conditions everywhere. Some species may benefit from site conditions that are adverse to the development of others. Hence, the performance of the studied species will be compared across three site types (street, square and park). This thesis will try to determine which tree species is the most suitable city tree for Bayreuth in the future, based on the following hypotheses:

Hypothesis 1: The site type (street, square, park) influences tree growth.

Hypothesis 2: Tree growth and the associated delivery of the ecosystem services shading, cooling by evapotranspiration and carbon storage are species-specific. Growth shall be defined as the change of the tree dimensions DBH, tree height, crown length, crown diameter, crown length, crown projection area (CPA), crown volume, biomass and LAI over time.

Hypothesis 3: The responses of tree ecosystem services delivery (of shading, cooling by evapotranspiration and carbon storage) to climate change are species-specific.

Hypothesis 4: The benefits of one studied tree species and its ability to thrive in urban sites surpass the benefits of the others, making it the most suitable tree for Bayreuth, according to the "good urban tree" criteria established before.

In order to test these hypotheses, a literature research on the species was performed (in order to collect general information on the suitability of the species) and the data of 413 individual trees around Bayreuth was collected and analysed (in order to obtain site-specific information).

2. Methods

2.1 Data collection

The search for a location of potential trees for measuring was aided by the *Stadtgartenamt* (urban green space administration department) of Bayreuth. The department keeps a large tree inventory and employees provided information on where to encounter the relevant species. Then, the measuring team, consisting of the author and another master student working in the CityTrees project, went to the indicated locations and identified suitable trees. Individuals that showed signs of extreme pruning (principal branches cut off), strong inclination, or strong physical damage were ignored. See appendix 1 for a map of the distribution of trees in Bayreuth.

Trees were grouped into three location categories: street, square or park. The location category was determined according to the same predefined criteria that had been used in Munich and Wurzburg: A tree qualified as a street tree if, were the horizontal crown radius to be projected next to the tree one more time, the branches would have been above a street. A large, sealed area around the tree, with little or no open soil around the trunk was considered a square or public place. Parks, on the contrary, were defined as areas with large amounts of unsealed soil and no buildings.

As street trees are the most common kind of urban tree under the administration of the *Stadtgartenamt*, most trees were sampled in streets, with 251 individuals sampled in total, versus 82 in parks and 80 in public places. This distribution was chosen to represent the relative distribution of street trees at the urban level (cf. table 4 for the exact numbers per species).

The first round of measuring was conducted from March – April 2016. All variables (cf. 2.2, Measured variables) were measured except for vitality ranking and LAI, as estimating LAI naturally requires leaves on the tree and the vitality is easier to estimate when a tree has foliage. LAI and vitality were measured during the second round of measurements took place in late June 2016.

Table 4: Number of measured trees by species and location in Bayreuth.

Site	*A. hippocastanum*	*P. acerifolia*	*R. pseudoacacia*	*T. cordata*	Total
Park	22	20	20	20	**82**
Square	20	20	20	20	**80**
Street	60	63	60	68	**251**
	102	**103**	**100**	**108**	**413**

2.2 Measured variables

The following measurements were taken from every tree:

- trunk diameter at breast height (1.3m)
- crown radii
- tree pit radii
- distance from other trees and buildings
- tree height and crown height
- vitality rating.

A DBH measurement tape was used to measure trunk diameter at 1.3 m. If the tree had an unusual trunk structure at this height (for example burs) the next possible height with regular tree growth was used.

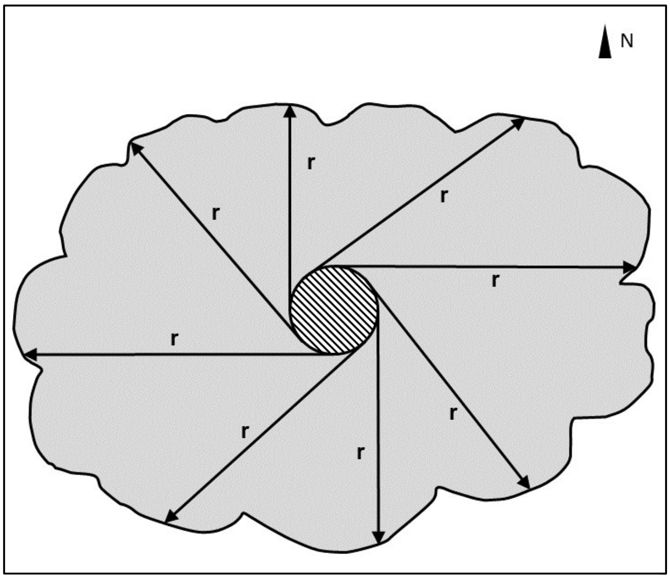


Figure 3: Tree crown measurement by spoke method.

2.2.1 Horizontal tree dimensions

The horizontal spatial dimensions of the tree were taken using a 30-meter measuring tape. All variables (horizontal crown dimension, size of tree pit, distance to other trees and buildings) were measured in the four cardinal directions (N,E,S,W) and the four intercardinal directions (NE,ES,SW,NW). Figure 3 shows how the horizontal crown dimension was measured this way, using the spoke method: The crown radius is measured from the centre of the stem until the tip of the furthest protruding branch, projecting the branches onto the ground.

The tree pit radii and distance from nearby trees and buildings were also taken. These variables are part of the standard catalogue of the CityTrees project. However, they were not part of the analysis conducted in this thesis. Possible uses of the data include estimating the competition intensity with other trees and extent of built-up structures in the vicinity producing microclimatic effects like shading. The size of tree pit could be related to tree growth, to find out if the superficial rooting space is influential.

2.2.2 Height

The total tree height and crown height (from the lowest primary branch until the highest point of the crown) were measured using the laser distance meters Vertex Forestor and Leica DISTO™ D510.

2.2.3 Vitality rating

In order to be able to estimate how healthy the trees in Bayreuth are and if the open area type has an influence on tree vitality, each tree received a vitality rating according to the scale proposed by Roloff, 2001. The rating ranges from 0 to 3 and describes four different growth phases of trees, namely

- 0: exploration
- 1: degeneration
- 2: stagnation
- and, 3: resignation.

The crown structure, including branch structure and distribution of leaved branches, serves as an indicator for the growth phase of a tree. To provide an example, figure 2 shows the growth phases of *T. cordata* which Roloff depicts together with *Tilia platyphyllos Scop.* due to their very similar crown development.

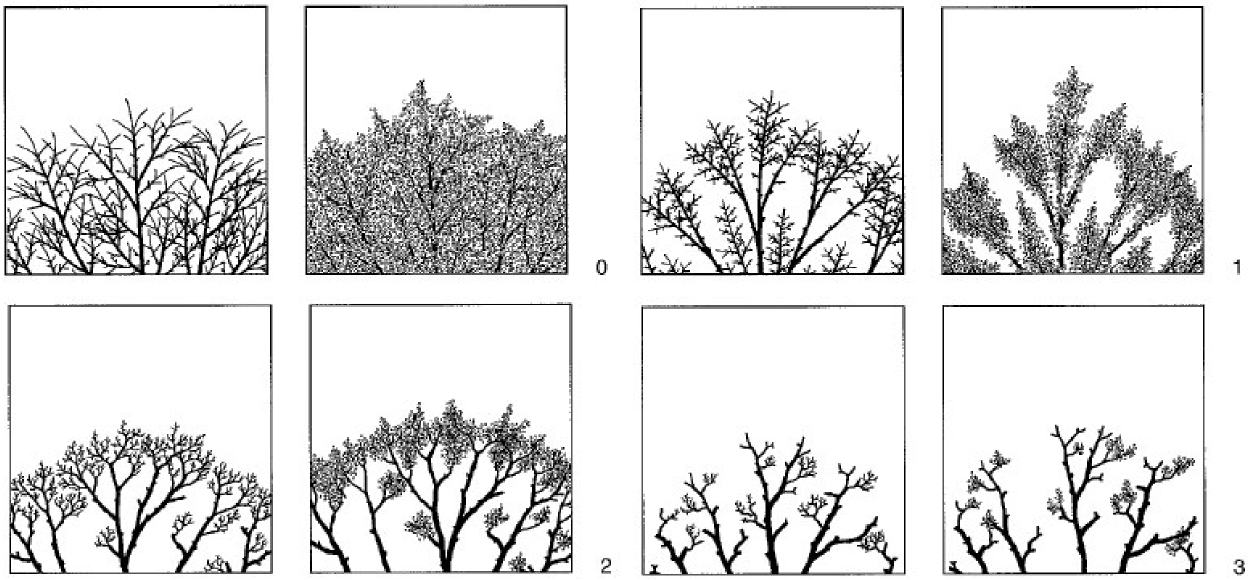


Figure 4: Vitality rating of *Tilia cordata* and *Tilia platyphyllos* Scop., according to crown structure (Roloff 2001, p. 116).

2.3 Calculated variables

The following variables were calculated from the measured values for each tree:

- horizontal crown dimensions
- size of tree pit
- biomass
- age
- LAI.

2.3.1 Crown extent

The eight radii measured according to figure 3 were used to calculate the average crown radius (cr):

$$cr = \sqrt{\frac{(r^2N + r2NE + \cdots + r^2NW)}{8}} \quad (1)$$

where rN is the longest crown extension to the north and rNW is the longest crown extension to the northeast and so forth.

The crown diameter (cd), CPA and crown volume can be calculated with the following formulas. The tree pit formula is the same as the one for CPA, except that it uses the unsealed soil radii.

$$cd = cr \times 2 \quad (2)$$

$$CPA = cr^2 \times \pi \quad (3)$$

$$cv = CPA \times cl \quad (4)$$

Lastly, crown length (cl) is calculated as follows:

$$cl = h - cb \quad (5)$$

Where h = tree height and cb= crown base height (height of the tree’s first major branch).

2.3.2 Biomass

The aboveground woody biomass (AWB) was calculated using species-specific allometric relationships. The formula of Tiwary et al. (2015) was used for *A. hippocastanum*:

$$ABW = e^{(a+(b \times \ln(DBH))} \qquad (6)$$

with a= -2.4800 and b= 2.4835.

Yoon et al. (2013) propose the following formula for the aboveground volume V of *Platanus orientalis*. Through multiplication with *Platanus'* average wood density of 590 kg/m³ (Lunin 2015) the AWB [kg] can be calculated:

$$V = a \times DBH^{b} \times h^{c} + RMSE \qquad (7)$$

with a = 0.000613, b= 1.510, c= 0.706 and root-mean-square error (RMSE)= 0.273.

For *R. pseudoacacia*, the formula of Clark & Schroeder (1986, converted from imperial to metric units) is:

$$AWB = a \times (((DBH \times 0.39370079)^{2})^{b} \times (h \times 3.2808)^{c}) \div 2.20462262 \qquad (8)$$

with a = 0.11081 b= 1.10786 c = 0.83091.

Lastly, for *T. cordata*, the formula of Čihák et al. (2014) was used:

$$AWB = e(b_0 + b_1 \times \ln DBH + b_2 \times \ln h) \times \lambda \qquad (9)$$

where $b_0 = -3.032$, $b_1 = 2.115$, $b_2 = 0.538$ and $\lambda = 1.020$ and DBH is tree diameter, h tree height and λ a correction coefficient.

2.3.3 Age

Tree age was estimated based solely on DBH or height and DBH, depending on the species. For *T. cordata* and *A. hippocastanum*, the formula of Lukaskiewicz & Kosmala (2008) is:

$$age = -a + e^{\left(b + c * \frac{DBH}{100} + d * h\right)} \qquad (10)$$

with a=264.073, b=5.5834, c=0.3397, d=0.0026 for *Tilia a.* and a=54.2714, b=4.0709, c=0.7988 and d=0.0209 for *A. hippocastanum*.

For *R. pseudoacacia*, a species dependent factor derived of the similar growing species *Gleditsia triacanthos* (Dwyer, 2009) was used:

$$age = DBH * 0.996 \qquad (11)$$

Lastly, Bühler et al. (2007) examined the growth of 690 *P. acerifolia* individuals and found a strong correlation between tree age and DBH, leading to a conversion of nearly one-to-one:

$$age = \frac{DBH}{1.01} \qquad (12)$$

2.3.4 Leaf area index

The LAI was deduced from hemispheric photographs of the trees (cf. figure 5). Pictures were taken from below the crown, at 90° upwards. The tripod was placed 1m from the tree if the area was not blocked by bushes or built-up structures. In this case, the nearest possible position was chosen. The camera used was a Nikon Coolpix E995, with a Nikon Fisheye Converter FC-E8 0.21x mounted on it. The data was then analysed with the software *Hemisfer* released by the Swiss Federal Institute for Forest, Snow and Landscape Research WSL (Schleppi et al., 2007; Thimonier & Schleppi, 2010) to determine the individual LAI of the trees. The LAI-analysis method used was the one developed by Norman and Campbell (1989) with correction for non-linearity of the light transmission according to zenith angle (Schleppi et al., 2007) and canopy clumping (Chen & Cihlar, 1995). As visible in the photograph of *A. hippocastanum*, in figure 5, crown overlaps with other trees and buildings are inevitable. Such crown areas were masked manually and then ignored in the analysis in order to avoid exaggerated LAI results, especially due to overlap with other crowns.

The LAI was calculated using the software R, version 3.3.1 (R Core Team, 2016). Generalized additive models (GAM, package: mgvc) with mixed smoothed predictor variables were created for each species, following Moser et al. (2015). The models were built using the measured LAI in combination with other measured tree variables in order to obtain more accurate results. For each species, the model with the lowest Akaike Information Criterion (AIC) was chosen. The resulting models were:

A. hippocastanum: $$\ln(LAI) = a + s(b_1) \times \ln(2 \times cr) + s(b_2) \times \ln(CPA) \quad (13)$$

P. acerifolia: $$\ln(LAI) = a + s(b_1) \times \ln(2 \times cr) + s(b_2) \times \ln(CPA) \quad (14)$$

R. pseudoacacia: $$\ln(LAI) = a + s(b_1) \times \ln(h) + s(b_2) \times \ln(cv) + s(b_3) \times \ln(CPA) \quad (15)$$

T. cordata: $$\ln(LAI) = a + s(b_1) \times \ln(DBH) + s(b_2) \times \ln(h) + s(b_3) \times \ln(2 \times cr) \quad (16)$$

with a = intercept and s= smooth function for each slope variable (b).

Figure 5: Hemispheric photographs of *A. hippocastanum*, *P. acerifolia*, *R. pseudoacacia* and *T. cordata* (from top left to bottom right).

2.4 Ecosystem services

Three ecosystem services provided by trees were modelled, using an environmentally sensitive individual tree growth model (Rötzer et al., 2010): **shading**, **cooling** by evapotranspiration and **carbon storage**. This process-based model is based on BALANCE, a model which simulates the water balance and growth of trees depending on their environment. However, at the current stage of development, the model calculates the ecosystem services based on growth, but it is not possible to receive an output of the tree dimensions the calculated ecosystem services are based on. Thus, an analysis of the ecosystem services delivered by the species under climate change was possible, but not a direct analysis of the changed growth. Hence, the ecosystem services provided will serve as a proxy for potential changes in growth under climate change, which is possible as ecosystem services strongly related to structural parameters (Pretzsch et al., 2015ab).

The data of the four species was compared to see how they perform under the current climate, and how and if their output of ecosystem services changes under future climate change. To this end, two different climate scenarios were used: To represent the current climate, a reference period (1982 to 2011) was chosen (DWD, 2016). For the future climate, the WETTREG scenarios A1B and B1 (2021 to 2050) were used (Spekat et al., 2007). The parameters of the climate scenarios and the reference period are given in table 5. The A1B scenario assumes rapid economic growth and a further rise of the global population which peaks in the middle of the 21st century and then diminishes. Further, in this scenario, the fast introduction of new, more efficient technology and a balanced energy use are expected (a mixture between fossil-intensive and non-fossil energy sources). The rapid economic growth leads to an increase in energy demand and a subsequent, strong increase in CO_2 emissions in the first decades of the 21st century. The effects of more effective technology can only be felt with a time lag. In the B1 storyline, the population development is the same as in the A1 scenario. However, the economy is expected to change to a service and information economy, leading to a decrease in material intensity. Additionally, clean and resource-efficient technology is assumed to be introduced (Nakicenovic & Swart, 2000). The carbon level was set to 390 ppm for the reference period, and 600 ppm in the future, following the CityTrees procedure (Pretzsch et al., 2015a).

Table 5: Parameters of the reference period and the climate scenarios WETTREG A1B and B1 (DWD, 2016; Spekat et al., 2007)

Climate	Radiation J/cm²	Temperature °C	Rel. humidity %	Wind speed m/s	Precipitation Mm	CO_2 ppm
Reference period	997	8.5	74	1.5	757	390
A1B scenario	1036	9.0	79	1.7	759	600
B1 scenario	989	8.6	80	1.8	841	600

The model calculates the ecosystem services delivered by trees in the following manner (as in Moser et al., 2015):

The shaded area is calculated based on crown length and radius for every hour of the day. The model output is the diurnal shaded area per tree on June 21 (summer solstice).

$$A_s = 2 \times cr \times l_c \times f \times \cot(Y) \qquad (17)$$

with A_s = shaded are in m², l_c = crown length, f = correction factor for crown shape, Y = elevation angle of the sun (calculated as a function of the latitude, day of the year and hour of the day). The calculation assumes an object on a horizontal surface in an upright angle (DVWK, 1996; Häckel, 2012).

The cooling is obtained by the model by combining the transpiration calculated with the process-based growth model BALANCE (Rötzer et al., 2010) and the annual transpiration sums of *Fagus sylvatica*, set in relationship to LAI by regression analysis:

$$tra_a\,[mm] = -0.0168 \times LAI^2 + 0.4555 \times LAI + 0.2844 \qquad (r^2 = 0.65) \qquad (18)$$

The yearly carbon storage per tree is a function of the yearly average net primary production and CPA (Pretzsch et al., 2015a).

2.5 Statistical analysis

The data was analysed using the software R. The following steps were performed: First, regression analyses were carried out to examine the connection between DBH and age and the variables tree height, crown height, crown diameter, CPA and crown volume per species. From these linear regressions, allometric relationships were determined. To this end, all tree dimensions were log-transformed, as allometric models use logarithmic transformed bivariate tree dimension data (Pretzsch et al., 2012). All allometric relations are expressed as simple linear regressions:

$$\ln(y) = a + b \times \ln(x) + \mathrm{CF} \quad (19)$$

with y = increase of tree dimensions over time, x= DBH or age, and CF= bias correction (CF). In order to correct for the bias that stems from back-transforming the logarithm, the bias correction of Baskerville (1971) and Sprugel (1983) was used:

$$CF = e^{\left(\frac{RMSE^2}{2}\right)} \quad (20)$$

with RMSE = root-mean-square error.

Depending on the available amount of light, trees can show very different growth dynamics (Harja et. al, 2012), especially light-demanding species like *P. acerifolia* and *R. pseudoacacia*. Also, the tree pit and subsequent superficial rooting space play a large role. Space can be very limited in case of roadside planting and squares, while parks leave more space for superficial roots. Moser et al. (2015) confirmed this, as they found that the growth of *R. pseudoacacia* und *T. cordata* was highly influenced by tree pit. Hence, in a second step, the mean values per species per open area type (street, park, square) were determined to identify the potential influence of the growth site on the tree dimensions, age, tree pit and vitality. These means were compared with a Kruskal-Wallis test with alpha=0.05 (package: agricolae, command: kruskal) as the normal distribution of the necessary to perform ANOVA was not given for all variables for all species. Normal distribution was tested with Shapiro-Wilk tests (shapiro.test) included in the standard package "stats". The p-values of the Kruskal-Wallis test were adjusted with the Bonferroni method for multiple comparisons included in the package agricolae, as suggested by Moser et al. 2015. The also important belowground rooting space and subsequent root system structure was not target of this study, but would potentially also have revealed interesting impacts on tree growth (Day, 1995; Day, 2010).

Species differences between ecosystem services were tested using ANOVA (aov) and the post hoc comparison Tukey Honestly Significant Differences (TukeyHSD) to compare the factors, i.e. different tree species.

2.6 Theoretical urban use suitability of the studied species

To determine which factors make the four species suitable or unsuitable for cities and how they perform in theory compared to the measured results in Bayreuth, a literature research was performed. The Deutsche Gartenamtsleiterkonferenz (German association of communal green space administrations, GALK) publishes a comprehensive list of trees that are commonly planted in German cities. Despite the name "Straßenbaumliste" (street tree list), the list generally describes how suitable certain species are for urban areas in terms of morphological and physiological features (growth, formation of roots, stem and crown, light permeability), habitat requirements (climate, soil, water, light) and information on vulnerabilities to sicknesses or environmental stress, care required and potential risks for traffic and the inhabitants of the city. This list, along with Roloff's 2013 book on urban trees served as a base for further research. A table comparing the most important traits of all species was created (cf. table 6).

As the occurrence of both extreme hot and cold periods are expected to increase in the future, winter hardiness, heat and drought tolerance were evaluated as far as possible. To this end, each species was assigned to a winter hardiness zone, following the United States Department of Agriculture's (USDA) system of assigning climate zones to plants. This way, it can easily be determined which minimum temperature a species can withstand. Table 6 gives a shortened overview over the zones. Usually, a tree grows well in at least three categories above its core zone. For example, a tree of the winter hardiness zone 4 (like *T. cordata*) can flourish in zones 5, 6 and 7 or more. Bayreuth is situated in zone 6b. In Germany, zones 5b to 8a occur (Van den Berk, 2004, cf. appendix 2 for a map of the USDA hardiness zones in Central Europe).

Table 6: USDA winter hardiness zones (shortened, after Van den Berk, 2004).

	USDA winter hardiness zones	
Zone	**Lowest temperature [C°]**	**Example areas**
4	-34.4 to -28.9	Russia, northern Scandinavia
5a	-28.9 to -26.1	Belarus, eastern Baltic States
5b	-26.0 to -23.4	Northeastern Poland, southern Ukraine, central Sweden, southern Finland
6a	-23.3 to -20.6	Eastern Poland, Slovakia, eastern/central south of Sweden, southern Finland
6b	-20.5 to -17.8	Central Poland, eastern Hungary, Czech Republic, southern Sweden
7a	-17.7 to -15.0	Eastern Germany, western Poland, east and west coast of Sweden
7b	-14.9 to -12.3	Eastern Netherlands, southern coast of Sweden, eastern Denmark
8a	-12.2 to -9.5	Central Netherlands, Belgium, northern and central France, northern England
8b	-9.4 to -6.7	Coast of the Netherlands, western France, northern Italy, central England

Additionally, Roloff (2013) developed a system of rating the future potential of urban trees in terms of climatic suitability called KLAM ("KlimaArtenMatrix", climate species matrix). The forty most common tree species of Germany received a pair of grades separated by a period, for example "2.1". The first number represents the drought stress tolerance, the second the winter hardiness. The best possible grade is 1 ("very well suited"), the worst 4 ("unsuited"). These evaluations are based on Roloff's own research, and a broad literature research. The pair of grades together indicates the overall suitability of the tree (cf. figure 6).

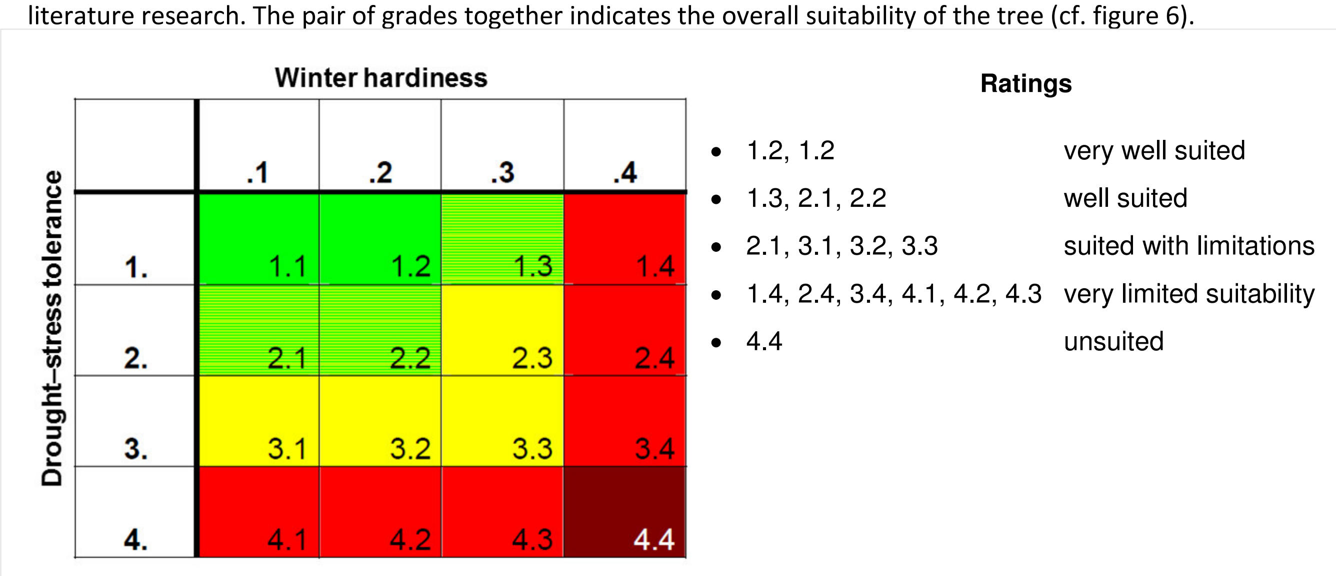


Figure 6: KLAM (KlimaArtenMatrix) diagram showing the future suitability of tree species for urban areas (adapted from Roloff, 2013).

3. Results and discussion

3.1 Results derived from the sampled data

3.1.1 Measured and calculated species traits

Tables 9&10 present the results of the data collection in Bayreuth, summarizing the measured and calculated tree dimensions in five age categories by species. The average tree age in Bayreuth was 48.7 years. Split up by the individual species the average is: 62.8 years (*A. hippocastanum*), 40.4 years (*P. acerifolia*), 39.6 years (*R. pseudoacacia*), and 52 years (*T. cordata*). The average tree age reported from Munich and Wurzburg was 8.7 years below the one in Bayreuth, with 40 years. *T. cordata* was only 41 years old on average, but *R. pseudoacacia* had a very similar average age as in Bayreuth, with 39 years (Moser et al., 2015). Roman and Scatena (2011) compared several studies on tree age and found a mean life expectancy of 19-28 years for urban trees.

Overall, the sampled *P. acerifolia* reached the largest average dimensions. The largest average **DBH** was found *in A. hippocastanum* (42.8 cm), closely followed *P. acerifolia* (40.8 cm), *R. pseudoacacia* (39.7 cm) and *T. cordata* (38.8 cm). The overall range was from 6.2 to 103.9 cm. In terms of **height**, the species reached similar means from 14 – 16.7 m. The highest individual tree measured 32 m, the shortest 4.4 m. The largest average **crown diameter** on average was reached by *P. acerifolia* (12.1 m). *A. hippocastanum* and *R. pseudoacacia* had the same average crown diameter of 9.3 m. *T. cordata* was marginally smaller, with 8.7 m. The largest overall crown diameter in the sample was 26.8 m, the smallest only 1.2 m.

As **CPA** is directly calculated from crown diameter, the order of the species remains the same. The mean CPA values ranged from 70.7 m² to 136 m². The minimum overall CPA was 1.1 m², the maximum 563 m².

Table 7: Measured and calculated tree dimensions in five age classes: DBH, height, crown length, and crown diameter.

Species	Age	n	DBH [cm]			Height [m]			Crown length [m]			Crown diameter [m]		
			Min	Mean	Max	Min	Mean	Max	Min	Mean	Max	Min	Mean	Max
A. hippocastanum	<20	6	6.5	9.1	14.0	4.4	5.1	5.9	1.7	2.6	3.5	1.6	2.7	3.9
	20-40	20	11.4	20.5	30.9	6.9	9.2	12.6	4.4	6.2	9.5	3.5	5.6	10.2
	40-60	28	20.7	37.4	51.3	10.8	13.0	16.0	6.5	10.0	13.2	6.5	8.7	11.1
	60-80	21	33.0	49.4	67.2	12.8	16.7	23.0	9.5	13.4	20.0	6.4	10.5	16.9
	>80	27	40.5	67.3	87.0	13.5	22.3	30.0	11.1	18.3	26.5	10.0	13.2	17.8
	Total			**42.8**			**15.0**			**11.7**			**9.3**	
P. acerifolia	<20	18	6.2	13.3	19.2	6.5	8.9	13.6	4.0	5.9	8.3	2.1	4.6	11.5
	20-40	43	21.4	31.8	40.0	10.1	15.3	22.3	6.8	10.9	18.0	5.9	11.0	16.2
	40-60	26	40.4	48.2	58.1	9.5	19.1	24.0	6.9	15.0	23.0	10.7	14.6	19.1
	60-80	6	61.0	69.6	79.4	18.0	21.6	26.0	15.7	18.9	23.7	13.7	19.4	24.9
	>80	10	83.6	92.9	103.9	22.0	27.2	32.0	17.9	23.7	27.6	16.3	19.8	26.8
	Total			**40.8**			**16.7**			**12.8**			**12.1**	
R. pseudoacacia	<20	3	11.8	15.6	18.4	8.4	8.6	9.0	5.3	5.6	5.8	1.2	4.4	7.5
	20-40	54	21.0	31.0	39.6	7.8	13.5	28.0	4.7	9.3	15.3	5.8	8.6	12.8
	40-60	34	40.2	47.3	58.1	11.0	18.3	27.1	8.4	13.8	21.9	6.1	10.3	14.9
	60-80	7	60.8	66.8	77.0	11.7	23.1	29.6	10.2	18.1	22.4	6.5	11.5	13.7
	>80	2	85.0	87.3	89.5	9.3	13.5	17.7	7.0	11.0	15.0	12.5	12.7	12.9
	Total			**39.7**			**15.7**			**11.4**			**9.3**	
T. cordata	<20	13	8.2	10.9	13.8	5.6	7.7	10.4	3.2	4.5	7.4	2.4	3.5	5.5
	20-40	36	13.0	21.6	30.6	7.0	10.0	14.3	2.6	6.4	9.2	3.5	6.2	10.1
	40-60	21	30.0	36.4	46.1	8.5	14.0	24.2	4.4	9.8	15.6	7.8	9.6	12.0
	60-80	15	38.0	52.8	61.6	8.1	18.6	28.7	4.7	15.0	25.0	8.9	11.3	14.5
	>80	23	59.1	74.7	99.1	12.0	20.8	32.0	9.2	16.5	27.3	9.1	13.3	20.6
	Total			**38.8**			**14.0**			**10.2**			**8.7**	

In terms of **crown volume**, again *P. acerifolia* reached the largest dimensions (2,232 m³). *A. hippocastanum* had the second largest average crown volume (1,147 m³), followed by *T. cordata* (946 m³) and lastly, *R. pseudoacacia* (885 m³). The smallest calculated crown volume was 5 m³, the largest 13,907 m³. The highest **biomass** was achieved by *A. hippocastanum* (1,292 kg), followed by *P. acerifolia* (1,083 kg) and *R. pseudoacacia* (755 kg), which had a similar value as *T. cordata,* with 744 kg.

In general, these values are similar to the ones found by Moser et al. (2015) during the CityTrees project in Munich and Wurzburg for *R. pseudoacacia* and *T. cordata*. What is remarkable, however, are high the CPA and crown volume reached by *P. acerifolia* and *T. cordata* in Bayreuth, as the highest found overall values in the other cities were a CPA of 313 m² and a crown volume of 5749 m³ (both for *R. pseudoacacia*). The highest CPA and crown volume found for *T. cordata* was even below that, as it reached only 267 m² and 5,276 m², compared to 334.8 m² and 7,265 m³ in Bayreuth.

The **LAI** calculated with GAM was highest in *T. cordata* on average (2.8), followed by *A. hippocastanum* (2.4), *P. acerifolia* and lastly, *R. pseudoacacia* (1.7). The maximum value of 8.8 attained by *T. cordata* is likely an outlier. Moser et al. found a lower mean for the studied species: the LAI of *T. cordata* was 2.60 (range 0.98 to 5.29), and *R. pseudoacacia* 1.49 (range: 0.42 to 5.0).

Dickmann et al. (1985) found a higher LAI for *R. pseudoacacia* and *P. occidentalis* (both 4.3-4.9. in pure plantings) and Rauner (1976) an LAI of 4.78 for *T. cordata*. However, Hipps et al. (2014) measured a similar LAI of 2.55 for unpruned *P. acerifolia* (drip line LAI mean May – August) and Nardini et al. (2004) a mean LAI of 2.5 for *A. hippocastanum*.

Table 8: Measured and calculated tree dimensions in five age classes: CPA, crown volume, biomass and LAI.

			CPA [m²]			Crown volume [m³]			Biomass [kg]			LAI [m²/m²]		
Species	**Age**	**n**	**Min**	**Mean**	**Max**	**Min**	**Mean**	**Max**	**Min**	**Mean**	**Max**	**Min**	**Mean**	**Max**
A. hippocastanum	<20	6	1.9	6.2	11.8	5	17	33	9	23	59	2.3	2.4	2.5
	20-40	20	9.4	25.8	81.4	49	163	513	35	165	420	2.0	2.4	2.7
	40-60	28	33.3	60.2	97.3	289	611	1110	155	700	1479	2.2	2.5	2.7
	60-80	21	32.3	90.5	225.3	427	1265	4505	495	1399	2892	2.1	2.4	2.7
	>80	27	78.9	140.2	248.8	1119	2591	5626	822	3005	5492	2.1	2.4	2.6
	Total			**77.7**			**1147**						**2.4**	
P. acerifolia	<20	18	3.5	20.9	104.7	15	140	869	183	248	359	1.9	2.7	3.4
	20-40	43	27.7	98.7	206.6	205	1134	2720	363	637	1004	1.7	2.0	2.5
	40-60	26	89.4	169.3	286.9	617	2651	6600	698	1178	1734	1.8	2.0	2.3
	60-80	6	146.9	303.7	487.1	2482	5663	7647	1612	2067	2488	1.7	2.1	2.4
	>80	10	208.0	316.1	563.0	4196	7572	13907	2723	3665	4796	2.0	2.4	2.9
	Total			**136.0**			**2232**			**755**			**2.2**	
R. pseudoacacia	<20	3	1.1	20.1	43.8	7	111	245	24	47		0.5	0.9	1.5
	20-40	54	26.0	60.4	129.6	161	566	1346	83	314	709	0.9	1.5	5.1
	40-60	34	29.4	86.0	175.2	335	1205	2716	514	1011	2061	0.8	1.9	6.7
	60-80	7	32.8	106.8	146.4	590	1935	3207	1901	2517	3540	0.9	2.5	4.0
	>80	2	123.0	126.4	129.9	909	1377	1844	2055	2993	3932	0.9	1.2	1.5
	Total			**72.5**			**885**			**755**			**1.7**	
T. cordata	<20	13	4.5	10.4	23.4	15	47	94	14	23	35	1.2	1.7	2.8
	20-40	36	9.7	31.5	79.9	25	216	591	35	123	251	1.5	2.4	3.9
	40-60	21	47.3	73.5	113.2	285	750	1766	256	413	664	1.3	3.0	5.2
	60-80	15	62.4	101.6	166.2	631	1494	3125	657	1023	1419	1.1	3.6	8.8
	>80	23	64.4	143.5	334.8	593	2420	7265	1449	2245	3848	1.6	3.3	6.2
	Total			**70.7**			**946**			**744**			**2.8**	

In all species, growth gradually slows with age. Hence, the difference between age categories drops from 40 to 50% (increment from >20 to 20-40 years) to 16-25% (60-80 years to >80 years). The growth rate from one age category to the next was on average 30.4%, with little difference among species: *A. hippocastanum* averaged 33.2%, *P. acerifolia*: 29.3%, *R. pseudoacacia*: 30.2%, and *T. cordata*: 28.8% (calculated from the change of mean values of DBH, height, and crown diameter). Consequently, species is not too relevant for how tree dimensions change with age, despite the description of *P. acerifolia* and *R. pseudoacacia* as fast-growing (e.g. Roloff, 2013).

3.1.2 Allometry

Allometric relations between DBH and age as response variables and tree height, crown diameter, crown length, CPA, crown volume, LAI and biomass as predictor variables were calculated. Table 11 gives an overview over the results of the calculated growth at ten ages (10-100), in which the differences between the studied species become evident.

Overall, *P. acerifolia* reaches the largest dimensions according to the allometric regression, followed by *R. pseudoacacia, T. cordata* and *A. hippocastanum*. When comparing this to the results of the allometric logistic regression of Moser et al. (2015), it is notable that intercepts in this study are higher, but the slopes lower for *T. cordata* (except for crown height, where both are lower). The intercepts of *R. pseudoacacia* are lower or very similar, the slope is lower or very similar, too. This indicates city-dependent differences in the growth patterns of the species, more pronounced in *T. cordata*. The calculated allometric regression of *P. acerifolia* projects a faster gain in biomass than the ones than the ones calculated by Yoon et al. (2013) for *P. orientalis*, which may be due to species differences, or the low number of trees used by Yoon et al. (n =10).

To be able to compare the temporal dynamics of the development of the structural parameters of the species, figure 7 shows DBH and age as predictors for the response variables tree height, crown diameter and crown volume. Here, the similiarity of the DBH-based allometry to age-based allometry shows the validity of basing the ecosystem service model on age instead of DBH (as Moser et al., 2015; Peper et al., 2014; Rust, 2014). The dimensions height, crown diameter and crown volume were chosen in order to represent both directly measured (height) and calculated variables (crown diameter, crown volume). To illustrate the individual species in more detail, figure 9 shows the linear logistic regressions of crown diameter per species, also with DBH and age as predictors (also cf. appendix 4 & 5 for height and crown volume).

When comparing the age regression lines of *P. acerifolia* and *R. pseudoacacia* to those of *A. hippocastanum* and *T. cordata,* it becomes evident that the former are more similar to the DBH regression lines and values (cf. tables 12 &13). This is due to autocorrelation, as DBH was the sole base for age calculation in case of *P. acerifolia* and *R. pseudoacacia*. Consequently, the slope and intercept only differ starting from the third decimal place. The regression lines of *A. hippocastanum* and *T. cordata* show more differences, as in both cases, height is included in the age calculation, making age not purely a function of DBH (cf. formula 10). In case of *T. cordata*, the age-based intercept is always lower than the DBH based one, except for the one of crown diameter (DBH: -0.29, age: -0.08). Conversely, the age-based slope is always higher, again except for crown diameter. The age-based allometry of *A. hippocastanum* generally shows lower intercept and higher slope values than the DBH based one, excluding crown diameter, for which the inverse is the case.

There are several other cases of autocorrelation that need to be considered for both DBH and age as predictors, as age is based completely or partly on DBH, so parameters that involve either predictor in their calculation will show autocorrelation. For all species, this is the case for biomass as a response variable (cf. formulas 6-9), and for *T. cordata,* also for LAI (cf. formula 16). This leads to r^2 of 1 or nearly 1 for the allometric regression of biomass, while the influence of autocorrelation on the LAI of the small-leaved lime appears to be smaller, as the r^2-values remain as low as 0.19 and 0.24. The reason for that is possibly that in the LAI calculation, DBH is only one of three factors, and in case of age (which is calculated from DBH and h for *T. cordata*, cf. formula 10), the influence of DBH on the calculated LAI becomes smaller yet due the dependence of age on DBH explained above.

However, robust r^2 values were also obtained for relations without autocorrelation in most cases, independent of the predictor (the mean r^2 of DBH as a predictor of all variables is 0.71, age is 0.70). Overall, the prediction of LAI is not very accurate with r^2-values from only 0.41 to as low as 0.09. *R. pseudoacacia* has the lowest overall r^2, as many values are >50, which means that the growth of this species is harder to predict than the one of the other studied species. Moser et al. (2015) observed the same phenomenon and explained it with the fact that *R. pseudoacacia* is a light-demanding species and might thus be more shaped by the light conditions than the shade species.

Table 9: Tree growth, illustrated by the values of structural parameters height, crown length, crown diameter, CPA, crown volume, LAI and biomass at 10 ages (10-100 years), calculated using allometric logistic regression.

Species	Age [a]	Height [m]	Crown length [m]	Crown diameter [m]	CPA [m²]	Crown volume [m³]	LAI [m²/m²]	Biomass [kg]
A. hippo.	10	5.0	3.2	3.3	5.1	9.8	3.2	10.9
	20	7.7	5.1	4.9	12.9	49.9	3.3	56.3
	30	10.0	7.0	6.3	23.3	133	3.3	153
	40	12.1	8.8	7.7	35.8	270	3.4	311
	50	14.0	10.6	8.9	50.1	469	3.4	541
	60	15.9	12.3	10.1	66.2	736	3.4	851
	70	17.6	14.0	11.3	83.7	1078	3.5	1248
	80	19.3	15.8	12.4	102.8	1500	3.5	1739
	90	21.0	17.5	13.5	123.1	2008	3.5	2331
	100	22.6	19.2	14.5	144.8	2607	3.5	3029
	Mean	**14.5**	**11.3**	**9.29**	**64.8**	**886.1**	**3.4**	**1027.0**
P. aceri.	10	8.8	5.8	4.8	12.3	55.2	3.5	157.5
	20	12.5	8.9	7.8	37.5	287.8	3.2	387.2
	30	15.5	11.5	10.6	73.5	761	3.1	656
	40	18.0	13.9	13.3	119.0	1520	3.0	954
	50	20.3	16.1	15.8	173.1	2598	3.0	1276
	60	22.4	18.2	18.3	235.3	4027	2.9	1618
	70	24.3	20.2	20.7	305.1	5834	2.9	1979
	80	26.2	22.1	23.0	382.1	8042	2.8	2355
	90	27.9	23.9	25.3	466.2	10675	2.8	2745
	100	29.5	25.7	27.6	557.0	13752	2.8	3149
	Mean	**20.5**	**16.6**	**16.72**	**236.1**	**4755.2**	**3**	**1527.7**
R. pseudo.	10	8.2	5.0	7.2	14.4	54	2.0	15.2
	20	11.5	7.7	9.8	31.6	203	2.2	93
	30	14.2	10.1	11.9	50.7	446	2.4	276
	40	16.5	12.3	13.8	71.0	780	2.5	598
	50	18.5	14.3	15.4	92.3	1203	2.6	1091
	60	20.4	16.3	16.9	114.5	1714	2.7	1782
	70	22.1	18.2	18.3	137.5	2313	2.8	2700
	80	23.7	20	19.7	161.1	2998	2.9	3870
	90	25.3	21.7	20.9	185.2	3769	3.0	5316
	100	26.7	23.4	22.1	209.9	4626	3.0	7063
	Mean	**18.7**	**14.9**	**15.6**	**106.8**	**1810.6**	**2.61**	**2280.4**
T. cordata	10	6.3	3.7	6.2	6.3	15.2	2.6	7.2
	20	9.0	5.7	9.7	15.9	71.1	3.0	38.5
	30	11.2	7.5	12.9	28.5	179	3.4	108
	40	13.1	9.2	15.7	43.3	346	3.7	226
	50	14.9	10.8	18.4	60.2	577	3.9	402
	60	16.4	12.3	20.9	78.8	878	4.1	643
	70	17.9	13.8	23.4	99.1	1251	4.3	957
	80	19.3	15.2	25.7	120.9	1700	4.5	1352
	90	20.7	16.6	28.0	144.1	2228	4.6	1832
	100	21.9	17.9	30.2	168.7	2839	4.8	2406
	Mean	**15.1**	**11.2**	**19.11**	**76.6**	**1008.4**	**3.89**	**797.2**

However, this would mean that the other more light-demanding species, *P. acerifolia*, should also show lower r²-values. However, this is not the case in this study. This could be a hint that either the growth of *R. pseudoacacia* is nonlinear, or that *P. acerifolia* does not have such a high light demand. The first theory seems more plausible as Roloff (2013) describes the habitus of older *R. pseudoacacia* as “bizzare” and “kinked” and the GALK list (2012) characterises the crown as “irregular”. In general, the allometric regression of *P. acerifolia* produces the highest total and mean values, followed by *R. pseudoacacia*, *T. cordata* and lastly, *A. hippocastanum*. This means that *P. acerifolia* grows fastest and becomes largest in the age span from 0-100 years, which is also supported by the measured values.

However, in case of the other species, it needs to be noted that the allometric calculation of the tree parameters leads to a shift in which species reaches the largest individual dimensions in comparison to the measured values. The sequence of the species by maximum mean per variable is the following (A = *A. hippocastanum*, P = *P. acerifolia*, R = *R. pseudoacacia*, T= *T. cordata,* ~ indicates very similar interspecies value):

Value	**Mean**: Measured/calculated	Allometric	**Sequence change**
• Height:	P>R>A>T	P>R>A~T	—
• Crown length:	P>R~A>T	P>R>A>T	—
• Crown diameter:	P>A=R>T	T>P>R>A	A ↑, P ↑, R = , T ↓
• CPA:	P>T>A>R	P>R>T~A	A ↓, P = , R ↑, T ↓
• Crown volume:	P>A>T>R	P>R>T>A	A ↓, P = , R ↑, T ↓
• Biomass:	A>P>R~T	R>P~A>T	A ↓, P = , R ↑, T =

Table 10: Results of the linear logistic regression for all four species with $\ln(y) = a + b \times \ln(x)$ with x= DBH, y = tree variable (age, height, crown diameter, crown length, CPA, crown volume, LAI or biomass) and a, b= regression coefficients. The other results listed are n = sample size, SE= standard error, r, r² = coefficients of determination (adjusted r²), RMSE= root-mean-square error for bias correction, F-values and p-values. * indicates autocorrelation caused by the use of the predictor (DBH) in the calculation of the variable.

Species	Variable	*n*	*a*	SE	*b*	SE	r	r²	RMSE	F	p
A. hippocastanum	DBH vs. tree height	99	0.34	0.13	0.63	0.04	0.87	0.75	0.21	292.80	<0.01
	DBH vs. crown diameter	99	-0.55	0.12	0.74	0.03	0.92	0.84	0.18	534.00	<0.01
	DBH vs. crown length	99	-0.65	0.17	0.82	0.05	0.87	0.76	0.26	310.00	<0.01
	DBH vs. CPA	99	-1.37	0.23	1.49	0.06	0.92	0.85	0.36	537.10	<0.01
	DBH vs. crown volume	99	-2.02	0.34	2.31	0.09	0.93	0.86	0.53	605.50	<0.01
	DBH vs. LAI	99	0.63	0.03	0.07	0.01	0.64	0.41	0.05	70.33	<0.01
	DBH vs. biomass*	98	-2.48	0.00	2.48	0.00	1.00	1.00	0.00	4.35E+10	<0.01
P. acerifolia	DBH vs. tree height	103	0.76	0.09	0.56	0.03	0.91	0.83	0.15	491.20	<0.01
	DBH vs. crown diameter	103	-0.62	0.12	0.84	0.03	0.93	0.87	0.19	671.20	<0.01
	DBH vs. crown length	103	-0.08	0.11	0.71	0.03	0.92	0.84	0.18	555.40	<0.01
	DBH vs. CPA	103	-1.49	0.24	1.69	0.07	0.93	0.87	0.39	668.00	<0.01
	DBH vs. crown volume	103	-1.57	0.27	2.40	0.08	0.95	0.91	0.45	1017.00	<0.01
	DBH vs. LAI	102	1.19	0.08	-0.12	0.02	0.46	0.22	0.13	29.09	<0.01
	DBH vs. biomass*	103	2.04	0.10	1.30	0.03	0.98	0.96	0.17	2203.00	<0.01
R. pseudoacacia	DBH vs. tree height	98	0.68	0.26	0.56	0.07	0.62	0.38	0.24	59.54	<0.01
	DBH vs. crown diameter	98	0.04	0.24	0.60	0.07	0.67	0.45	0.22	79.22	<0.01
	DBH vs. crown length	98	-0.37	0.26	0.75	0.07	0.73	0.53	0.24	107.70	<0.01
	DBH vs. CPA	98	-0.17	0.49	1.19	0.13	0.67	0.44	0.45	78.66	<0.01
	DBH vs. crown volume	98	-0.52	0.55	1.94	0.15	0.80	0.63	0.50	167.20	<0.01
	DBH vs. LAI	98	-0.96	0.44	0.38	0.12	0.29	0.08	0.41	70.33	<0.01
	DBH vs. biomass*	99	-3.56	0.21	2.70	0.06	0.98	0.96	0.20	2135.00	<0.01
T. cordata	DBH vs. tree height	108	0.81	0.13	0.50	0.04	0.80	0.63	0.25	186.40	<0.01
	DBH vs. crown diameter	108	-0.29	0.09	0.68	0.03	0.93	0.87	0.17	742.70	<0.01
	DBH vs. crown length	108	-0.18	0.17	0.68	0.05	0.81	0.66	0.31	211.00	<0.01
	DBH vs. CPA	108	-0.85	0.18	1.37	0.05	0.94	0.88	0.33	752.50	<0.01
	DBH vs. crown volume	108	-1.03	0.28	2.05	0.08	0.93	0.87	0.52	687.40	<0.01
	DBH vs. LAI*	108	0.04	0.18	0.26	0.05	0.43	0.19	0.35	25.60	<0.01
	DBH vs. biomass*	108	-2.44	0.15	2.34	0.04	0.98	0.97	0.28	3221.00	<0.01

When comparing the sequence changes this involves, it becomes evident that dimensions of *R. pseudoacacia* may be overestimated by the linear allometric regressions, while *A. hippocastanum* and *T. cordata* may be underestimated. The reason for this potentially is a sampling bias which lead to an uneven age distribution of the measured individuals per species (cf. tables 9 & 10). While only one age category of *A. hippocastanum* lacks a higher number of individuals (14, in the category below 20 years) necessary for a perfectly equal distribution of 20 sampled individuals per age category, nearly no older individuals (>60 years) were sampled at all for *R. pseudoacacia* and *P. acerifolia*. This leads to an overrepresentation of middle aged (20-60 years) individuals of these species. In *T. cordata*, only the category 20 – 40 years contains several (16) trees more than necessary for an equal distribution. A possible explanation for this sample bias is the low total number of *P. acerifolia* and *R. pseudoacacia* (cf. table 3) in Bayreuth, combined with the fact that these two species are not commonly planted in squares and especially not in parks in the city, which made it difficult to sample across all age categories in these sites.

An uneven distribution among the age categories also occurred in the sample of Moser et al., 2015. This sampling bias may have led to a biased allometry as well, as the development of the dimensions of both young and old trees was not considered adequately, depending on the species. In *A. hippocastanum*, this underestimates the fact that the tree grows fast when young (Roloff, 2013), while the slowed growth at older ages (cf. figure 2) of *P. acerifolia* and *R. pseudoacacia* is underestimated, in turn overestimating the average growth. Ultimately, this leads to a slower growth calculated by the linear logistic regression of *A. hippocastanum*, and a faster growth calculated for the other two species. In *T. cordata*, the age category with a noticeable surplus is 20-40 years, which also leads to a potential overestimation of the growth speed of the species (cf. appendix 6 for percentage change from age category to age category).

Table 11: Results of the linear logistic regression for all four species with $\ln(y) = a + b \times \ln(x)$ with x= age, y = tree variable (age, height, crown diameter, crown length, CPA, crown volume, LAI, biomass) and a, b= regression coefficients. The other results listed are n = sample size, SE= standard error, r, r² = coefficients of determination (adjusted r²), RMSE= root-mean-square error for bias correction, F-values and p-values. * indicates autocorrelation caused by the use of the predictor (DBH) in the calculation of the variable.

Species	Variable	*n*	*a*	SE	*b*	SE	r	r²	RMSE	F	p
A. hippocastanum	age vs. tree height	99	-0.29	0.09	0.73	0.02	0.15	0.76	0.13	974.20	<0.01
	age vs. crown diameter	99	0.18	0.26	0.24	0.07	0.33	0.11	0.35	12.76	<0.01
	age vs. crown length	99	-1.37	0.14	0.93	0.04	0.94	0.87	0.19	683.50	<0.01
	age vs. CPA	99	-2.17	0.28	1.55	0.07	0.91	0.83	0.38	476.30	<0.01
	age vs. crown volume	99	-3.54	0.34	2.48	0.09	0.95	0.89	0.46	835.60	<0.01
	age vs. LAI	99	0.60	0.04	0.07	0.01	0.63	0.39	0.05	66.04	<0.01
	age vs. biomass*	98	-3.44	0.28	2.49	0.07	0.96	0.93	0.38	1294.00	<0.01
P. acerifolia	age vs. tree height	103	0.76	0.09	0.56	0.03	0.91	0.83	0.15	491.20	<0.01
	age vs. crown diameter	103	-0.61	0.12	0.84	0.03	0.93	0.87	0.20	668.50	<0.01
	age vs. crown length	103	-0.07	0.11	0.71	0.03	0.92	0.84	0.18	554.00	<0.01
	age vs. CPA	103	-1.47	0.24	1.69	0.07	0.93	0.87	0.39	665.30	<0.01
	age vs. crown volume	103	-1.54	0.27	2.40	0.08	0.95	0.91	0.45	1011.00	<0.01
	age vs. LAI	102	1.19	0.08	-0.12	0.02	0.46	0.22	0.14	29.04	<0.01
	age vs. biomass*	103	2.05	0.10	1.30	0.03	0.98	0.96	0.17	2194.00	<0.01
R. pseudoacacia	age vs. tree height	98	0.68	0.26	0.56	0.07	0.62	0.38	0.24	59.51	<0.01
	age vs. crown diameter	98	0.04	0.24	0.60	0.07	0.67	0.45	0.22	79.11	<0.01
	age vs. crown length	98	-0.37	0.26	0.75	0.07	0.73	0.53	0.24	107.70	<0.01
	age vs. CPA	98	-0.16	0.49	1.19	0.13	0.67	0.44	0.45	78.55	<0.01
	age vs. crown volume	98	-0.52	0.54	1.94	0.15	0.80	0.63	0.50	167.10	<0.01
	age vs. LAI	98	-0.96	0.43	0.38	0.12	0.30	0.09	0.42	9.91	<0.01
	age vs. biomass*	99	-3.55	0.21	2.70	0.06	0.98	0.96	0.20	2133.00	<0.01
T. cordata	age vs. tree height	108	0.30	0.13	0.60	0.04	0.85	0.73	0.21	287.20	<0.01
	age vs. crown diameter	108	-0.08	0.11	0.75	0.03	0.93	0.87	0.17	690.00	<0.01
	age vs. crown length	108	-0.84	0.17	0.80	0.05	0.86	0.74	0.27	313.50	<0.01
	age vs. CPA	108	-1.80	0.22	1.50	0.06	0.93	0.87	0.35	694.10	<0.01
	age vs. crown volume	108	-2.64	0.29	2.30	0.08	0.95	0.89	0.46	904.20	<0.01
	age vs. LAI*	108	-0.29	0.21	0.33	0.06	0.49	0.24	0.34	34.40	<0.01
	age vs. biomass*	108	-4.12	0.17	2.59	0.04	0.98	0.97	0.27	3331.00	<0.01

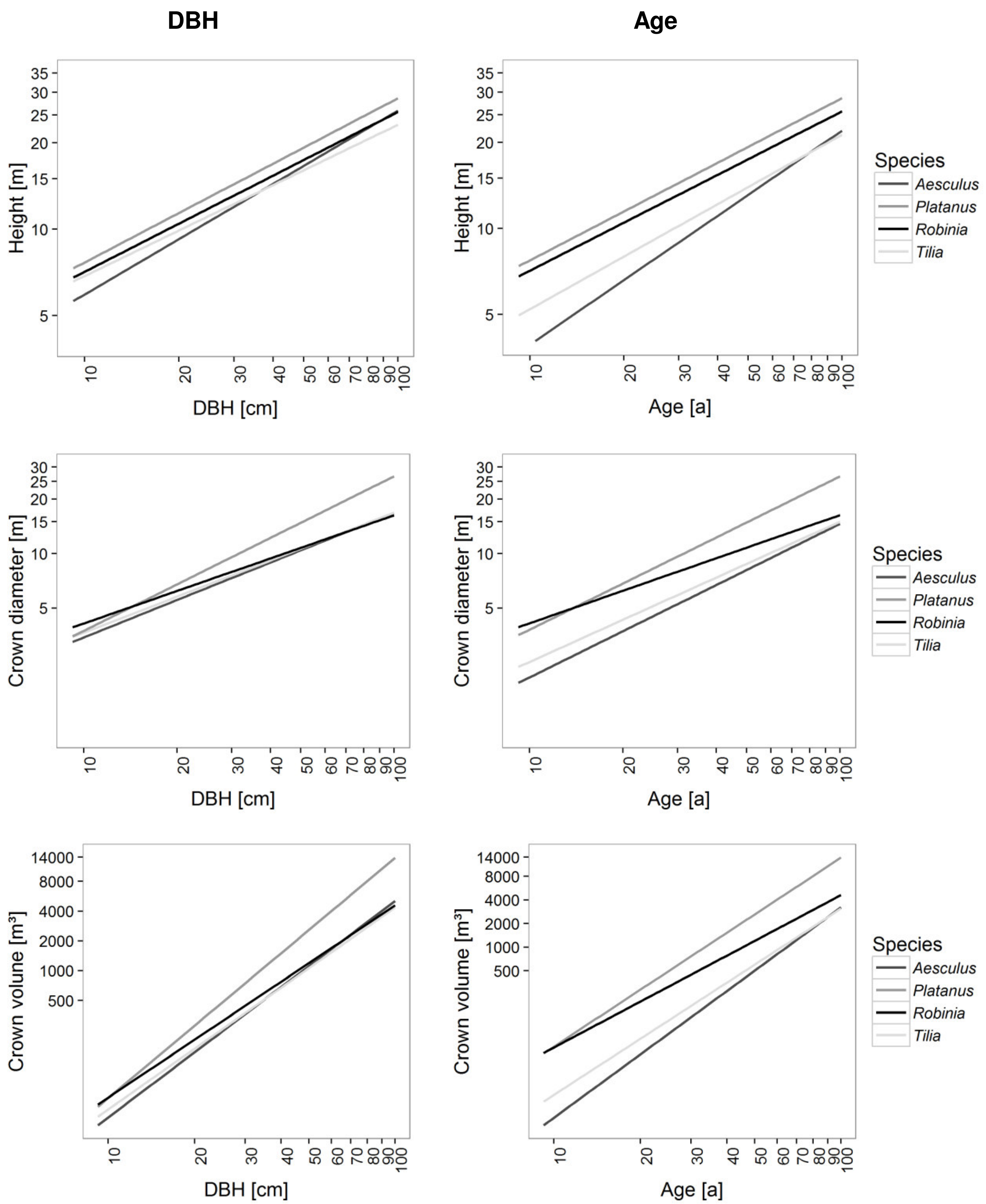


Figure 7: Comparison of the logistic linear regression of all studied species plotted for the response variables height, crown diameter and volume with DBH as predictor (left column) and age as predictor (right column). For the equation and values of the regressions, cf. tables 12 & 13.

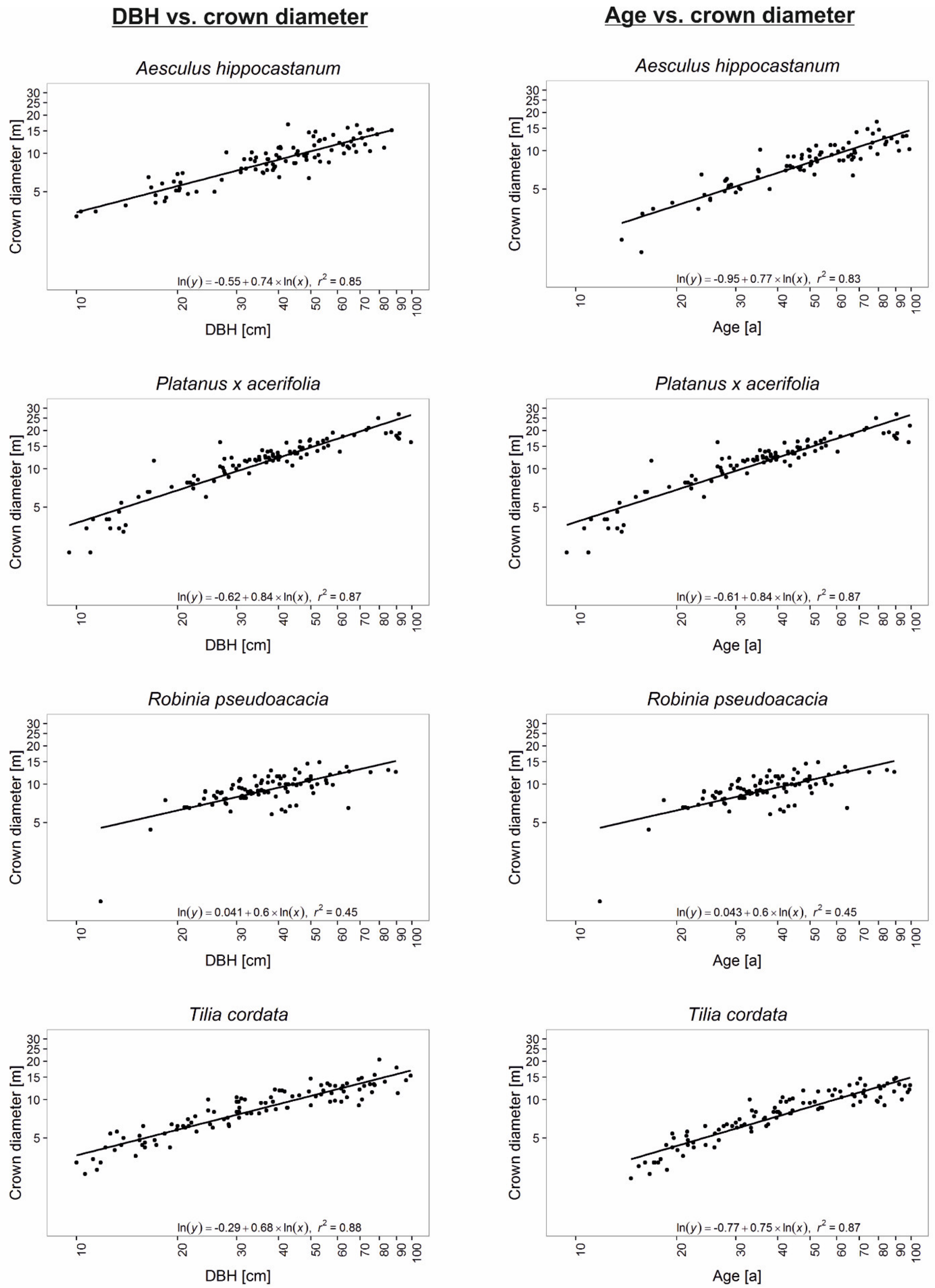


Figure 8: Allometric relationships between DBH and crown diameter (left column) and age and crown diameter (right column) for all four studied species. Cf. tables 12&13 for the exact values of the regression lines.

3.1.3 Influence of tree location

Statistical analysis of trees from different site types revealed that the growth site did have an influence on the dimensions, age and available superficial rooting space (inferred on from tree pit size) of the trees. These results are presented in table 14 and 15. The Kruskal-Wallis tests performed on the data often revealed highly significant differences ($p < 0.001$) between the three examined site types street, square, and park. In contrast, the results for the vitality comparisons showed no significance, except in the case of *T. cordata*. The analysis of two variables in *A. hippocastanum* (DBH, crown base) and three in *R. pseudoacacia* (crown diameter, CPA, crown volume, vitality) had p-values above 0.05, indicating no statistically significant difference between the sites. In the next paragraphs, the species-specific differences between the sites will be discussed in detail, excluding tree pit and crown base, as these are special cases and will be dealt with separately.

Due to autocorrelation, CPA and crown volume automatically showed a similar behaviour as crown diameter, because the calculation of the former involves the latter (cf. formulas 2 – 4). Additionally, a taller tree potentially has a larger crown volume if the CPA is not much smaller in relation (cf. formula 4. Lastly, total height, crown base and crown length are related parameters by nature, as they all concern stem growth allocation. Mathematically, crown length is the result of the relation of both other stem height variables (cf. formula 5). Lastly, age is connected to DBH, or DBH and height (cf. formulas 10 – 12).

Overall, the highest mean values of tree parameters were found in parks, followed by streets. The least favourable sites were squares. For example, the oldest trees were sampled in parks (mean age: 62.7 years), followed by streets (mean: 47 years), while those in squares were the youngest (mean: 39.5 years).

Across species, the order of magnitude park> street> square for all parameters is true for all species except *R. pseudoacacia*, which has a higher DBH, age, crown diameter and CPA in squares than in streets. Yet, the last crown parameter, crown volume, is higher in streets because the height of street *R. pseudoacacia* was found to follow the standard pattern park > street > square, resulting in higher crown volume values. Potentially, the better performance of *R. pseudoacacia* in squares is caused by the higher irradiation (as there are fewer other trees and often more reflective surface) and higher heat sums compared to streets, which the species prefers (Sitzia et al., 2016).

The mean vitality across all sites was between 0 and 1, indicating that the sampled trees were in good shape. Interestingly, however, the vitality was worst in parks, even though the best results were expected in this site as more rooting space is available and some urban stresses, such as heat stress caused by heat stored in sealed surfaces, should be negligible. However, park settings in Bayreuth commonly have dense tree stands, leading to a high competition for light and less physical space for the crowns. This may have led to a certain bias in the vitality rating of the trees, as the rating strongly depends on the crown structure (cf. figure 4). The suspicion of a bias in the sampled data is supported by the fact that Moser el al. (2015) found no significant difference in vitality across site types for *T. cordata* and *R. pseudoacacia*, which indicates that the sites plays no role in vitality.

For A. hippocastanum, growth in parks differed from streets and squares, while tree dimensions were not significantly different in streets and squares. This indicates that *A. hippocastanum* profited from a park setting, possibly due to its sensitivity to soil compaction and road salt, stressors which are less prevalent or absent in parks (Roloff, 2013). The only deviations from this pattern (in DBH and age) showed not statistically significant difference ($p = 0.325$, $p=0.023$), indicating that *A. hippocastanum* lived equally long in all sites, but grew better in parks.

The results of *P. acerifolia* show two principal patterns: a-b-a for age, DBH, height; and a-b-c for crown length, crown diameter, CPA, and crown volume. The a-b-a pattern indicates that London planes in the sample are similar in streets and parks. This could be due to the species' high resistance to urban stressors such as soil compaction and drought stress (Roloff, 2013), which enabled it to grow nearly equally well in streets as in parks. Nonetheless, there seemed to be some loss of performance in squares, the most stressinducing site. However, this may have also be caused by the large age difference between the individuals sampled in squares and the other locations (table 14), and is not necessarily a reflection of better growth conditions per se. Hence, these differences should not be over-interpreted, as *P. acerifolia* is the sample species with the highest sample spread across locations. For example, the mean DBH (and thereby nearly equivalently: age) goes from 27.1 cm (square) to 52.6 cm (park), leaving a margin of 25.5 cm (compared to *A. hippocastanum* 8.4 cm, *R. pseudoacacia* 13.8 cm, *T. cordata* 19 cm). The a-b-c pattern of crown length, crown diameter, CPA, and crown volume implies that the entire crown structure was very site-dependent. Parks were the most favourable location to crown growth, followed by squares. Lastly, London planes had the best overall vitality of all species with an average of 0.43, which is even below the general mean of 0.6.

R. pseudoacacia is the species with the least evidence for site-dependent growth. Nonetheless, the results that are significant (age, DBH, height and crown length), indicate that *R. pseudoacacia* grows similarly well in streets and squares, but both of these sites are different from parks. Moser et al. (2015) found the same pattern for *R. pseudoacacia* in terms of height, crown length, crown base and tree pit. In case of crown diameter, CPA and crown volume they found that all sites are different, while the study at hand found no significant differences.

Table 12: Results of the analysis of tree age, DBH, total height, height of the crown base and crown length by site. The number of trees in the test (n), mean, standard deviation and *p*-value are given for each species. If followed by different letters, mean values differ significantly (Kruskal-Wallis test, alpha=0.05 with Bonferroni p-value adjustment). For comparison with the total sample, mean and SD per site and overall are given.

Site		**n**	**Age [a]**			**DBH [cm]**			**Height [m]**			**Crown base [m]**			**Crown length [m]**		
			Mean		**SD**	**Mean**		**SD**	**Mean**		**SD**	**Mean**		**SD**	**Mean**		**SD**
			p = 0.023			*p = 0.325*			*p < 0.001*			*p = 0.059*			*p < 0.001*		
A. hippo.	Street	60	59.9	ab	28.7	42.3	a	19.5	14.3	a	4.9	3.3	a	1.3	10.9	a	4.7
	Square	20	53.6	a	33.5	39.1	a	21.5	12.4	a	5.8	2.7	a	0.6	9.7	a	5.6
	Park	22	79.1	b	34.6	47.5	a	19.7	19.5	b	6.3	3.8	a	1.6	15.7	b	5.9
			p < 0.001			*p < 0.001*			*p < 0.001*			*p < 0.001*			*p < 0.001*		
P. aceri.	Street	63	40.9	a	20.1	41.3	a	20.3	17.2	a	4.9	4.4	a	1.0	12.8	a	5.0
	Square	20	26.8	b	24.0	27.1	b	24.3	11.9	b	5.6	3.0	b	0.8	8.9	b	5.1
	Park	20	52.6	a	22.6	53.1	a	22.8	19.8	a	5.8	3.1	b	0.9	16.8	c	5.8
			p = 0.009			*p = 0.009*			*p < 0.001*			*p = 0.428*			*p = 0.002*		
R. pseudo.	Street	60	36.8	a	11.0	36.9	a	11.0	15.1	a	4.0	4.0	a	1.4	11.1	a	3.7
	Square	20	37.0	a	13.2	37.2	a	13.3	13.2	a	4.1	3.7	a	1.1	9.5	a	3.4
	Park	20	50.5	b	18.4	50.7	b	18.5	19.8	b	6.2	5.7	a	3.2	14.1	b	4.5
			p = 0.013			*p* = 0.038			*p = < 0.001*			*p* = 0.002			*p < 0.001*		
T. cordata	Street	68	50.4	a	30.1	38.5	ab	24.4	12.6	a	4.7	3.6	a	0.9	9.0	a	4.6
	Square	20	40.4	a	19.8	30.0	a	15.9	12.1	a	4.3	3.6	a	1.1	8.7	a	3.8
	Park	20	68.8	b	30.2	49.0	b	23.0	20.2	b	7.2	5.0	b	1.7	15.8	b	6.7
Mean/SD by site																	
	Street	251	47.0		22.5	39.7		18.8	14.8		4.6	3.8		1.2	10.9		4.5
	Square	80	39.5		22.6	33.3		18.7	12.4		4.9	3.3		0.9	9.2		4.5
	Park	82	62.7		26.4	50.1		21.0	19.8		6.4	4.4		1.9	15.6		5.7
Total mean			49.7		23.9	41.1		19.5	15.7		5.3	3.8		1.3	11.9		4.9

Hence, crown growth of *R. pseudoacacia* is more uniform in Bayreuth than in Wurzburg and Munich. Potentially, this has to do with city size and the subsequent size and shading capacity of buildings. Bayreuth, as a small city, is characterised by rather small buildings, while extremely large structures can be found especially in Munich, which might result in a more intense shading of street canyons. That *R. pseudoacacia* in squares perform similarly as in roadsides could be connected to the high drought stress and soil compaction tolerance of the species, which allows it to tolerate the disadvantages of square sites (Roloff, 2013; Sitzia et al., 2016). At the same time, street canyons might offer less light than squares and lead to photosynthetic limitations (Kjelgren and Clark, 1992), which is not ideal for a light-demanding species like *R. pseudoacacia*.

The results of *T. cordata* were dominated by an a-a-b pattern, indicating that the species had a similar growth in streets and squares, different from parks. Like in *A. hippocastanum*, this could be due to the species preference for less compacted or even loose soil (GALK, 2012), allowing it to prosper better in parks. As *T. cordata* was the only species with significant results in the vitality category, no comparison to the other species was possible. The vitality in parks was worse than in squares, street sites took an intermediate position.

Table 13: Results of the analysis of crown diameter, CPA, crown volume, tree pit and vitality by site. The number of trees in the test (n), mean, standard deviation and *p*-value are given for each species. If followed by different letters, mean values differ significantly (Kruskal-Wallis test, alpha=0.05 with Bonferroni p-value adjustment). For comparison with the total sample, mean and SD per site and overall are given.

Site		**n**	**Crown diameter [m]**			**CPA [m]**			**Crown volume [m³]**			**Tree pit [m²]**			**Vitality [0,1,2,3]**		
			Mean		**SD**	**Mean**		**SD**	**Mean**		**SD**	**Mean**		**SD**	**Mean**		**SD**
			p = 0.003			*p = 0.003*			*p = 0.003*			*p < 0.001*			*p = 0.672*		
A. hippo.	Street	60	9.0	a	3.5	73	a	54	998	a	1047	5.4	a	2.4	0.4	a	0.5
	Square	20	7.6	a	3.0	52	a	35	638	a	675	4.2	a	2.0	0.5	a	0.8
	Park	22	11.4	b	3.7	113	b	63	2016	b	1474	9.1	b	1.7	0.5	a	0.6
			p < 0.001			*p < 0.001*			*p < 0.001*			*p < 0.001*			*p = 0.554*		
P. aceri.	Street	63	12.2	a	3.5	126	a	66	1891	a	1725	4.1	a	1.4	0.1	a	0.3
	Square	20	8.4	b	6.4	86	b	116	1290	b	2207	2.9	a	2.4	0.2	a	0.4
	Park	20	15.8	c	5.5	218	c	143	4248	c	3708	7.9	b	2.2	0.3	a	0.6
			p = 0.401			*p = 0.419*			*p = 0.408*			*p < 0.001*			*p = 0.053*		
R. pseudo.	Street	60	9.1	a	2.1	69	a	29	818	ab	570	4.9	a	2.3	0.8	a	0.7
	Square	20	9.3	a	2.0	71	a	33	763	b	638	2.2	b	1.6	0.5	a	0.6
	Park	20	10.0	a	2.6	84	a	41	1204	a	692	9.1	c	1.0	1.0	a	0.9
			p = 0.018			*p* = 0.018			*p* = 0.018			*p* = 0.005			*p = 0.003*		
T. cordata	Street	68	8.3	a	3.8	65	a	54	773	a	933	4.3	a	2.6	0.4	ab	0.6
	Square	20	8.0	a	2.9	57	a	38	613	a	610	4.9	ab	2.6	0.1	a	0.3
	Park	20	10.9	b	3.5	103	b	69	1869	b	1644	6.7	b	3.0	0.8	b	0.7
Mean/SD by site																	
	Street	251	9.7		3.2	83		51	1120		1069	4.7		2.2	0.4		0.5
	Square	80	8.3		3.6	66		55	826		1033	3.6		2.2	0.3		0.5
	Park	82	12.0		3.8	130		79	2334		1880	8.2		2.0	0.6		0.7
Total mean			10.0		3.5	93		62	1427		1327	5.5		2.1	0.4		0.6

The small sample size in squares and streets, as well as a vitality rating bias towards bad ratings in parks, may have contributed to trees appearing to be in a better condition in squares rather than parks. Moser et al. (2015) found no statistically significant site differences in age, DBH, height, crown base, crown diameter, CPA and vitality for *T. cordata*. Considerable differences between street and park trees were found for crown length and tree pit ($p = 0.02$ and $p < 0.001$). Individuals planted in squares had crown heights similar to those of park and street trees. As in *R. pseudoacacia*, these results differ from the ones in Bayreuth. While in Munich and Wurzburg site had little influence on the growth of small-leaved lime, parks were more favourable to growth in Bayreuth. Possibly, this is related to the high average age of park trees in Bayreuth compared to the other two sites (68.8 years to 50.4 in streets at 40.4 in parks) leading to an overestimation of performance in parks, while the average age in the other cities was more uniform (park: 44, square 48, street 41).

In all species, the assumption that parks offer the most superficial rooting space was confirmed, as the tree pit was always largest in parks and smallest in squares, except in *T. cordata*, where the mean tree pit was smaller next to streets.

The height of the crown base is determined to a large extent by pruning measures usually implemented by the municipal administration and has little to do with the natural tree growth (Pauleit et al., 2002). Especially street trees need to leave enough space for vehicles (Dujesiefken et al., 2005). As a result of this, the average crown base height had a mean of 3.8 with a standard deviation of only 1.3 and was ignored in the analysis, as it tells little or nothing about the natural growth of urban trees.

Moser et al. (2015) critically remark that the older average age of the trees in parks may lead to an overestimation of the differences between the sites in terms of tree growth. A marked age difference between streets and squares on the one hand, and parks on the other hand, was found for both *T. cordata* and *R. pseudoacacia*. As a result, performance differences between site types may have been overestimated in these species. In case of *P. acerifolia*, the age of street trees is similar to park trees, leaving square trees as a separate category, while in *A. hippocastanum,* the age of street trees takes an intermediate position between the other two, but park trees are also markedly older.

As age is calculated partly or completely from DBH and no direct age measurement, e.g., taking drill cores, was performed, it can also not be determined if the trees in parks truly grew better, or if they simply were larger than in the other sites due to their high age.

Overall, it is not clear whether **Hypothesis 1**, “The site type (street, square, park) influences tree growth,” is true, since the effects of age and growth could not be clearly distinguished.

3.1.4 Ecosystem services

What are the effects of the climate change on growth of the trees? Unfortunately, the model currently is not able to directly answer this question, as there is no output on the growth of the tree dimensions that were calculated. Instead, it outputs only the resulting, changed ecosystem services provided by the species. Of course, these ecosystem services are based on the tree dimensions, potentially changed by climate change. Hence, the relative changes of tree dimensions can be inferred on.

Table 14: Yearly average ecosystem services cooling by evapotranspiration, carbon storage, and shading delivered per tree, by species, climate (current, B1 scenario, A1B scenario) and age. The given shaded area is the average per tree of the species on June 21. The change given is the change in percent from the current climate to the respective scenario.

Species	Age	Cooling by evapotranspiration [kWh/y]					Carbon storage [kg C/y]					Shading [m²/d]
		Current	B1	Change	A1B	Change	Current	B1	Change	A1B	Change	
A. hippo.	0 -30	4,271	3,892		3,718		14.8	17.3		17.8		29.7
	30-70	18,621	16,725		15,991		93.2	83.7		86.1		123
	70-100	39,518	35,133		33,608		235.2	186.4		191.9		261.3
	Mean	20,803	18,583	-11%	17,772	-15%	114.4	95.8	-16%	98.6	-14%	137
P. aceri.	0 -30	11,893	10,227		9,823		33.7	36.8		38		81
	30-70	59,959	51,333		49,353		70.3	76.4		78.9		328.8
	70-100	134,709	115,098		110,715		101.3	109.9		113.6		673
	Mean	68,854	58,886	-14%	56,630	-18%	68.4	74.4	+9%	76.8	+12%	358
R. pseudo.	0 -30	9217	7,779		7,501		23.9	26.2		27.1		85.3
	30-70	29,837	25,414		24,458		65	71		73.4		276.1
	70-100	53,467	45,817		44,039		108.1	117.6		121.4		504.3
	Mean	30,840	26,337	-15%	25,332	-18%	65.7	71.6	+9%	74	+13%	287
T. cordata	0 -30	5,171	4,668		4,457		9.2	10.3		10.6		64
	30-70	21,944	19,999		18,798		42.8	48.9		49.8		254.3
	70-100	45,610	41,796		38,948		92	106.4		107.9		514.7
	Mean	24,241	22,155	-9%	20,734	-14%	48	55.2	+15%	56.1	+17%	275

How did the species perform in terms of ecosystem services under the current and modelled climate? First of all, age had no influence on the relative order of magnitude of the ecosystem services attained by the species, i.e. if A. hippocastanum performed best when young (0-30 years) it also performed best when middle aged (30-70) compared to the other species.

T. cordata stores the least mean amounts of **carbon** (48 kgC), *P. acerifolia* and *R. pseudoacacia* nearly store the same amount (68.4 kgC and 65.7 kgC), across all scenarios. Most carbon is stored by *A. hippocastanum* (114.4 kg). When comparing these values to the tree dimensions calculated by allometric regressions in table 10, this order of species was to be expected as carbon storage is related to biomass and the sequence of species from large to small remains the same. ANOVA showed no significant differences between species (p = 0.342).

Now, to the future development of carbon storage. Under both future climate scenarios, the carbon storage ability of *A. hippocastanum* decreases (by -16% under B1, and -14% in A1B), but it still stores the highest total amount of carbon, with gains of +9 to +17%. Conversely, all other species store more carbon under both scenarios (+9 to +17%). In theory, the net primary production of trees increases up to a carbon concentration of about 700 ppm, where it reaches a point of saturation. With an increasing CO_2 concentration in the atmosphere, water use becomes more efficient as the stomata can remain more closed due to their high internal CO_2 partial pressure, and transpiration decreases (Pretzsch et al., 2015). However, 600 ppm, which is below the saturation point, were used in modelling the ecosystem services in this study, so a general increase could be expected. Possibly, *A. hippocastanum* suffers from the increase in temperature and potential drought stress due to its water demands being relatively higher than the ones of the other species (Roloff, 2013), leading to the necessity to close its stomata more often than the more drought resistant species, which in turn decreases its production.

P. acerifolia provides the highest average amount of **cooling by evapotranspiration** (cf. figure 10, table 16). *A. hippocastanum* and *T. cordata* deliver similar results, while the cooling ability of *R. pseudoacacia* is between these two and *P. acerifolia*. It is noteworthy that the amount of energy removed from the atmosphere by *P. acerifolia* is more than three times the one of *A. hippocastanum*, and double the one of *R. pseudoacacia*, whereby it outperforms all other species by far. ANOVA of the cooling under the current climate showed significant differences between the species (p= 0.005). When compared with TukeyHSD, the result showed that *P. acerifolia* is different from all other species.

Under both future climates, the amount of cooling is going to decrease in all cases, by -9% to -18%. Partly, this is due to the increase in water use efficiency leading to a decrease in transpiration, described above. The amounts of cooling achieved by *R. pseudoacacia* and *T. cordata* under the current climate are similar to the findings of Pretzsch et al. (2015) in Munich and Wurzburg, where black locust averaged 26,100 kWh/y (Munich: 29,747, Wurzburg: 20,633, Bayreuth: 30,840 kWh/y), and small-leaved lime 23,400 kWh (Munich: 26,713, Wurzburg 20,041, Bayreuth: 24,241 kWh/y). Cooling in Bayreuth was higher than in the other two cities on average, and overall closer to the values in Munich. Under the A1B1 scenarios (dry and wet) tested by Pretzsch et al. (2015), cooling for both species decreased, by up to 9,300 kWh. In Bayreuth, the most severe decrease is 12,000 kWh in P. acerifolia under A1B, but this is only relative change of 18% to the current climate, while 9,300 kWh is about one third to half of the original cooling value *T. cordata* achieved in Wurzburg. The effects in Munich were less pronounced, but a decrease in cooling was visible, too. Generally, the trees in Wurzburg reacted more strongly to climate change, as an average yearly temperature of up to 11.6 °C under A1B dry is expected, with only 552 mm yearly precipitation. Even under A1B, which is the more severe scenario, for Bayreuth only 9.0 °C are expected, and precipitation remains at 749 mm. (cf. table 5). Munich will have 11.8 °C under A1B dry, and 817 mm precipitation (Pretzsch et al., 2015). Hence, Bayreuth is the city that can expect the least severe consequences of climate change, which explains why the effect on the cooling ability of the trees is less pronounced: if the trees close their stomata due to heat stress, there is no transpiration, and if there is less water available, less transpiration is possible, too). Among species in Bayreuth, there are no large differences in the effect of climate change. *T. cordata* is least affected with relative decreases of -9% and -14%, followed by *A. hippocastanum*.

The **shaded** area per tree is championed by *P. acerifolia* (358 m²), followed by *R. pseudoacacia* (287 m²) *and T. cordata* with a similar value of 275 m². The smallest area (137 m²) is shaded by *A. hippocastanum*. Again, this modelled result was expected, as *P. acerifolia* generally reaches the largest dimensions and hence, blocks most direct sunlight. Also, the order of magnitude of shading of the other species mirrors the distribution of average crown volume (cf. table 10). Species differences were nearly significant (p = 0.092), TukeyHSD found differences between A. hippocastanum and P. acerifolia, due to the large difference between the values. The area shaded by *P. acerifolia* is more than double the one shaded by *A. hippocastanum*, probably caused by the big difference in crown diameter (cf. table 11). Moser et al. (2015) obtained a higher average shaded area for *R. pseudoacacia* (312 m²) and smaller value for *T. cordata* (246 m²). The model provides no climate-dependent output of shading, which is why this information cannot be shown.

As the model used to calculate the ecosystem services of the trees is based on these allometric calculations, it should be kept in mind that the measured ecosystem services provided by *A. hippocastanum* and *T. cordata* potentially are higher due to the sampling bias caused by uneven age distributions in age categories described in 3.2.2.

Overall, **Hypothesis 2**, "Tree growth and the associated delivery of the ecosystem services shading, cooling by evapotranspiration and carbon storage are species-specific," can be confirmed by the measured and calculated results and modelled ecosystem services. However, the differences were not statistically relevant in all cases.

Similarly, **Hypothesis 3**, “The responses of tree ecosystem services delivery (of shading, cooling by evapotranspiration and carbon storage) to climate change are species-specific,” can be confirmed, but only cooling by evapotranspiration showed statistical differences.

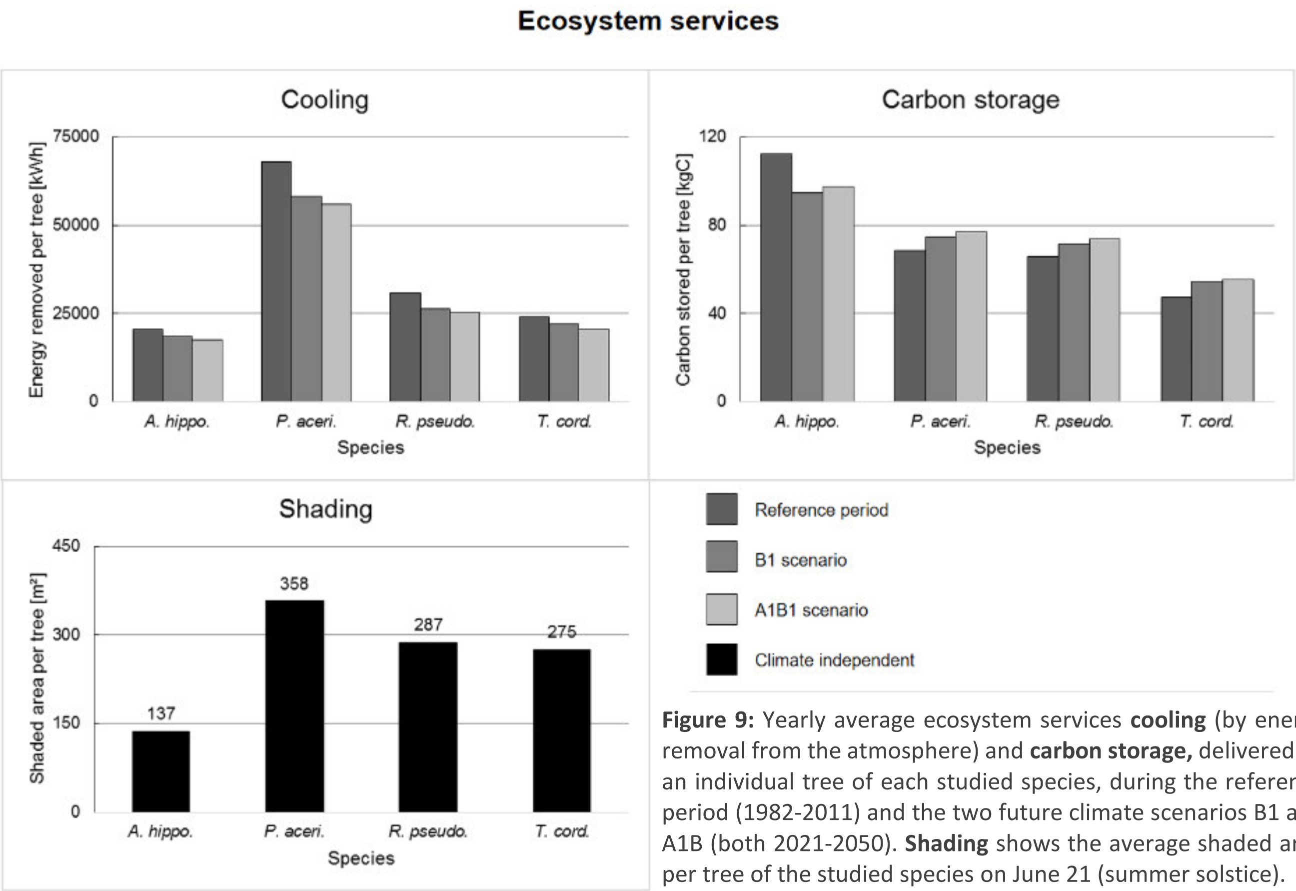


Figure 9: Yearly average ecosystem services **cooling** (by energy removal from the atmosphere) and **carbon storage,** delivered by an individual tree of each studied species, during the reference period (1982-2011) and the two future climate scenarios B1 and A1B (both 2021-2050). **Shading** shows the average shaded area per tree of the studied species on June 21 (summer solstice).

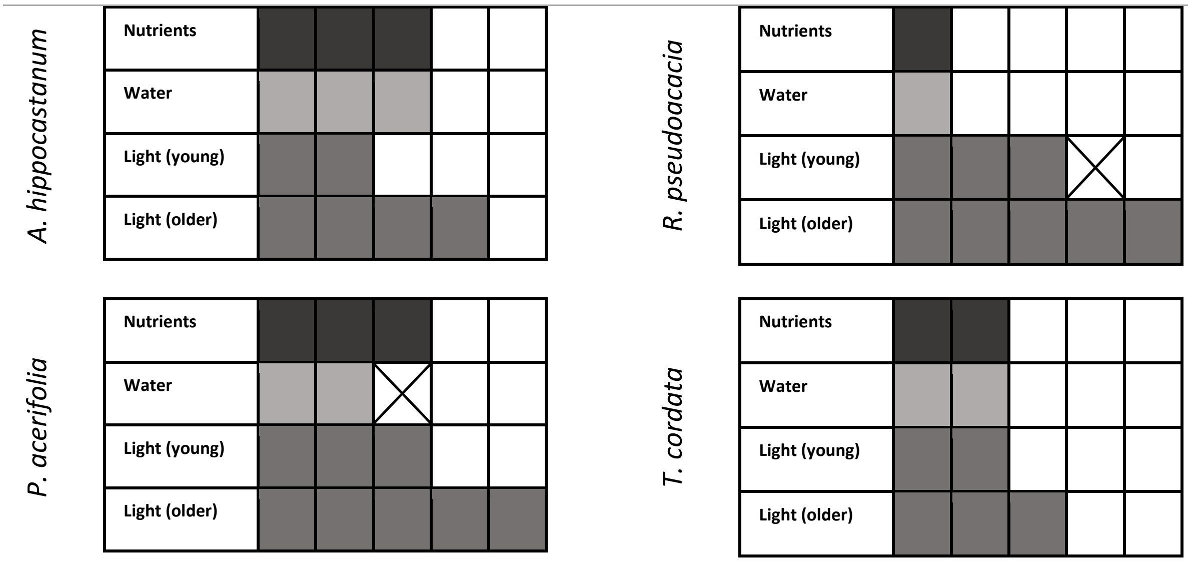
3.2 Species traits in theory: Literature research results

The general traits of the studied species as urban trees are summarised in table 7, which presents the main positive and negative aspects of each species and their demands as presented in the literature. In order to understand how these traits contribute to the suitability of the species as urban trees, first, a general overview over the species will be given, before comparing them in more detail in terms of light, water and nutrient demands, soil, climate, susceptibility to sicknesses and ability to recover from damage, health and safety and maintenance requirements, rating received in the literature. Where the literature had information on provisioning and cultural ecosystem services, these were assessed, too, to complement the quantitative assessment of regulating ecosystem services in this paper.

3.2.1 Growth

All species are fast growing when young and are therefore suitable to quickly create larger tree stands, even though the growth of *A. hippocastanum* and *T. cordata* becomes less rapid with age (Roloff, 2013).

Table 15: Demand rating of the studied species. Roloff (2013) evaluated species according to their demands in terms of nutrients, water and light on scale from 1 to 5: 1 = very low, 2= low, 3= moderate, 4= higher, 5= very high, represented by the boxes. Crossed boxes signify ranges, e.g. 3-4. Also see 3.1.2.



3.2.2 Light, water and nutrient demands and soil requirements

As established in the introduction, a good city tree is an undemanding tree. The nutrient, water and light demands of the trees will be evaluated according to Roloff's (2013) tree demand rating (cf. table 8), which ranges from 1 – 5 (1 = very low, 2= low, 3= moderate, 4= higher, 5= very high demands).

As the light demand of all trees increases with age, the table differentiates between younger (0 – 10 or max. 20 years) and older trees of the species (Roloff, 2013). *T. cordata* is a shade tolerant species and hence has the lowest light demands of all studied species (2 when young, 3 when older). *A. hippocastanum* has a low light demand when young as well (2). However, when the tree grows older, it needs a free crown on at least one side, leading to a light demand rating of 4. *P. acerifolia* and *R. pseudoacacia* are the most light-demanding, with a rating of 5 when old and 3 or even 3-4 in the case *R. pseudoacacia* when young. A high light demand can be useful in the city, as shade species may suffer from sunburn because of the large amounts of radiation in urban areas (Roloff, 2013). However, it may also be a hindrance when the planting site is a park with dense tree stands, or an urban canyon with buildings shading the planting site, where not much light may be available. Also, if planted as a street tree, *P. acerifolia* tends to grow towards the brighter centre of the street, as it is a light demanding species (GALK, 2012). This can cause problems with traffic safety. In summary, the tree site needs to suit the light demands, making *A. hippocastanum* and *T. cordata* more suitable for partly shaded sites, and *P. acerifolia* and *R. pseudoacacia* for sites with intense irradiation.

The water and nutrient demands differ between species. *A. hippocastanum* has medium nutrient (3) and water (3) requirements, making it the most demanding among the studied species. The next most nutrient and water intensive tree is *P. acerifolia* (3 and 2-3). *T. cordata* needs less nutrients and water (2 and 2) but is still outperformed by *R. pseudoacacia,* with a rating of 1 and 1.

Road salt and soil immissions are problematic for *A. hippocastanum* and *T. cordata* as the leaf margin turns brown on soils with these conditions. They prefer open, uncompacted soil, while the other two species tolerate these stressors well. Nonetheless, all species can grow on a whole range of soil types, and even poor (*R. pseudoacacia*), very compacted (*P. acerifolia*) or waterlogged (*T. cordata*) soils (cf. chapter 1.5).

Considering the overall water and nutrient demands and soil requirements, *P. acerifolia* and *R. pseudoacacia* can be planted in any urban location, while the other two species are less suited for larger roads due to the increased traffic emissions and amounts of road salt used. When the water and nutrient requirements are also considered, this leads to the conclusion that *R. pseudoacacia* can be planted in any urban location, except on very nutrient rich soils (as these lead to instability, cf. chapter 1.5). *T. cordata* is also suitable for most locations, except next to large roads, due to its salt intolerance. *P. acerifolia* can tolerate drought, but requires moderate amounts of water, which leads to an ambivalent picture. Possibly, sites where acute and not chronic drought occurs are suitable. *A. hippocastanum* is suited for parks, yards, beer gardens and green pedestrian areas, rather than squares, parking lots and other very dry sites with large amounts of sealed area as the species is less drought tolerant.

3.2.3 Climatic requirements

R. pseudoacacia and *T. cordata* have a high drought stress tolerance, making them well-suited for urban environments. *P. acerifolia* also has a good a drought stress tolerance, but in recent years it has been suffering from the so called “Massaria” disease caused by the fungus *Splanchnonema platani*, which is thought to infest London plane trees weakened by acute or chronic drought. It occurs especially often on hot, sealed, dry sites and leads to the partial or complete die-off of branches and soft rot (Roloff, 2013). That means even if *P. acerifolia* tolerates the primary, climatic consequences of drought, it may suffer secondary damage from *Splanchnonema platani*. However, *T. cordata* also suffers secondary heat and/or drought damage through *Eotetranychus tiliarius* due to similar reasons (cf. 3.1.3).

A. hippocastanum only has a moderate drought stress tolerance. However, it has a very dense crown, which leads to an intense cooling effect. *R. pseudoacacia*, on the other hand, is susceptible to late frost (Roloff, 2013) and, according to Sitzia et al., 2016 prefers sub-Mediterranean to warm continental climates and requires high heat-sums.

When assessing the studied species based on their climatic requirements, *R. pseudoacacia* and *T. cordata* appear to be most suitable, as they seem least prone to suffer from a future warmer, drier climate and the already heat-prone urban environment, as *A. hippocastanum* generally has a lower resistance to drought, and *P. acerifolia* may suffer intense secondary drought damages. The frost hardiness of all studied species are sufficient for Bayreuth, as *P. acerifolia* and *R. pseudoacacia* can tolerate up to -25°C, the other two species even -35°C. The lowest monthly average temperature of Bayreuth in the reference period is -7.0 °C (DWD, 2016).

Table 16: Criteria for the suitability of the species *A. hippocastanum, P. acerifolia, R. pseudoacacia* and *T. cordata* as city trees (GALK street tree list, 2012; Roloff, 2013, Wojda et al., 2015). Ecosystem services were only listed if exceptional.

Trait	***A. hippocastanum***	***P. acerifolia***	***R. pseudoacacia***	***T. cordata***
Growth	+ fast when young	+ fast	+ fast	+ fast when young
Soil demands	+ undemanding, prefers fresh, open soil - sensitive to soil compaction & road salt	+ undemanding	+ undemanding - avoids wet and compacted soils	~ undemanding but prefers fresh, open soil - sensitive to road salt + can tolerate water
Resistance to urban climate	~ moderate drought stress tolerance	+ good - may suffer secondary drought damage	+ very good + very good drought stress tolerance	+ good resistance to high temperatures + very good drought stress tolerance
Susceptibility to disease and damage	- horse chestnut leaf miner, *Pseudomonas syringae* pv. *aesculi*. - weak reiteration propensity & compartmentalisation	+ very strong compartmentation - Massaria (*Splanchnonema platani*) - plane wilt /canker stain disease (*Ceratocystis fimbriata f. platani*)	~ moderate reiteration & compartmentalisation	+ resistant to illnesses/damage + very strong reiteration & compartmentalisation - young trees susceptible to sunburn
Health or safety risks or risk avoidance	none reported	- moderate health risk (hairs from leaves/fruit irritate respiratory tract)	- susceptible to windthrow on nutrient-rich soils - fruits poisonous - thorns	+ stable branches
Maintenance requirements, practical consider-ations	- very dark below crown - fruits and leaves need to be cleared from ground	- grows side roots near soil surface (can cause root lift) - tendency to grow crookedly, towards street - oozes honeydew	- grows spiny root sprouts (intense self-dispersal) - formation of deadwood in advanced age	- oozes honeydew (through coccidae & aphids) - intense formation of stem buds
Aesthetic and cultural value	+ attractive florescence, bark and leaves + popular with children (seeds as toys) + traditional in Bavaria - aesthetic problems due to leaf miner infestations	+ attractive bark + crown also attractive in winter thanks to hanging seeds	+ attractive florescence	+ fragrant florescence + traditional tree in Europe
Provisioning ecosystem services	+feeds bees and bumblebees	none reported	+ important honey plant	+ important honey plant
Regulating ecosystem services	+ strong cooling effect of dense crown	+ filters air pollutants	none reported	none reported
Frost hardiness *GALK rating* *KLAM rating*	-35°C (zone 4) suitable with limitations 3.2	-25°C (5a) suitable with limitations 1.2	-25°C (5a) suitable 1.1	-35°C (4) suitable with limitations 2.1

3.2.4 Susceptibility to disease and ability to recover from damage

The studied species were also evaluated with respects to their ability to reiterate and propensity to compartmentalise. “Reiteration” is the ability of a tree to adjust itself to its environment by modifying its architecture, often by activating resting apical meristems to grow new branches (Hallé et al., 1978). Compartmentalisation, on the other hand, is a process by which boundaries are formed to isolate injured tissues, a defence mechanism to avoid the spread of pathogens in the tree (Shigo, 1984). Both of these abilities can help trees recover from physical damages.

A. hippocastanum only has a weak tendency to reiterate and cannot compartmentalise wounds easily. The most infamous leaf-damaging insect in Bavaria probably is the horse-chestnut leaf miner, which causes strong aesthetic issues in *A. hippocastanum*, and may lead to a reducing shading ability. Similar to Massaria in *P. acerifolia*, there also is a potentially deadly pest targeting horse chestnut in Germany, the bacterium *Pseudomonas syringae* (Glynn et al., 2011; Roloff, 2013).

P. acerifolia, in contrast to *A. hippocastanum*, has a very strong propensity to compartmentalise, which can be especially useful if the tree suffers mechanic damage, for example from road traffic or construction (which are both plausible scenarios in urban areas) (GALK, 2012; Pauleit, 2012, Roloff, 2013). As stated in 3.1.2, *P. acerifolia* suffers from *Splanchnonema platani* infestations. Moreover, it is endangered by the fungus *Ceratocystis fimbriata* f. sp. *platani,* which is potentially deadly to the tree currently only in the neighbouring countries of Germany (United Kingdom Forestry Commission, 2015). Also, London planes are the target of sycamore lace bug *Corythucha ciliate* which damages the leaves and can lead to the secretion of honeydew, rendering the tree less suitable for traffic areas (Glynn et al., 2011; Roloff, 2013).

R. pseudoacacia only shows a moderate ability to reiterate and compartmentalise (Roloff, 2013). In terms of diseases, there does not seem to be a large threat in Germany. The literature on the species does mention different pests that target this species in Germany (cf. chapter 1.5), but none of them is described as the cause of severe problems.

T. cordata is a very stable, sickness- and damage-resistant tree. It recovers well from damage as its reiteration and compartmentalisation capacity are high (Roloff, 2013). As explained in 1.5, the species is the target of some pests. Under climate change, the lime mite *Eotetranychus tiliarius* probably is most interesting as it causes damage to the leaves and early leaf fall in dry, inner cities sites, and due to warm and arid spells. *T. cordata* is known to ooze honey dew on parked cars and bicycles, mostly caused by aphids.

Overall, *R. pseudoacacia* and *T. cordata* perform best with regard to susceptibility to disease and ability to recover from damage. Both are not targeted by severe diseases and pests, and *T. cordata* additionally recovers well from damages. *P. acerifolia* may also recover well from physical damages, but is threatened by a multitude of diseases.

3.2.5 Health and safety risks and maintenance requirements

All species have certain practical limitations. Firstly, *P. acerifolia* is a potential health risk in direct contact as both the leaves and fruits of are covered with fine hair that can can irritate the respiratory tract of humans. Also, it can cause the uplift of roads and sidewalks as the tree forms shallow lateral roots (GALK, 2012).

R. pseudoacacia is thorny, the seeds are poisonous (not suitable for planting next to kindergartens and playgrounds), it forms spiny root sprouts, becomes unstable on nutrient-rich soils, forms larger quantities of deadwood when older and, most importantly, disperses itself intensely and is extremely invasive. The species is counted among the 100 most invasive alien species in Europe (GALK, 2012; Roloff, 2013; Sitzia, 2016).

All species form stem buds in good light conditions, but in *T. cordata* the formation is very intense in all light conditions, making work-intensive removal necessary. The seeds of both *T.* cordata and *A. hippocastanum* have to be removed from the ground and the size of the conkers of horse chestnut make the tree unsuitable for planting directly next to streets. Additionally, horse chestnut leaf miner can only be controlled by a work-intensive, complete removal of dead foliage from the ground (GALK, 2012; Roloff, 2013).

R. pseudoacacia performs worst with regards to health and safety risks and maintenance requirements, as it leads to many nuisances. There are *R. pseudoacacia* varieties which are less prone to form root sprouts, but that still leaves the tree with other issues, such as poisonous fruits (Roloff, 2013).

Except for the necessary leaf and fruit removal, *P. acerifolia* appears to be the least maintenance intensive tree, but can cause respiratory problems, especially during the pruning process (GALK, 2012, Roloff, 2013), while *T. cordata* is slightly more work intensive, but otherwise causes little problems. *A. hippocastanum* requires yet more maintenance than *T. cordata* due to the necessary fruit removal and problems with the horse chestnut leaf miner. In many cities, *Aesculus x carnea* as an alternative by now, as it is more resistant to the pest (Roloff, 2013).

3.2.6 GALK and Roloff Rating

As the GALK rating is focused on street trees, it is applicable to the high number of street trees in Bayreuth. However, Roloff's rating is also taken into consideration for the park and square sites to get a more comprehensive overview for the species suitability in urban areas. The GALK rates three species "suitable with limitations" for street tree use, and *R. pseudoacacia* even "suitable", while the Roloff's KLAM rating gives a more differentiated picture for the general use as urban trees. *R. pseudoacacia* receives the best score 1.1 (very well suited), *P. acerifolia* second with 1.2 (very well suited), *T. cordata* is rated 2.1 (well to very well suited) and *A. hippocastanum* comes last with 3.2 (suited with limitations) (cf. figure 7). Judging solely from the overall rating by GALK and Roloff, *R. pseudoacacia* is the most suitable urban tree, followed by *P. acerifolia*, *T. cordata* and last, *A. hippocastanum.*

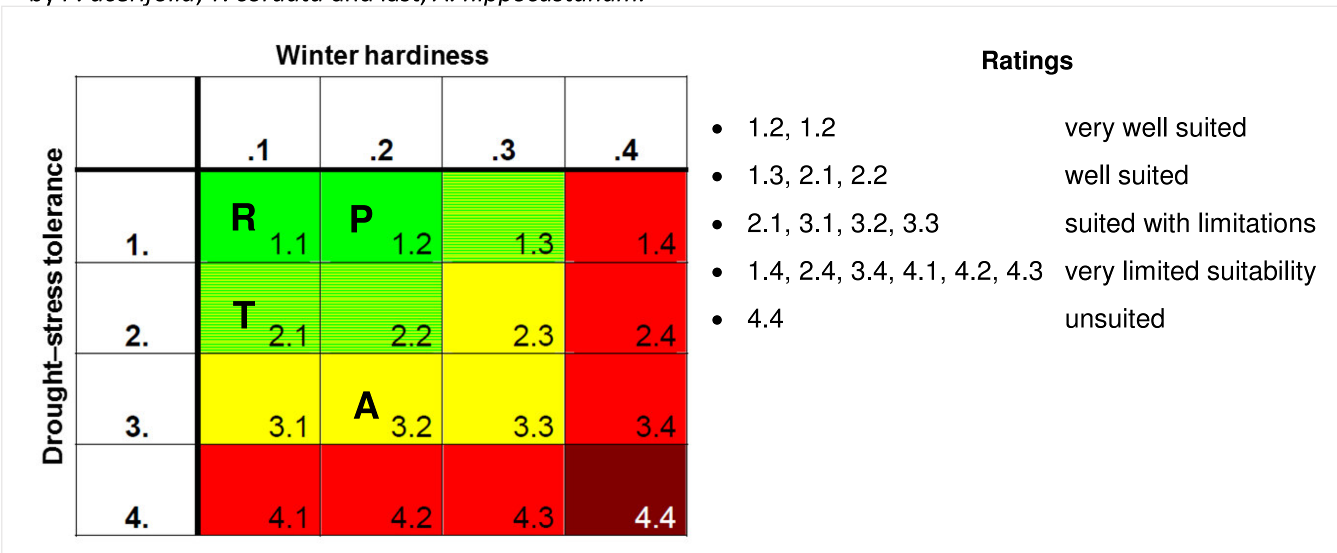


Figure 10: KLAM diagram ratings of the studied species (modified after Roloff, 2013). Abbreviations for the studied species were added: A= *A. hippocastanum*, P. = *P. acerifolia*, R. = *R. pseudoacacia* and T = *T. cordata*.

3.2.7 Ecosystem services and aesthetic value

Potential tree ecosystem services can be regulating (e.g., carbon sequestration, micro-climate regulation (shading, cooling by evapotranspiration), reduction of stormwater runoff, as estimated in this paper), provisioning (habitat or food), and cultural and aesthetic. Furthermore, they may reduce noise, serve as a habitat for birds, insects and other animals, absorb air pollutants, and provide aesthetic value to the city, as well as cultural services (Bolund et al., 1999; UK National Ecosystem Assessment, 2011).

As the sources did not directly describe the ecosystem services of the species, they can only be inferred. For example, both *A. hippocastanum* and *T. cordata* were described as forming large crowns, which should lead to a good ability to shade and cool. Both species also have cultural significance, as stated in 3.1.4. All three honey plants among the species (*A. hippocastanum, T. cordata,* and *R. pseudoacacia*) also serve as a source of food for honey insects, and the wood and leaves of the species feed different insects and fungi,

thereby contributing to biodiversity and serving as habitat (Roloff, 2013). No assessment of species performance in terms of these ecosystem services will be conducted, as there was no species-specific information available.
However, all species are characterised by definite positive particularities. The species *A. hippocastanum* and *R. pseudoacacia* are described as visually very attractive thanks to their inflorescence, while both *A. hippocastanum* and *P. acerifolia* carry appealing fruits. *P. acerifolia* in turn has a distinct bark structure and keeps its decorative fruits in winter. *T. cordata* is visually the least noticeable tree, but has fragrant flowers that feed bees and bumblebees. *A. hippocastanum* and *R. pseudoacacia* are honey plants, too. Culturally, *A. hippocastanum* plays a big role in Bavaria, as it is the traditional beer garden tree and the conkers are extremely popular among children, while lime trees generally have a large cultural significance in Europe, for example as central meeting points. The dense crown leads to intense shading which can be perceived as either very dark or providing pleasant shade by city residents (GALK, 2012; Roloff, 2013).
As *R. pseudoacacia* is not the only honey plant among the species, it is not distinguished by this feature. Additionally, it brings certain disservices with it, like the allelopathic influence it has on its surroundings, which may reduce biodiversity (Wojda et al., 2015). Its capacity to enrich the soil with nitrogen can both be positive or negative, depending on the context. For example, in an environment characterised by species growing on poor soils, it may be detrimental to biodiversity, while it may create habitat for other species in its role as a pioneer species in other cases. Due to their ecological and cultural benefits, *A. hippocastanum* and *T. cordata* can be assessed as quite positive in this category. *P. acerifolia* has least added value, but also no disservices (like *R. pseudoacacia*).

3. Conclusion: Synthesis of theoretical and measured species traits

Based on the criteria established in 1.6, a final recommendation on which tree(s) to use and why will be given.

1) **Habitat demands** – a good future city tree will require little water and nutrients and thrive on a wide range of soils;

The species that fulfils all of these conditions is *R. pseudoacacia*. No other species is less demanding in terms of water and nutrients and can tolerate very poor soil conditions due to its ability to fix nitrogen (cf. chapter 3.2). When also taking light demand into consideration, the requirements of *T. cordata* were described as lowest. However, *R. pseudoacacia* did not show site-dependent growth differences in Bayreuth, possibly due to the low elevation of the buildings and subsequent lower shading, which reduces the importance of light demands in this particular city. Hence, *R. pseudoacacia* is best suited for dry, ideally open areas with high amounts of radiation, irrelevant of site type.

Nonetheless, *T. cordata* should be considered for darker, potentially wet settings away from large streets. This is because it can tolerate adverse soil conditions related to water, such as waterlogging, which *R. pseudoacacia* avoids. Lastly, *T. cordata* is susceptible to road salt, making it better suited for parks, squares or smaller streets.

Both other species have higher demands in terms of nutrients and water. The light-demanding nature *of P. acerifolia* also loses in importance in light of the results of the findings on *R. pseudoacacia*. It is the least demanding species in terms of soil, making it the third best urban tree for Bayreuth. It grows best in parks and similarly well in both other site types.

As *A. hippocastanum* additionally neither tolerates de-icing salt nor compaction, it is least suitable in this category. However, it grows well in unsealed settings and hence is a good park tree.

2) **Climate endurance** – good city trees will withstand current and future urban climatic conditions

The tree most suited to urban stressors, namely drought and heat stress, is *R. pseudoacacia*. It was the only species in which growth was not significantly negatively influenced by the extreme conditions prevalent in squares (cf. chapter 3.1). An intensification of these stressors under climate change, as simulated by the climate scenarios WETTREG A1B and B1, had a similar effect on all species in the model. After R. pseudoacacia, *T. cordata* suffered the least relative decrease in ecosystem services under climate change, making it the species most resistant to future challenges. Also, it has a good resistance to both drought stress and high temperatures, which is why it is classed second best suited in this category. The same tolerance to heat and drought is described for *P. acerifolia*, but this positive assessment from the literature is qualified by secondary drought damage the tree may suffer through *Splanchnonema platani*. The least suitable species in this category, *A. hippocastanum* was described to only have a moderate drought stress tolerance, which manifested in its decreased carbon storage under climate change, owing to the rise in temperatures. As all species were found suitable in terms of frost hardiness, it is not a deciding factor in this category. However, *A. hippocastanum* and *T. cordata* are more frost tolerant (up to -35°C) than *P. acerifolia* and *R. pseudoacacia* (up to -25°C), which may be relevant for extreme frost events under climate change.

3) Ecosystem service delivery – a good city tree will deliver a range of ecosystem services (across its lifespan and in a range of climatic conditions)

P. acerifolia clearly provides the largest amount of cooling and shading, making it *P. acerifolia* the number one, especially when climate change adaptation is the goal, as these ecosystem services for example directly counteract the negative effects of hot days. Additionally, it was described as able to filter air pollutants in the literature. The other three species performed very similar in the modelled ecosystem services, as *A.*

hippocastanum is best at storing carbon but worst at shading and cooling, while the other two species take the middle places with mean values close together. The strong cooling effect of the dense crown of *A. hippocastanum* described in the literature could not be confirmed empirically in this study, though it may still be high compared to other tree species. As *A. hippocastanum*, *R. pseudoacacia*, and *T. cordata* all deliver the provisioning service of being honey plants, no differentiation is possible either. Yet, what can be concluded is that if the desired effect of planting urban trees is climate change mitigation, *A. hippocastanum* is best suited among the species, due to its high capacity to store carbon.

4) Practical and added value – a good future city tree will have high safety and low maintenance requirements, a high aesthetic value and as many other benefits (such as cultural relevance) as possible

Judging from the literature, *A. hippocastanum* is a less maintenance intensive species, and provides the most aesthetic and cultural values, unless infested with the horse chestnut leaf miner, which leads to additional maintenance requirements. In case of problems with this pest or the even worse, *Pseudomonas syringae* pv. *aesculi* in the area, *T. cordata* becomes the number one in this category due to its robustness, fragrance and traditional role in European culture. *P. acerifolia* does not require large amounts of maintenance, but can be harmful to the arborists during the process due to its hairs. Additionally, it has no tradition in Germany or beautiful florescence, and can be the target of two diseases that can make it unsafe (Massaria and canker stain disease). *R. pseudoacacia* has an attractive florescence, but other than that it causes a long list of problems: It is invasive, tends to disperse itself, has poisonous fruits, grows spiny root sprouts and is susceptible to windthrow. Additionally, it may unwantedly transform habitats and decrease biodiversity due to its allelopathic effect. As all species showed similar growth speeds, this factor did not play into the evaluation of their practical value.

Finally, the last hypothesis, **Hypothesis 4**: "The benefits of one studied tree species and its ability to thrive in urban sites surpass the benefits of the others, making it the most suitable tree for Bayreuth, according to the "good urban tree" criteria established before," is refuted. There is not one single tree better than all others, but the best species depends on the reason for planting the tree(s). If an undemanding or climate prove tree is desired, it should be *R. pseudoacacia*. If it is about aesthetic and cultural value, the choice is *A. hippocastanum*. If a robust tree is desired, the choice is *T. cordata*. For climate adaptation, *P. acerifolia* is best suited, for climate mitigation*, A. hippocastanum*.

The knowledge gained in this study can aid the planning authorities in making such choices, as they provide insight on the space and site requirements and the ecosystem services of the four studied species.

4. Outlook

The knowledge about the structural parameters and ecosystem services of the four species gathered in this thesis can be the base for planning and management of urban inventories (Pretzsch et al., 2015a). There are several ways the research conducted on tree growth and ecosystem services conducted in this study and in the CityTrees project could be expanded:

To fit the knowledge about urban trees to the needs of Bayreuth, it would be beneficial to perform a study on the tree genera that are actually most common in the city. This study would have to sample and analyse data of *Acer* spp., *Quercus* spp. and *Carpinus* spp.. For *Tilia*, the second most common genus in the city, the results of the study at hand could be used if the new study takes place soon (in order to keep the shifts caused by the temporal difference of sampling as little as possible).

Another possibility would be to widen the geographic scope of the CityTrees project, for example by including other German federal states or provinces of neighbouring countries with a similar climate, for example Austria or the Czech Republic. Additionally, a comparison of different study cities like the one of Wurzburg and Munich (Moser et al., 2015) could be expanded to include the newer cities Bayreuth, Hof, Kempten im Allgäu and Nuremberg. Possibly, the collected data could be used to generate tools like the ones published by USDA Forest Service in their “i-Tree” project (www.itreetools.org). The i-Tree tools allow forestry analyses on an urban scale and are mainly intended for use by communities, in order to help them manage their trees. The i-Tree tools can quantify both present and future structure, risk and environmental services of trees. Hence, the information they provide to end users is similar to that which the CityTrees project is aiming to collect. The great benefit is that i-Tree is free to use and therefore, widely available. However, it is currently US-based, involving North American urban tree species. Hence, a similar tool could be developed for Germany or even Europe.

Generally, it would also be possible to include more species in the CityTrees project, in order to be able to model a diverse urban forest. This would of course also involve developing the model to be able to include different species at the same time, and to represent the geographical features of a city. Probably a more urgent step in developing the model would be to enable it to provide an output of the climate-dependent calculated tree growth. The most popular urban tree species on a European scale that are also planted in Germany are horse chestnut, ash, plane, maple, oak and lime (*Aesculus* spp., *Fraxinus* spp., *Platanus* spp., *Males* spp., *Quercus* spp., and *Tilia* spp.) (Pauleit et al., 2002) Hence, if aiming to extend the research to a larger geographical scale, it could make sense to extend the scope of the CityTrees study to include all of the above.

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Title images:

From top left to bottom right:

Unknown artist (1904). Aesculus hippocastanum. In: Meijer, B. (Ed.) *Nordisk Familjebok Konversationslexikon Och Realencyklopedi*. Stockholm. Retrieved from: http://runeberg.org/nfba/0118.html, September 20, 2016.

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Step, E. (1895).Plate 136, *Robinia pseudoacacia.* In: *Wayside and woodland blossoms; a pocket guide to British wild flowers for the country rambler*. This edited version has been paper-masked for better colour restoration.

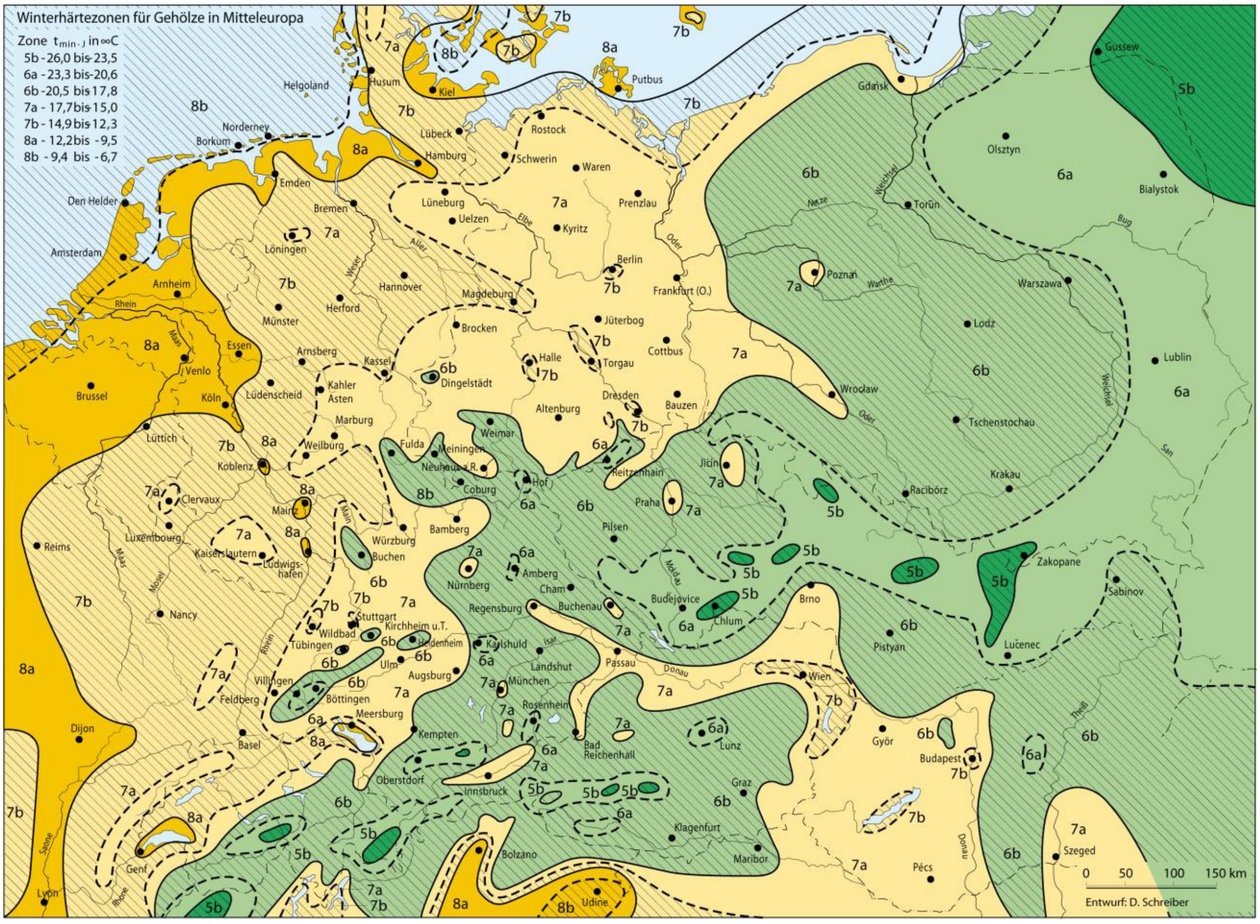
Step, E. (1895).Plate 133, *Tilia parvifolia* (*Tilia cordata*). In: *Wayside and woodland blossoms; a pocket guide to British wild flowers for the country rambler*. This edited version has been paper-masked for better colour restoration

Appendices

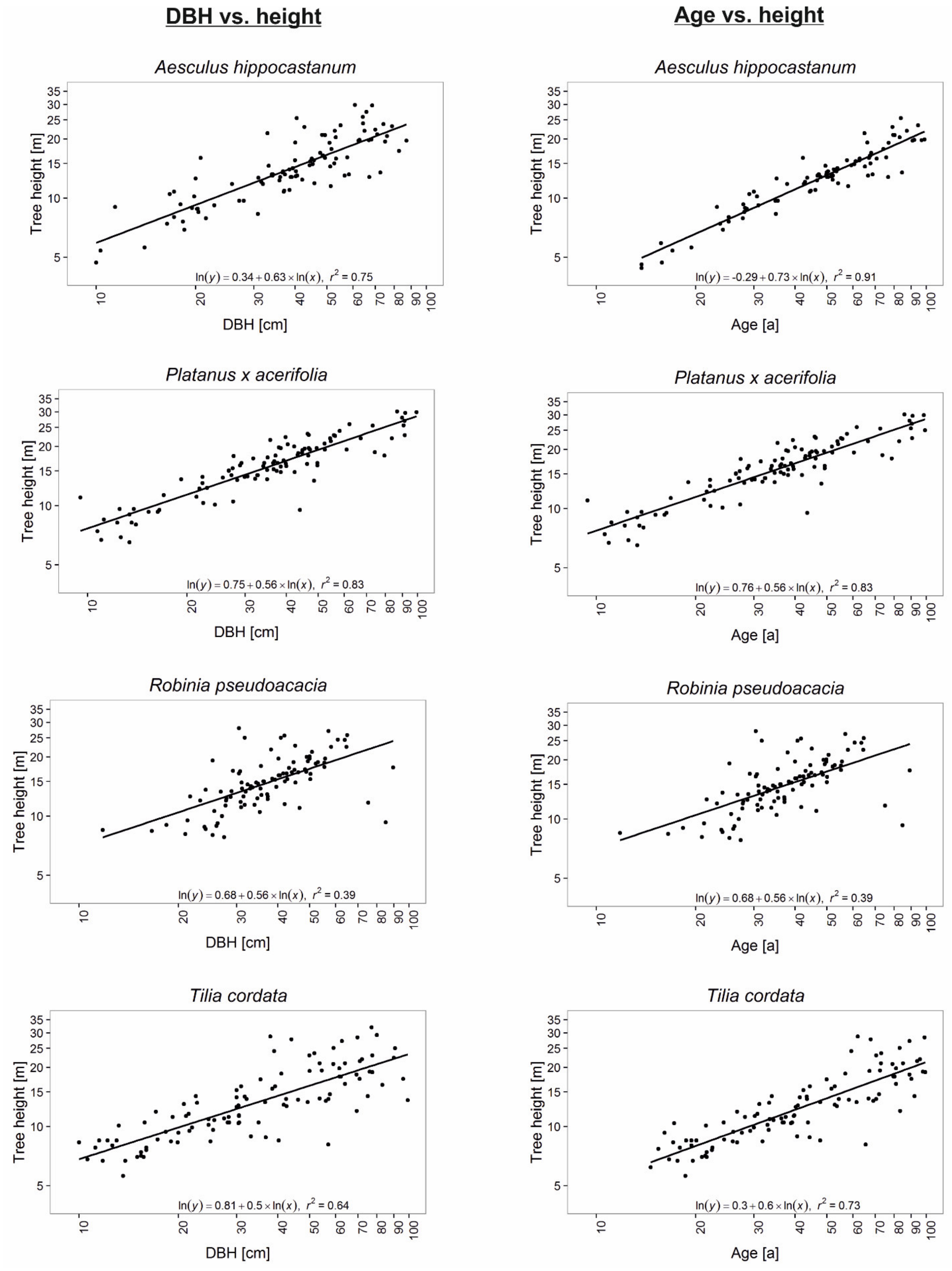
Appendix 1: Map of study sites in Bayreuth.

Appendix 2: Number of trees of the genera examined in this study in Bayreuth. These numbers do not include trees on private land and in areas under the administration of the *Bavarian Administration of State-Owned Palaces, Gardens and Lakes* which includes the central park Hofgarten (Sattelmann, 2016).

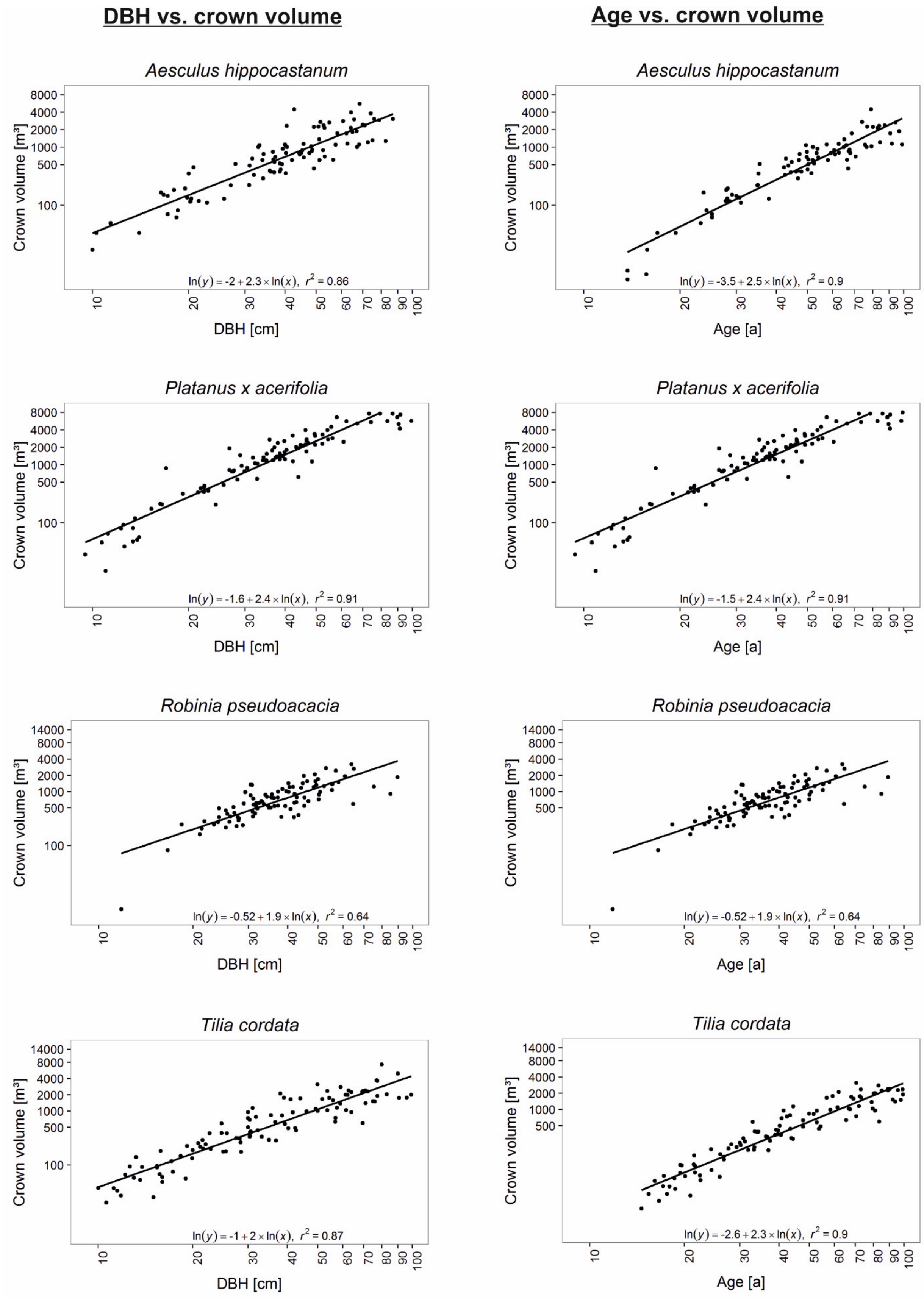
Genus	Number of individuals	% of total trees
Conifers	759	3.70%
Acer	3,986	19.42%
Aesculus	885	4.31%
Alnus	413	2.01%
Betula	1,175	5.72%
Carpinus	1,387	6.76%
Crataegus	255	1.24%
Fagus	326	1.59%
Fraxinus	1,226	5.97%
Malus	262	1.28%
Platanus	252	1.23%
Populus	249	1.21%
Prunus	658	3.21%
Quercus	2,596	12.65%
Robinia	684	3.33%
Salix	562	2.74%
Sorbus	437	2.13%
Tilia	3,846	18.74%
Genera, percentage <1%	570	2.78%



Appendix 3: USDA climate hardiness zones of Central Europe (Van den Berk, 2004).



Appendix 4: Allometric relation of DBH and tree height (left column) and age and tree height (right column) for all four species. Cf. table 12&13 for the exact values behind the regression lines.



Appendix 5: Allometric relation of DBH and tree height (left column) and age and tree height (right column) for all four species. Cf. table 12&13 for the exact values behind the regression lines.

Appendix 6: Change of relative mean measured growth per tree age category in percent for DBH, height, and crown diameter, mean change per species and total mean change.

* Mean change compared to one age category younger (e.g., *A. hippocastanum*: change from <20 to 20-40= +55.6%).

** Mean of mean change from category to category for DBH, height and crown diameter.

*** This age category was excluded as it only comprises two trees.

Species	Age	n	DBH Mean	Change *	h Mean	Change *	cd Mean	Change *	Mean change **
A. hippo.	<20	6	9.1		5.1		2.7		
	20-40	20	20.5	55.6%	9.2	44.5%	5.6	51.8%	**50.7%**
	40-60	28	37.4	45.2%	13.0	29.3%	8.7	35.8%	**36.8%**
	60-80	21	49.4	24.4%	16.7	21.9%	10.5	17.2%	**21.1%**
	>80	27	67.3	26.6%	22.3	25.5%	13.2	20.7%	**24.3%**
	Total		**42.8**		**15.0**		**9.3**		**33.2%**
P. aceri.	<20	18	13.3		8.9		4.6		
	20-40	43	31.8	58.3%	15.3	42.2%	11.0	57.9%	**52.8%**
	40-60	26	48.2	34.0%	19.1	19.7%	14.6	24.4%	**26.0%**
	60-80	6	69.6	30.8%	21.6	11.6%	19.4	24.9%	**22.4%**
	>80	10	92.9	25.1%	27.2	20.6%	19.8	2.3%	**16.0%**
	Total		**40.8**		**16.7**		**12.1**		**29.3%**
R. pseudo.	<20	3	15.6		8.6		4.4		
	20-40	54	31.0	49.7%	13.5	35.8%	8.6	49.4%	**45.0%**
	40-60	34	47.3	34.5%	18.3	26.4%	10.3	16.0%	**25.6%**
	60-80	7	66.8	29.1%	23.1	20.9%	11.5	10.2%	**20.1%**
	>80	2	87.3	23.4%	13.5	-71.2%	12.7	9.7%	***
	Total		**39.7**		**15.7**		**9.3**		**30.2%**
T. cordata	<20	13	10.9		7.7		3.5		
	20-40	36	21.6	49.6%	10.0	22.6%	6.2	42.7%	**38.3%**
	40-60	21	36.4	40.5%	14.0	28.6%	9.6	35.7%	**34.9%**
	60-80	15	52.8	31.2%	18.6	24.7%	11.3	15.0%	**23.6%**
	>80	23	74.7	29.3%	20.8	10.7%	13.3	15.3%	**18.4%**
	Total		**38.8**		**14.0**		**8.7**		**28.8%**

Total mean change across all species in the categories DBH, height and crown diameter: 30.4%

Eidesstattliche Erklärung

Hiermit erkläre ich, dass ich die vorliegende Arbeit selbständig und ohne Benutzung anderer als der angegebenen Hilfsmittel angefertigt habe. Alle Stellen, die wörtlich oder sinngemäß aus veröffentlichten oder unveröffentlichten Schriften entnommen wurden, sind als solche kenntlich gemacht. Die Arbeit hat in gleicher oder ähnlicher Form noch keiner anderen Prüfungsbehörde vorgelegen.

Bayreuth,