HET HANGT IN DE LUCHT

OP ZOEK NAAR KLIMAATBESTENDIGE BOOMSOORTEN VOOR URBAAN VLAANDEREN

MASTERPROEF ENGELSTALIG

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Finding Climate Resilient Urban Tree Species for Flanders

Op zoek naar Klimaatbestendige Boomsoorten voor Urbaan Vlaanderen

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Abstract

This thesis is dedicated to finding climate resilient urban tree species for Flanders. The effects of climate change will impact the living quality of both humans and trees. Especially in urban areas, where the Urban Heat Island effect will enlarge the effects of climate change. Heat waves will become longer and more frequent in Flanders, which can have fatal consequences for vulnerable urban inhabitants. This is a reason for concern, as Flanders is one of the most urbanized regions in the world.

Trees are passively subject to the urban climate, but can also actively mitigate it through shading and evapotranspiration. They can thus be a powerful tool in designing liveable urban areas. Urban areas pose great challenges to trees through poor soil quality, pollution and water stress. Only trees which can withstand all of these challenges, can be utilized as urban trees. Luckily, trees that can survive these urban challenges exist and are presently applied in urban areas in Flanders. But trees suffer from the effects of climate change as well. Especially the mutually reinforcing effects of climate change and the Urban Heat Island pose a great threat to tree vitality. This is because of the demand driven water stress imposed by a large vapour pressure deficit. This large vapour pressure deficit is the result of the hot and dry urban atmosphere. Urban trees thus not only have to be able to withstand the urban challenges, they should also be able to survive in the future urban climate of Flanders. The evaluation of the climate resilience of said urban trees forms the core of this thesis.

The climate resilience of these trees was evaluated through species distribution modelling, using the ensemble modelling approach. It is a method to establish an empirical link between the geographical distribution of a species and its ecological niche. This niche can then be projected in space or time. For this thesis, the climatic niche was constructed and projected over four climate scenarios: a middle-of-the-road scenario for 2050 and 2100, and a worst case scenario for 2050 and 2100. Species occurrence data were downloaded from the Global Biodiversity Information Facility. Climate data were downloaded from the WorldClim website. A species list of potentially climate resilient urban tree species and traditional urban tree species was constructed in collaboration with urban green managers, tree nurseries and other institutions. Traditional urban tree species were observed to not be climate resilient. From all the proposed potentially climate resilient species, Mediterranean species with small leaves generally showed the greatest climate resilience.

Abstract (Nederlands)

Deze thesis is gewijd aan de zoektocht naar klimaatbestendige boomsoorten voor urbaan Vlaanderen. De effecten van de klimaatverandering hebben gevolgen voor zowel de mensen als de bomen die in verstedelijkt gebied wonen. In deze gebieden zal het Stedelijk Hitte-eiland effect de effecten van de klimaatverandering vergroten. Hittegolven zullen in Vlaanderen langer en frequenter worden, wat fatale gevolgen kan hebben voor kwetsbare stadsbewoners.

Bomen zijn passief onderhevig aan het droge en warme stadsklimaat, maar kunnen dit ook actief verzachten door schaduw en evapotranspiratie. Ze kunnen een krachtig instrument zijn bij het ontwerpen van leefbare stedelijke omgevingen. Urbane bomen staan onder druk door slechte bodemkwaliteit, vervuiling en waterstress. Enkel bomen die al deze beperkingen kunnen weerstaan, zijn bruikbaar als stadsbomen. Er zijn reeds bomen die toegepast worden in urbaan Vlaanderen. Maar ook deze bomen lijden onder de effecten van klimaatverandering. De elkaar versterkende effecten van de klimaatverandering en het Stedelijk Hitte-eiland vormen een grote bedreiging voor de vitaliteit van deze bomen. Dit is te wijten aan de waterstress die wordt veroorzaakt door een groot dampdruktekort. Dit dampdruktekort is het gevolg van de hete en droge stedelijke atmosfeer. Stadsbomen moeten dus ook kunnen overleven in het toekomstige stadsklimaat van Vlaanderen. De evaluatie van de klimaatbestendigheid van deze stadsbomen vormt de kern van deze thesis.

De klimaatbestendigheid van deze bomen werd geëvalueerd door middel van Species Distribution Modelling Een methode om een empirisch verband te leggen tussen de geografische verspreiding van een soort en zijn ecologische niche. Deze niche kan vervolgens geprojecteerd worden in de ruimte of de tijd. Voor deze thesis werd de klimaatniche geconstrueerd en geprojecteerd voor vier klimaatscenario's: een middle-of-the-road scenario voor 2050 en 2100, en een worst case scenario voor 2050 en 2100. Gegevens over het voorkomen van soorten werden gedownload van de Global Biodiversity Information Faciliteit. Klimaatgegevens zijn gedownload van de WorldClim-website.

In samenwerking met stedelijke groenbeheerders, boomkwekerijen en andere instellingen is een soortenlijst opgesteld van potentieel klimaatbestendige stedelijke boomsoorten en traditionele stedelijke boomsoorten. Traditionele stedelijke boomsoorten bleken niet klimaatbestendig te zijn. Van alle voorgestelde potentieel klimaatbestendige soorten vertoonden Mediterrane soorten met kleine bladeren over het algemeen de grootste klimaatbestendigheid.

Abbreviations

ANN	Artificial Neural Networks
BIEN	Botanical Information and Ecology Network
CHELSA	Climatologies at High resolution for the Earth’s land surface Areas
CMIP	Coupled Model Intercomparison Project
GAM	Generalised Additive Models
GBIF	Global Biodiversity Information Facility
GCM	Global Circulation Model
IPCC	Intergovernmental Panel on Climate Change
KMI	Koninklijk Metereologisch Instituut
MaxEnt	Maximal Entropy model
RCP	Representative Concentration Pathways
RF	Random Forest Model
ROC	area under the Relative Operating Characteristic curve
RURA	Ruimterapport Vlaanderen
SDM	Species Distribution Model(ling)
SRE	Rectilinear Envelope method
SSP	Shared Socio-Economical Pathway
TSS	True Skill Statistic

Table of figures

Table of tables

Content

1. Literature Study

1.1. Global change

1.1.1. Urbanization

Globally, there exists an ongoing demographic shift from rural to urban spaces. When urban areas are saturated, they expand. This causes a transformation of formerly rural areas to more densely populated and built-up urban areas. This socio-economic process is called urbanization (Department of Economic and Social Affairs United Nation, 2018). Urbanization is a diffusive process controlled by social and economic factors (Antrop, 2004). The United Nations' Department of Economic and Social Affairs (2018) state that this continuing growth has known a rapid pace since 1950. Then, the world contained 751 million urban inhabitants. In 2018, the world contained 4.1 billion urban inhabitants. Not only is there an absolute rise in the urban population, this rise is also larger relative to the rise in the rural population. They also notice there is a larger increase in medium or big cities relative to small ones.

In Europe, the urbanization process does not limit itself only to the growth of cities, but also influences the rural countryside (Antrop, 2004). Even though the urban land area is estimated to hold only 1 % of the European land area (Antrop, 2004; Schneider et al., 2009), the urban population of most European countries accounts for at least 75 % of the total population (Antrop, 2004; United Nations, Department of Economic and Social Affairs, 2018; The World Bank, 2021, http://data.worldbank.org/indicator/, access date: 26/01/2021).

In the year 2019, 98 % of the Belgian population lived in urban areas. Making it one of the most urbanized countries in the world (The World Bank, 2019, http://data.worldbank.org/indicator/, access date: 26/01/2021). In 2018, the population density of Belgium was calculated at 377 inhabitants per km^2, putting it in the top 5 most densely populated European countries (The World Bank, 2021, http://data.worldbank.org/indicator/, access date: 26/01/2021). A clear difference in population density exists between Flanders, the northern part of Belgium, with a density of 400 inhabitants/km^2, and Wallonia, the southern part, with a density of 50 inhabitants/km^2 (Antrop, 2004). The urban population in Flanders is also growing. Be it less through migration from rural to urban, and more through transnational immigration and higher birth rates within the urban borders. Flanders' population is projected to grow from 6.5 million people in 2017 to 7.5 million in 2060 (Departement Omgeving, 2018). *Departement Omgeving* (Environmental department) of the Flemish government distinguishes two types of urbanized area: central urban area and peripheral urban area, the latter being characterized by a lower economic activity. The central urban area encompasses 7 % of the land area and holds 44% of the population in Flanders, while the peripheral urban area accounts for 13 % of the land area and 20 % of the population (RURA, 2018), this sums up to 20 % urban land area which holds 75 % of the population.

1.1.2. Climate change

1.1.2.1. Temperature

In 2014, the IPCC released a synthesis report in which it is stated that under all emission scenarios, the surface temperature will rise (IPCC, 2014). Not only will the central statistics of climatic data shift, the temperature extrema will also change in frequency, duration and intensity. On daily and seasonal temporal scales, the IPCC predicted that, above land masses, hot temperature extremes will be more frequent and cold temperature extremes will be less frequent. Different projections across Europe and for regions within Europe all show a rise in mean temperature (Brune, 2016; Hosseinzadehtalaei et al., 2018; Jacob et al., 2014; KMI, 2020). Simulations for different representative concentration pathways (RCPs) project an increase in mean annual temperature of 1,0-4,5 °C for RCP4.5 and 2,5-5,5 °C for RCP8.5 across Europe, with regional differences (Jacob et al., 2014). On a global and on a European scale, heat waves[1] will have higher occurrence and longer duration (IPCC, 2014). The mean number of heat waves[1] will increase strongest in Southern Europe, but this increase will expand to the rest of Europe by the end of the 21st century (Jacob et al., 2014).

The mean seasonal and yearly temperatures in Brussels (Belgium) have risen unequivocally. Comparing the period of 1880-1909 to the period of 1990-2019, there was an increase in yearly average temperature of between 1,8 °C and 1,9 °C, chiefly explained by a rise in spring and summer temperatures (KMI, 2020). For the period of 2071-2100 compared to 1971-2000, mean annual temperatures in Belgium are projected to rise 1,5-2,0 °C under the RCP4.5 scenario and 3,0-3,5 °C under the RCP8.5 scenario. In Belgium, the amount of heatwaves[1] has increased with one or more every three to four years, relative to the 19th century. Relative to 1981, there

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[1]Defined as a period of five consecutive days with a maximum daily temperature of at least 25 °C, encompassing 3 days or more with a maximum daily temperature of at least 30 °C.

is a significant positive trend in the duration of heat waves[1], being an increase of two days every decade (KMI, 2020). For the period of 2071-2100 compared to the period of 1971-2000, the mean number of heat waves[2] during the months of May until September in Belgium is projected to increase with 10-20 number of heat waves under the RCP4.5 scenario and 25-35 number of heat waves under the RCP8.5 scenario (Jacob et al., 2014).

The increasing occurrence of heat waves should be a reason for concern, as their presence has proven to generate an excess mortality on top of the expected linear rise in mortality due to higher temperatures (D'Ippoliti et al., 2010; Gasparrini & Armstrong, 2011; Hajat et al., 2006; IPCC, 2014; Oudin Åström et al., 2015). Not only daytime temperatures, but especially night-time temperatures have a large influence on the excess mortality (Hajat et al., 2006). The duration of heat waves has a larger impact than its intensity (D'Ippoliti et al., 2010; Gasparrini & Armstrong, 2011). Especially the elderly are most vulnerable to succumb to the effects of heat waves (D'Ippoliti et al., 2010; Oudin Åström et al., 2015). Gasparrini & Armstrong (2011) also suggest a mutually reinforcing interaction effect between air pollution and the effect of heat waves on mortality.

1.1.2.2. Precipitation

Extreme precipitation events are predicted to be more frequent and more intense over mid-latitude land areas on a global scale, as well as on a European scale (IPCC, 2014). Climate change projections of Europe show a statistically significant increase of mean annual precipitation in Central and Northern Europe and a decrease in Southern Europe for both the RCP4.5 and RCP8.5 scenarios, the absolute difference being higher in the latter (Jacob et al., 2014). Also the projections of precipitation seasonality changes show regional differences. Increase in heavy precipitation[3] in winter is projected to be highest for Central and Eastern Europe. Heavy percipitation[3] in summer is projected to decrease in some parts of South-Western Europe, while it is projected to increase in other parts of South-Western Europe (Jacob

[2] Defined as a period of more than 3 consecutive days exceeding the 99th percentile of the daily maximum temperature of the May to September season for the control period (1971–2000).

[3] Defined as the intensity of precipitation events of the 95th percentile of daily precipitation (only days with precipitation > 1mm/day are considered).

et al., 2014). Projections for Germany also show that summers will become drier in the future (Brune, 2016). A small increase in dry spells is projected for Central Europe, while a decrease in dry spells is projected for Scandinavia (Jacob et al., 2014). Effects of expected drought conditions on tree vitality can be intensified by high temperatures due to an increase in vapour pressure deficit, increasing evapotranspiration (Brune, 2016).

For Belgium, and by inclusion Flanders, a report of the KMI (2020) shows that the mean annual precipitation statistics show no significant trend. The total amount of yearly precipitation changes only slightly, but the distribution is becoming increasingly more episodic. The amount of meteorological droughts[4] has increased significantly with 1,5 days per decade since 1981. The maximal length of meteorological droughts[4] during spring has increased over the last decades (KMI, 2020). The amount of heavy precipitation[3] events have shown a significant increase of 0,6 days per decade, since 1981. The maxima of extreme rainfall cumulated over 10 days and over 24 hours show a positive trend since 1898. During storm season (most often from April until September), the hourly maxima show a significant increase of 2,8 mm per decade, since 1981 (KMI, 2020). Belgium, and by inclusion Flanders, will also experience significant changes in its seasonal precipitation profiles (Hosseinzadehtalaei et al., 2018; Jacob et al., 2014), where periods of meteorological droughts[4] and periods of heavy precipitation[5] will become more frequent (Hosseinzadehtalaei et al., 2018; KMI, 2020). For the period of 2071-2100 compared to 1971-2000, mean annual precipitation in Belgium is projected to rise 5-15 % under the RCP8.5 scenario (Jacob et al., 2014).

1.1.3. Urban Heat Island

The IPCC (2014) states that urban areas will experience the largest impact of climate change. One of the reasons for this, is the Urban Heat Island effect. The difference between urban and rural zones lies in the amount of built-up area. While rural landscapes are characterized by natural land cover, urban areas are composed of anthropogenic infrastructure. The difference in radiative and thermal properties of this anthropogenic infrastructure compared to natural infrastructure, lie at the base of the Urban Heat Island effect (USA EPA, 2013). Anthropogenic

[4] Defined as a series of consecutive days with less than 1 mm of precipitation.

[5] Defined as a daily precipitation of 20 mm or more.

structures generally have lower albedo, higher emissivity and greater heat storage capacity than organic structures (Grimm et al., 2008; Oke, 1989; USA EPA, 2013). This causes urban infrastructure to absorb and store heat in warm conditions and later dissipate this heat, when the atmospheric temperature drops. This results in higher temperatures in urban areas compared to the surrounding rural areas. The quantitative difference in temperature between urban and rural areas defines the magnitude of the Urban Heat Island effect (USA EPA, 2013). When buildings are located near other buildings, they can obstruct each other's energy dissipation because of their high thermal load (USA EPA, 2013). Densely built-up areas often form urban canyons. These urban canyons diminish the overall urban albedo by reabsorption of reflected solar radiation or radiated heat (USA EPA, 2013). Also the inability of urban infrastructure to cool down by evapotranspiration contributes to the Urban Heat Island effect (Oke, 1989; USA EPA, 2013).

The Urban Heat Island has the potential to add to excess mortality already seen as a result of heat waves (D'Ippoliti et al., 2010; Gasparrini & Armstrong, 2011; Hajat et al., 2006; IPCC, 2014; Oudin Åström et al., 2015). Urban areas are projected to experience an enlarged impact of climate change, with an increased urban temperature and decreased relative humidity, compared to the rural surroundings (Langendijk et al., 2019; Zhao et al., 2021). The impact of heat stress is projected to be twice as large in cities, compared to rural surroundings, towards the end of mid-21st century (Wouters et al., 2017). Given the high urban fraction of the Flemish population (The World Bank, 2021, http://data.worldbank.org/indicator/, access date: 26/01/2021) and the future increase of heat waves across Europe (IPCC, 2014; Jacob et al., 2014; KMI, 2020), Flemish city planners need to be aware of the menace the Urban Heat Island effect can be to the inhabitants of the increasingly urbanized landscapes. Not only do we need to tackle these problems, we need to tackle these problems with instruments that will stand the test of climate change.

1.2. Urban Green Infrastructure

The effects of climate change are clearly more pronounced in urban areas. These areas are projected to hold an increased risk for people, assets, economies and ecosystems. These risks include heat stress, storms, extreme precipitation events, drought, water scarcity and air pollution (IPCC, 2014). Urban inhabitants need to be protected from dangers posed by these challenges. To do this, we need to adapt our cities and their periphery to climate change. The

IPCC (2014) defines adaptation as: "*Adjustment in natural or human systems in response to actual or expected climatic stimuli or their effects, which moderates harm or exploits beneficial opportunities*." Trees have been put forward as one of the possible instruments to adapt our cities to increase their resilience to the challenges above, and more (IPCC 2014; USA EPA 2008; Salmond et al. 2016; Gillner et al. 2015; Flies et al. 2017; Oke 1989; Gill et al. 2007). For this thesis, urban trees are interpreted as trees located at densely built up areas. This includes locations like streets, squares, etc. This excludes trees in parks and urban forests, as the effects of the Urban Heat Island will be less pronounced for these trees.

1.2.1. Ecosystem Services

In 2005, the Millennium Ecosystem Assessment popularized the term "ecosystem service" as a way to concretize and classify the instrumental values of natural systems. The term was defined as follows:

> "*Ecosystem services are the benefits people obtain from ecosystems. These include **provisioning services** such as food, water, timber, and fiber; **regulating services** that affect climate, floods, disease, wastes, and water quality; **cultural services** that provide recreational, aesthetic, and spiritual benefits; and **supporting services** such as soil formation, photosynthesis, and nutrient cycling."* (Millennium Ecosystem Assessment, 2005)

A word of caution, one may not maximize a single ecosystem service and lose track of the ecological, social and geographic context or possible disservices. One must always be aware of the fact that the impact of the ecosystem service is always location-dependent (Oke, 1989; Salmond et al., 2016). The ecosystem service view is reductionist, as it reduces the entire functionality and existence of a living organism to a single or few functionalities. No amount of ecosystem services can fully capture the entire value of an ecosystem. Nevertheless, it allows policymakers to make cost-benefit analyses, helping them in deciding what measures would make the best investment.

Trees can be a powerful climate adaptation tool, they are passively subject to the urban climate and actively regulate it (Lüttge & Buckeridge, 2020). Through shading and evapotranspiration, trees can reduce the impact of the Urban Heat Island (Gillner et al., 2015; Oke, 1989; Rahman et al., 2017; Salmond et al., 2016; Shiflett et al., 2017; USA EPA, 2008). In doing so, they actively control the urban microclimate and reduce thermal loads, illustrating the climatic regulating services they can provide (Gill et al., 2007; Gillner et al., 2015; Oke, 1989; Salmond et al., 2016; USA EPA, 2008). Trees can also positively impact the urban air quality (Oke, 1989; Salmond et al., 2016; USA EPA, 2008), increase soil quality (Day et al., 2010), reduce surface runoff (Day et al., 2010; Gill et al., 2007; Oke, 1989; Smets et al., 2019) and improve general human health (Flies et al., 2017; Wolf et al., 2020). It might look like trees are the silver bullet in overcoming all of the urban challenges. Yet, the use of trees in the urban environment is also linked with disservices. These can include the emissions of volatile organic compounds (Salmond et al., 2016; USA EPA, 2008), the formation of ozone (USA EPA, 2008), allergic reactions to pollen (Lyytimäki et al., 2008; Salmond et al., 2016) and economic costs due to maintenance or property damage (Lyytimäki et al., 2008).

1.2.2. Impact of Urban Environment on Trees

The different negative effects of the urban environment on tree vitality are well documented. Most problems can be allocated to poor soil properties (Cregg & Dix, 2001; Day et al., 2010; Lüttge & Buckeridge, 2020; M. A. Rahman et al., 2014; Sanders & Grabosky, 2014; P. Wang et al., 2018; Widrlechner, 1994; Zhang & Brack, 2020), pollution (Lüttge & Buckeridge, 2020; Seppälä et al., 2009), and water stress (Chen et al., 2011; Cregg & Dix, 2001; Lüttge & Buckeridge, 2020; X. M. Wang et al., 2019; Whitlow et al., 1992; Zhang & Brack, 2020). Below, we will discuss the general effects of water stress on trees. Subsequently, the contribution of poor soil properties and a high vapour pressure deficit will be reviewed. The impact of pollution will not be investigated any further.

1.2.2.1. Water stress

An immediate response of trees to water stress is a closing of the stomata, reducing transpiration but also restricting gas exchange needed for the photosynthetic process (Raven et al., 2014; X. M. Wang et al., 2019). Prolonged water stress will cause morphological changes of the leaves; a thicker cuticula, more but smaller stomata, and shedding of leaves (Lüttge & Buckeridge, 2020; Raven et al., 2014). Long term water stress can lead to mortality through xylem cavitation and the consumption of non-structural carbohydrates, the latter leading to carbon starvation. Both diminish overall vitality, making trees more susceptible to pests and diseases (Allen et al., 2010; N. McDowell et al., 2008; N. G. McDowell, 2011; Savi et al., 2015). The processes of cavitation and carbon starvation seem to be interlinked (N. G. McDowell, 2011). Water stress induced by the urban environment can be supply driven, because of low groundwater contents due to impervious land cover, or demand driven, because of a higher evaporative demand due to the warm and dry urban atmosphere.

1.2.2.2. Soil properties and Supply driven water stress

Urban soils have a chemical as well as a physical impact on the underground metabolism of trees. The chemical properties of the urban soil that trees have to endure take the form of more alkaline soil acidity, low organic matter content, contamination with salts, pesticides and heavy metals, the latter often originating from leaks in wastewater pipelines (Day et al., 2010; Lüttge & Buckeridge, 2020; Morgenroth et al., 2013; P. Wang et al., 2018). Paved sidewalks and underground urban infrastructure reduce the soil volume available to the root system (Day et al., 2010). It has been shown that reduced soil area negatively impacts the canopy cover (Sanders & Grabosky, 2014). The restricted rooting space, together with soil temperature and soil compaction, form the largest underground physical constraints to urban trees (Cregg & Dix, 2001; Day et al., 2010; M. A. Rahman et al., 2014; T. Whitlow & Bassuk, 1987; T. H. Whitlow et al., 1992). Impervious urban land cover and soil compaction promote surface runoff and reduce the infiltration capacity of urban soils, diminishing the amount of water available to urban trees and inducing supply driven water stress (Cregg & Dix, 2001; Day et al., 2010; Lerner, 1990; Savi et al., 2015; P. Wang et al., 2018; T. Whitlow & Bassuk, 1987; T. H. Whitlow et al., 1992).

1.2.2.3. Urban Heat Island effect and Demand driven water stress

The limited groundwater replenishment as a consequence of impervious urban land cover is often regarded as the sole reason for water stress of trees in the urban environment, however, proof for this intuitive hypothesis remains scarce. In fact, not only the water supply but also the atmospheric evaporative demand can be the main culprit of drought stress in urban trees, even when plenty of soil moisture is available (Chen et al., 2011; Clark & Kjelgren, 1990; Cregg & Dix, 2001; Kjelgren & Montague, 1998; Lerner, 1990; Oke, 1989; Savi et al., 2015; T. Whitlow & Bassuk, 1987; T. H. Whitlow et al., 1992).

This evaporative demand, and thus the amount of water loss of urban trees, is linked to the vapour pressure deficit of the atmosphere (Brune, 2016; Chen et al., 2011; Cregg & Dix, 2001; Savi et al., 2015). When this atmospheric demand exceeds the water supply, which is possible even when adequate soil moisture is present, water stress will occur. Withlow & Bassuk (1987) identified low absolute humidity, high temperatures and high wind speeds in cities as the main factors explaining the high atmospheric demand. The geometric, thermal and radiative properties of buildings and pavements described in section *1.1.3*, cause the atmospheric properties inducing the demand driven water stress (Oke, 1989; X. M. Wang et al., 2019). Trees also suffer from the direct radiation of pavements (Kjelgren & Montague, 1998; T. Whitlow & Bassuk, 1987). Furthermore, Cregg & Dix (2001) explain that because of the exponential relation between temperature and saturation vapor pressure, a small rise in temperature due to the Urban Heat Island effect can cause a drastic increase in evaporative demand, inducing water stress. They state that "*it is difficult to overestimate the impact of UHI on trees moisture stress and health*" (Cregg & Dix, 2001). Lüttge & Buckeridge (2020) claim that heat is one of the biggest urban stress factors. Demand driven water stress and heat stress are directly linked to the effects of the Urban Heat Island and climate change. Therefore both of these factors pose a direct threat to the vitality and longevity of urban trees (Allen et al., 2010; Cregg & Dix, 2001; Savi et al., 2015; Zhang & Brack, 2020). Thus, the inherently dry and hot atmospheric conditions of the urban environment can induce demand driven water stress in trees.

1.2.3. Impact of Climate Change on Urban Trees

It has been established that climate change indeed has an impact on the composition and dynamics of natural ecosystems (Allen et al., 2010; IPCC, 2014; Kijowska-Oberc et al., 2020; Millennium Ecosystem Assessment, 2005; Parmesan, 2006; Seppälä et al., 2009; Wagner et al., 2014). In this subsection, we will describe the impact of climate change on trees in urban ecosystems.

Firstly, some of the current negative effects of the urban environment on trees will be increased. A rising occurrence of heat waves and the increasingly episodic distribution of rainfall (Brune, 2016; IPCC, 2014; Jacob et al., 2014; KMI, 2020), combined with the slow infiltration rate of urban soils (Cregg & Dix, 2001; Morgenroth et al., 2013; P. Wang et al., 2018; T. Whitlow & Bassuk, 1987; T. H. Whitlow et al., 1992), will increase the occurrence of atmospheric evaporative demand exceeding the water supply, increasing the risk of water stress (see section *1.2.2*). Also outside of urban areas, increasing heat and water stress cause a lower general resilience of trees. This increased mortality in natural systems around the globe (Allen et al., 2010; Seppälä et al., 2009). Combining the rising frequency and duration of heat waves (Brune, 2016; IPCC, 2014; Jacob et al., 2014; KMI, 2020) with the intricate link between heat, atmospheric water content and building properties (Oke, 1989; USA EPA, 2013), shows the hardships that urban trees will need to endure. With the Urban Heat Island as a reinforcer, the effects of increased heat and drought will have a great impact on urban trees (Zhang & Brack, 2020).

Secondly, the meteorological changes brought by climate change have a direct impact on the metabolism of trees, in both urban and natural ecosystems. The change in rainfall distribution and temporal temperature profiles can bring forth a change in phenology (Parmesan, 2006; M. A. Rahman et al., 2014; Seppälä et al., 2009; Xie et al., 2015). This renders metabolic strategies of trees, which are a product of evolution within a certain climatic envelope, less applicable to the environment in which they are established. Tree species with only a few generations per century are at risk of local extinction, as they cannot adapt fast enough to climate change (Allen et al., 2010). A possible advantage of climate change is a lengthening of the growing season (Kijowska-Oberc et al., 2020; Millennium Ecosystem Assessment, 2005; Moser et al., 2017; Parmesan, 2006; Pretzsch et al., 2017; Vitasse et al., 2011). However, Pretzsch et al. (2017) found urban trees in temperate zones to grow slower than rural trees in temperate zones, contrary to other climatic zones where accelerated growth was observed. The main effect the lengthening of the growing season will have in temperate regions, is its contribution to the poleward latitudinal range shift of tree species (Kijowska-Oberc et al., 2020). Haesen (2019) has modelled this species range shift for 881 Red List species in Flanders, which showed a general northern shift in species distributions. Therefore, we will probably need to invoke species originating from more southern areas.

Thirdly, the effects of climate change can present a more favourable environment for native or non-native tree pathogens (Kijowska-Oberc et al., 2020; Tubby & Webber, 2010). Furthermore, trees will be more susceptible for infection due to water and heat stress (Allen et al., 2010; N. McDowell et al., 2008; N. G. McDowell, 2011; Savi et al., 2015; Tubby & Webber, 2010) induced by climate change.

The same way climate change forces natural ecosystems to welcome new species, it will force urban green managers to adapt and look for new instruments to improve the quality of urban life. That is, instruments adapted to the present and future climate of urban Flanders. The need for these new instruments and their importance have already been posed (Brune, 2016; Burley et al., 2019; Nitschke et al., 2017).

1.2.4. Trees as an Instrument against Climate Change

Trees thus seem to be a powerful adaptation tool, but they need to be applied with care, as the potential impact of ecosystem services is location and context-dependent (Oke, 1989; Salmond et al., 2016). The possible impact of trees is not only dependent on *which* tree you use, but also on *where* and *how* you use it. For example, the effectiveness of trees to reduce the urban thermal load is linked to tree size, tree planting density and tree planting pattern (Y. Wang & Akbari, 2016). We have the tools to adapt our environment to the challenges we face, it's our task to put these instruments in the right place. Adaptation can be done either anticipatory or reactive. As the effects of climate change have a time lag and the impact of the drivers cannot be reduced for years or decades (Millennium Ecosystem Assessment, 2005), reactive adaptation might not suffice. Failing to act now can bring large costs in the future (Seppälä et al., 2009). Hence, we need to anticipate the effects of climate change in the choice of our urban tree species. Also, the impact of trees on the urban environment are is largest when they have reached maturity. We thus need to select trees that will reach maturity in their urban lifespan.

1.2.5. Urban Tree Species Selection

When urban planners wish to plant trees, they have to decide which tree species they will use. Not only aesthetic values are taken into consideration, also tree dimensions and other properties of the tree take a prominent role in the decision process. Local governments of urban areas also provide frameworks for urban green, or even urban trees specifically, more and more often (Greater London Authority, 2005; Sjöman & Busse Nielsen, 2010). It thus seems that urban city planners and urban green managers are stimulated to use trees in the public space, and to make the chosen trees conform with an ever growing list of criteria.

In 2017, an interview with members of different tree management authorities across Britain showed that local authorities adopted a reactive tree management approach, driven by the urge to reduce complaints and human disservices (Davies et al., 2017). Davies et al. (2017) suggest these problems mainly find their origin in the underfunding of local tree authorities. Local urban green managers are aware of the available scientific information, and its importance, but lack the means to apply this information.

Different urban tree databases already exist. Some have been constructed qualitatively, based on knowledge and experience, such as a wide array of fora and pamphlets (Larenstein, 2017;

Verschoren, 2018). Others have been constructed in a more quantitative way (Ossola et al., 2020; Vogt et al., 2017), sometimes already integrating the climate change dimension (Roloff et al., 2009). Information about the climate resilience of species is of rather scientific nature, and is either too general to be applied directly by urban green managers (Kijowska-Oberc et al., 2020; N. McDowell et al., 2008; McKenney et al., 2007; Savi et al., 2015) or too specific to be applied in a context different from that of the performed study (Moser et al., 2016; Pataki et al., 2011; Zhang & Brack, 2020).

The climate resilience of tree species is a relatively new concept within the urban planning field. Nevertheless, it is of greatest importance to apply this knowledge in a robust way, as we need to prepare the urban areas for future challenges sooner, rather than later (IPCC, 2014; Millennium Ecosystem Assessment, 2005; Seppälä et al., 2009; Wagner et al., 2014).

1.3. Aim of this Thesis

1.3.1. Evaluating the Climate Resilience of Urban Tree Species for Flanders

Practical knowhow of which trees can withstand the hardships of the urban environment are already present. This practical knowledge will form the starting point of this thesis. The information presently available will be expanded by evaluating the climate resilience of the trees known to be applicable in urban environments. As stated in section 1.2.1, trees can actively impact the urban microclimate, by reducing thermal loads (Gillner et al., 2015; Oke, 1989; Mohammad A. Rahman et al., 2017; Salmond et al., 2016; Shiflett et al., 2017; USA EPA, 2008). They generally have large management costs because of their size and extended lifespan, compared to shrubs and herbs. Therefore, it is of utmost importance that urban trees are chosen carefully, so that local governments can make ecologically and financially sound decisions regarding tree species selection. To increase the resilience of urban green to climate change, we are in need of proactive selection and planting strategies (Zhang & Brack, 2020). The impact of certain atmospheric conditions on trees is species specific (Clark & Kjelgren, 1990; Cregg & Dix, 2001; Kjelgren & Montague, 1998; Moser et al., 2016; Pataki et al., 2011; Ryan, 2011; Savi et al., 2015; X. M. Wang et al., 2019; Zhang & Brack, 2020), illustrating the importance of selecting the right species for future urban tree plantings. Most likely, this will be small-leaved (Kjelgren & Montague, 1998; T. Whitlow & Bassuk, 1987), drought-tolerant (Cregg & Dix, 2001) trees with high hydraulic conductance (Kijowska-Oberc et al., 2020) originating from (semi-)arid environments (Kjelgren & Montague, 1998). The effects of climate change enforce a latitudinal shift of species distributions towards the poles (McKenney et al., 2007; Parmesan, 2006; Seppälä et al., 2009), implying we will need to invoke species from more southern regions in Europe.

One way often used to project the impact of climate change on species distribution is by use of Species Distribution Models (henceforth referred to as SDMs), a method that is on the rise and versatile in applicability. It will be used to evaluate the climate resilience of trees under different climate scenarios. The primary aim of this thesis is thus to test the climate resilience of tree species that are applicable in urban areas.

1.3.2. Integration of Knowledge

To conquer the challenges of urbanization and climate change, we need cooperation and coordination of governments on all levels. Especially local governments and municipalities play a key role in adapting the growing urban environment to future changes (IPCC, 2014; Seppälä et al., 2009). Even though there is still much to be known, it is crucial that information is gathered, shared and, most of all, used to improve the quality of life for present and future generations (Corburn, 2009; Millennium Ecosystem Assessment, 2005; Seppälä et al., 2009). Information about the climate resilience of urban trees is present, but scattered and sometimes inaccessible for urban green managers. Theoretical knowledge is not translated to practical knowledge, creating practical knowledge "gaps" that could be filled by proper communication between the theoretical and practical world. This communication exercise forms the second aim of thesis. The so-called practical knowledge gaps will be identified in cooperation with agents of urban green in Flanders on different organisational levels. These include urban green managers, tree nurseries and different governmental and private institutions. After identifying these gaps, a solution will be constructed in collaboration with the knowledge users.

2. Material & Methods

2.1. Modelling

2.1.1. Species Distribution Modelling

Species Distribution Models (SDMs) are an empirical method of linking georeferenced species occurrence data to environmental data (Elith & Leathwick, 2009; Guisan & Thuiller, 2005), based on the ecological niche theory (Naimi, 2015). SDMs have become an important and powerful tool to project species' extinction risks in the face of climate change. The goal of SDMs is to establish a model which links the geographical distribution of a species to its ecological niche. Once the model is established and evaluated, the modelled ecological niche is then used to predict the plausibility of occurrence in a new habitat. This new habitat can be a different geographical area, or the same geographical area under different ecological conditions (Elith & Leathwick, 2009). In short, SDMs aim to delineate the ecological niche of a species based on its geographical distribution. It then projects this ecological niche in either space or time. In this thesis, we will do the latter.

SDMs need two sets of data to demarcate the ecological niche of a species. Firstly, georeferenced occurrence data of the researched species are needed. Secondly, georeferenced environmental data of the geographical area of the occurrence data are needed. This environmental data will be used to model the ecological niche of the species. It is of major importance that the selection of these environmental variables are ecologically justified (Araújo & Guisan, 2006; Bradie & Leung, 2017; Elith & Leathwick, 2009). When forecasting the species distribution in time, it is crucial that the environmental data is available for the present as well as for the point in the future for which we wish to project.

The importance of data preparation and model evaluation have commonly been neglected when SDMs are used to make predictions (Araújo & Guisan, 2006; Naimi, 2015). An inherent problem of working with georeferenced data is spatial autocorrelation (Naimi, 2015). When building an SDM, the use of sufficient predictor variables and a model that is adequately fitted, can minimise the impact of spatial autocorrelation (Elith & Leathwick, 2009). Overfitting is a concern however (Merow et al., 2014).

2.1.2. Ensemble modelling

There is a wide array of modelling methods, each with its own advantages and disadvantages (Beale & Lennon, 2012). New methods are developed frequently (Elith et al., 2006), and different model types can give different results in species distribution (Thuiller et al., 2009). Which model can be used best, depends on the technical, geographical and taxonomical context of the research-objective. Choosing the right modelling method for your research-question can be a tricky situation, especially when the results of certain methods show large discrepancies. One is truly confronted with the fact that choosing is losing. This is where *ensemble modelling* can offer solace. While you have to choose the results of a certain model in single method modelling, you can combine the results of different methods into one, more robust, result when you adopt the ensemble modelling approach (Thuiller et al., 2009). In this approach, you select different models that will make a prediction. The predictive performance of each individual model is evaluated. The user can then choose how, and which, results will be combined. This can be done by weighted mean (where the weight of the result of a certain modelling method depends on its predictive performance), mean, median, or committee averaging. The BIOMOD-platform offers a package in which users can build SDMs, according to the ensemble modelling approach (Thuiller et al., 2009). The SDM in this thesis was constructed by use of the biomod2-package (Thuiller et al., 2009).

2.2. Species data

2.2.1. Species selection

The species lists were constructed in collaboration with experts and knowledge users of urban green in Flanders. Our first set of species will be one consisting of potentially climate resilient urban tree species, henceforth they will be referred to as “climate species”. This list was constructed together with urban green managers in Flanders and “Klimaatbomen Limburg” (https://www.klimaatbomeninlimburg.be), a project of the Belgian province Limburg. The list was complemented by a selection of tree species made by Belgian tree nurseries, within the Green Cities initiative (Verschoren, 2018). This resulted in a list of 161 climate species, see appendix 7.1. This list is the starting point in the search for climate resilient urban tree species. By involving the final users of the generated knowledge early on in the selection process, the output based on the species list is expected to be directly applicable for urban green managers in Flanders.

Secondary to the search for climate resilient urban tree species, the climate resilience of the currently most used urban trees in Flanders will be tested. This list, which will henceforth be referred to as “traditional species”, was constructed in cooperation with the green management offices of three local governments. The green offices of the cities of Brussels (De Wandeler Hans, pers. comm.) and Ghent (ANB, 2008) provided a tree inventory. The inventory of the city of Antwerp was extracted from *Groeninventaris Antwerpen* (https://stadantwerpen.maps.arcgis.com/apps/webappviewer/). The resulting tree species lists for each city can be found in appendix 7.2 . These three tree inventories were compilated to create a list of traditional urban tree species. Species that were present on the climate species list as well as on the traditional species list, were removed from the traditional species list. The resulting list of the most used city species in Antwerp, Brussels and Ghent can be found in Table 1: Traditional Urban Tree species .

Table 1: Traditional Urban Tree species ranked by their total absolute frequency in Antwerp, Brussels and Ghent

Species	Frequency	Species	Frequency
Tilia platyphyllos	1,315	*Populus nigra*	69
Carpinus betulus	774	*Betula pendula*	60
Fagus sylvatica	630	*Platanus occidentalis*	56
Fraxinus excelsior	545	*Prunus serrulata*	55
Acer pseudoplatanus	483	*Quercus rubra*	37
Aesculus hippocastanum	424	*Populus alba*	25
Prunus avium	71	*Salix pentandra*	10

2.2.2. Data source

With a selection of climate and traditional species at hand, occurrence data about these species can be gathered. The selected method, being SDM, is in need of a large number of occurrence data with a spatial extent that is adapted to the particular goal of the research question (Guisan & Thuiller, 2005). We are thus in need of so-called *big data*. The georeferenced occurrence data was downloaded from the Global Biodiversity Information Facility (henceforth: GBIF).

GBIF compiles georeferenced occurrence-data of species based on national inventories, citizen-science and other institutions. In 2020, already more than 1.3 billion records of 1 400 publishing institutions were merged. GBIFs strong suits are its taxonomical and geographical coverage, together with its easy accessibility worldwide. The biggest drawback of the GBIF-database is the need for extensive data cleaning, as many taxonomical and geographical errors still remain. Nevertheless, GBIF has been recognised as a game-changer when it comes to species distribution modelling (CODATA et al., 2020). The data was downloaded using the rgbif-package (Chamberlain et al., 2021).

2.2.3. Data cleaning

Data quality is a concern when using an openly accessible big data source such as GBIF. Taxonomical and geographical errors and duplicates are the most occurring issues, making data cleaning a necessity (CODATA et al., 2020; Serra-Diaz et al., 2017). Another problem in GBIF data are geographical gaps in concurrence data, but this problem is less pronounced in Europe (CODATA et al., 2020).

Taxonomical issues were dealt with during the downloading of the occurrence data. Data was downloaded based on species lists containing the different taxonomical synonyms observed to be present in the GBIF database. Data requests and downloads were done within the R-environment by making use of the rgbif-package (Chamberlain et al., 2021). We followed the cleaning process of Serra-Diaz et al. (2017). The first step was a removal of occurrences that were not georeferenced. In a second step, geographical duplicates were removed. Both of these steps were performed using the CoordinateCleaner-package (Zizka et al., 2019) available in R. Data with coordinates describing a location in lakes, seas or oceans were relocated to the nearest land area, by use of the biogeo-package (Robertson, 2016). Again a removal of geographic duplicates followed. The remaining occurrence data underwent a series of independent tests, to prepare the data for an optimal use in SDM. First of all, data in regions with no environmental information were omitted, as they could not contribute to the quality of the model. Occurrence data of trees that were taken out of their natural habitat by humans to be planted and maintained out of their ecological niche, would also fail to add to the quality of the model. Therefore, occurrence data located in botanical gardens and hyper-anthropogenic environments were removed. In data digitization, automatic assignment of occurrence data to the capital of the country is a common error. Therefore, all occurrence data linked to capitals or the GBIF-headquarters are removed. Also geographical and environmental outliers were removed. Subsequently, occurrences with a coordinate uncertainty of more than 5000 m were removed. Observations made before 1970 were removed as well, as the existence of these organisms after more than 50 years can be questionable. Of the 161 original climate species, 138 had data available on GBIF. Of these, 98 remain after the cleaning process. Of the remaining species, only 49 species had more than 100 occurrences. From the 14 original traditional species, only 4 survived the downloading and cleaning process.

2.2.4. Pseudo-absence generation

Although models built on presence-absence data generally outperform those based on presence-only data, the use of pseudo-absences in SDM has been evaluated to be useful (Marx & Quillfeldt, 2018; Wisz & Guisan, 2009). Although presence-absence data are available on GBIF, the majority of the occurrence data is presence-only. Omitting presence-only data and only making use of presence-absence data will drastically diminish the amount of available data. As the limited presence-only data originates from relatively few and spatially aggregated data sources, the observations will be spatially autocorrelated, causing problems when constructing SDMs (Naimi, 2015). Therefore we will make use of the pseudo-absence generation option, available in the biomod2-package (Thuiller et al., 2009).

The extent of the background from which pseudo-absences are taken, can have great impact on the performance of the built model (VanDerWal et al., 2009). As we will generally work on a European scale, we will take pseudo-absences over the entirety of Europe. Different kinds of modelling methods react differently to pseudo-absence generation (Barbet-Massin et al., 2012). Ideally, every model would have their individual method of pseudo-absence generation. However, if one uses evaluation criteria to assign weight to the prediction of each of the models in the ensemble-modelling approach (Thuiller et al., 2009), each model needs to be based on the same data. Otherwise the evaluation criteria cannot be compared between individual models. For that reason a single method of pseudo-absence generation was used. That is, randomly selected pseudo-absences across the entirety of Europe, with an amount equal to that of the presence data. Only one set of pseudo-absences was generated.

2.3. Climate data

2.3.1. Data source

Traditionally, coarse-grained air-temperature datasets form the training base of SDMs, but other sources for climate data, besides downscaled or interpolated data, exist as well. Two other possibilities are in-situ measurements and the use of remote-sensing data. Modern-Era Retrospective Analysis for Research and Application (henceforth referred to as MERRA) data uses remote-sensing data and in-situ measurements to create a temporally and spatially consistent meteorological grid (Waltari et al., 2014). The goal of this thesis is to make future projections. Therefore, the use of in-situ measurements and remote-sensing data are excluded. These data sources only contain information about the past and/or present. This would make it impossible to make bioclimatic consistent future predictions.

After omitting in-situ and remote-sensing measurements as the best choice of data source, we are left with the choice of which downscaled and interpolated data to use. Two high-resolution climate datasets will be discussed: "Climatologies at High resolution for the Earth's Land Surface Areas" (henceforth referred to as CHELSA) (Karger et al., 2017) and WorldClim2 (henceforth referred to as WorldClim) (Fick & Hijmans, 2017). Both are publicly available, at https://chelsa-climate.org/ and https://www.worldclim.org/data/index.html, respectively, and show high correlation on a global scale (Malanson, 2020). Both datasets include temperature, precipitation, solar radiation and vapour pressure parameters as well as 19 bioclimatic variables. These parameters are constructed as historical data and as future predictions, with projections for 2040, 2070 and 2100. CHELSA has extra parameters that cannot be found in the WorldClim dataset, e.g.: parameters on snow cover. WorldClim has a future prediction for 2050, which is absent in the CHELSA dataset (Fick & Hijmans, 2017; Karger et al., 2017; Malanson, 2020).

For this thesis, the WorldClim dataset was chosen, as it allows for projections over a larger array of GCMs and over more different timeframes, compared to CHELSA. This will result in a more robust estimation of climate resilience for the evaluated urban tree species.

WorldClim2 is the refined and expanded version of the first version of WorldClim. The data available on WorldClim is constructed by interpolating data from weather stations with different covariates, like elevation, distance to the coast and satellite data obtained from the MODIS satellite platform (Fick & Hijmans, 2017). Weather stations are not distributed homogeneously over the globe, so 23 distinct regions were delineated based on weather station density. The climate data for each region were then modelled individually (Fick & Hijmans, 2017). The set of 19 bioclimatic variables (O'Donnell & Ignizio, 2012) available on WorldClim were taken as predictor variables. The data were downloaded at a spatial resolution of 2,5 arcminutes. A list with a short description of each of these variables can be seen in table 2.

As a concluding remark, single-source models give less robust results than multi-source models (Morales-Barbero & Vega-Álvarez, 2019). The best way to reduce bias introduced by climate-data is to compare and compilate results from different sources. Yet, we will focus on only one of both data-sources as multi-source modelling is not the scope of this thesis.

Table 2: Bioclimatic predictors downloaded from WorldClim2 and their short description

Bioclimatic predictor	Description	Bioclimatic predictor	Description
Bio 1	Annual mean temperature	**Bio 11**	Mean temperature of coldest quarter
Bio 2	Annual mean diurnal range	**Bio 12**	Annual precipitation
Bio 3	Isothermality	**Bio 13**	Precipitation of wettest month
Bio 4	Temperature seasonality	**Bio 14**	Precipitation of driest month
Bio 5	Maximum temperature of warmest month	**Bio 15**	Precipitation seasonality
Bio 6	Minimum temperature of coldest month	**Bio 16**	Precipitation of wettest quarter
Bio 7	Annual temperature range	**Bio 17**	Precipitation of driest quarter
Bio 8	Mean temperature of wettest quarter	**Bio 18**	Precipitation of warmest quarter
Bio 9	Mean temperature of driest quarter	**Bio 19**	Precipitation of coldest quarter
Bio 10	Mean temperature of warmest quarter		

2.3.2. Climate scenarios

A common way to deal with the uncertainty linked to climate change, is by evaluating different possible scenarios (Brune, 2016; Gill et al., 2007; Hosseinzadehtalaei et al., 2018; IPCC, 2014; Jacob et al., 2014; McKenney et al., 2007; Millennium Ecosystem Assessment, 2005; Seppälä et al., 2009), this tactic will also be applied by constructing SDMs under different climate scenarios. Two distinct Shared Socio-economic Pathways (SSPs) are evaluated. Each SSP is based on global socio-economic responses to climate change and the resulting rise in greenhouse gas concentrations (Riahi et al., 2017). Each SSP will be projected in the period

2041-2060 and the period 2081-2100, resulting in four scenarios. The chosen SSPs were SSP2-4.5 and SSP5-8.5. The first SSP (SSP2-4.5) represents a middle of the road scenario (Riahi et al., 2017). The second SSP (SSP5-8.5) represents the worst case scenario (Riahi et al., 2017). This way the results cover the 'worst' half of possible future climate scenarios. Projections are made for the period of 2041-2060 and 2081-2100 because these timeframes correspond with the expected lifetime of urban trees planted in the upcoming decade. Two SSPs were evaluated over 2 different timeframes, resulting in a total of four separate scenarios.

The results in each of these four scenarios, will be a consensus of three Global Circulation Models (GCMs). The consensus is calculated as the mean of the results of each of the three GCMs within a certain scenario. Each GCM is constructed differently and makes different assumptions. Some GCMs can thus be interpreted to be more closely related to each other, than to other GCMs. This relatedness is based on the mechanics and assumptions that lie at the base of each GCM (Knutti et al., 2013). Three criteria were taken into account during the selection process: predictive performance, relatedness between the GCMs, and the availability on WorldClim. Fernandez-Granja et al. (2021) made a process-based evaluation on the predictive performance of different CMIP6 models and their CMIP5 counterparts. This resulted in a ranking of different GCMs. The top ranking GCMs that were available on WorldClim were noted, only taking into account the CMIP6 data, as they generally perform better than their CMIP5 predecessors (Cannon, 2020; Fernandez-Granja et al., 2021). Afterwards, three different GCMs were selected with the largest genealogical distance, based on Knutti et al. (2013). This last step was done to ensure maximum coverage over the spectrum of possible future situations. The choice of GCM can greatly impact the results of the predictions, especially at high SSPs (IPCC, 2014). By calculating a consensus of three distinct GCMs, the robustness of the made predictions increased. The three resulting GCMs are: IPSL-CM6A-LR, MIROC6 and CNRM-CM6-1.

We thus have a total of four scenarios (two timeframes with a middle of the road and worst case scenario) projected over three different GCMs to increase the robustness of the results.

2.4. Model construction

Different packages for ensemble SDM modelling exist in the R-environment (Hao et al., 2019). We will focus on the "biomod2-package" (Thuiller et al., 2009). This package allows for an ensemble-modelling approach, with several different modelling methods available. There is also a feature to generate pseudo-absences. Additionally, the package also allows for different ways of evaluating the goodness-of-fit and the accuracy of the trained models. The main feature of the biomod2-package is the amount of control the user has on the model parameterization (Naimi & Araújo, 2016; Thuiller et al., 2009).

The package allows for the use of ten different model classes. Five different model classes were used to obtain an extensive methodological coverage: maximal entropy model (MaxEnt), rectilinear envelope method (SRE), generalised additive models (GAM), random forest (RF) and artificial neural networks (ANN). For each model class, the default settings were used. There was a total of three runs and evaluations for each of the individual models. The results of each of the model classes could be included in the ensemble prediction. The model was constructed without any dispersal limitations. Only species that had at least 100 occurrences left after the data cleaning process were modelled.

The evaluation of the model accuracy (predictive power) is described by the following three evaluation metrics: Cohen's Kappa, the true skill statistic (TSS) and area under the relative operating characteristic curve (ROC). Cohen's Kappa shows the accuracy of the prediction relative to random chance. It ranges from -1 to 1, where 0 implies random prediction and 1 implies perfect prediction. TSS is similar to Cohen's Kappa, with the difference that the predictions are compared to an unbiased random chance prediction. ROC measures the ability of the model to distinguish between occurrence and non-occurrence. It ranges from 0 to 1, where 0,5 implies no distinction and 1 implies perfect distinction. The predictive power of each individual model was evaluated by a 20% cross-validation.

The TSS was chosen as the criterium on which to base the weighted mean in constructing the ensemble prediction. Model types with a higher predictive power for a certain species thus have larger weights in the ensemble model for that species. The cut-off threshold for the TSS of the individual models is set at 0,7. Individual models with a lower TSS, will be omitted from the ensemble-model. In doing so, the ensemble model is fitted to the data of a certain species.

2.5. Predictor variables

The importance of selecting ecologically and functionally relevant predictors in SDM has been widely recognised (Araújo & Guisan, 2006; Bradie & Leung, 2017; Elith & Leathwick, 2009).

Also the superiority of using proximal as opposed to distal variables has been identified (Bradie & Leung, 2017; Elith & Leathwick, 2009; Merow et al., 2014). Temperature and precipitation were found to be largest contributors to the predictive performance of SDM, where the variability of temperature and the minimum precipitation generally had the highest contribution (Bradie & Leung, 2017).

To make an ecologically and functionally relevant selection of predictors, we need again to take a look at the aim of this thesis: finding climate resilient urban tree species for Flanders. We do not aim to find species which can germinate and develop independently in urban areas. Rather, we are looking for trees that can survive for several decades in the urban environment after being planted. Variables that represent biological interaction have no added functional value within this research. Soil and near-soil temperature variables are not included as they were seen to have no added value in constructing SDMs for trees and shrubs (Lembrechts et al., 2019). Also other soil factors were not included as predictor variables. Firstly because no quantitative and relevant data on urban soils (in Flanders) exist. Additionally, it is a substantial challenge to sufficiently match urban soils to natural soils. Secondly, the added functional value of soil predictors would be limited. It is not claimed that soil properties have no impact on the habitat suitability for trees, but in the conceptual context of this research, including soil properties would not help in the species selection process. We assume all species put forward by the knowledge users can withstand the urban soil conditions. Furthermore, the species-specific soil needs can be tended to by green managers when planting trees, which cannot be done for species-specific atmospheric needs. Moreover, green managers of urban areas in Flanders generally make use of a universal soil substrate when planting green infrastructure.

For all these reasons, the atmospheric conditions of the urban environment is the factor with the largest species-specific impact on trees, that can be included in the model. Therefore, we will only make use of climatic variables, being temperature and precipitation data. A summation of the used bioclimatic predictors can be seen in table 2.

2.6. Model limitations

Maps which quantify the suitability of the future climate of Flanders to the species-specific needs were constructed. In no way can the generated maps be used as species distribution maps since dispersal limitations, biological interactions and soil suitability are not accounted for. This research solely focusses on the climatic suitability for species. The result is thus a map of the climatic niche projected in the future.

In this research, only a single source of environmental data is used. The downside to this is that predictions made by single-source models are less reliable than those of multi-source models (Morales-Barbero & Vega-Álvarez, 2019), the same way models based on a single GCM projection are less reliable than those based on multiple GCM projections.

The ultimate goal of this thesis is to evaluate the climate resilience of urban trees for Flanders. Individuals within a species can show great differences, but especially cultivars within a species can differ greatly in the way they react to the environment. Many cultivars were present on the lists of possible climate species that was put forward by the interviewees. But these cultivars cannot be tested, as no occurrence data of these cultivars are present on GBIF. Extensions of the climatic resilience of a species to a cultivar of that species cannot be assured.

In section 1.1.3, the Urban Heat Island effect is posed as a threat to both human and tree health. The effects of the Urban Heat Island are not integrated in the constructed models. This has a pronounced impact on the results. The generated climatic suitability maps show the future climatic suitability of Flanders to a species without the Urban Heat Island effect. When trees are planted in an urban area, the effects of climate change will be enlarged. This means that the climatic suitability for a species in urban areas is actually different from those represented on the generated maps. The magnitude and direction of this difference is based on the species' ecology, which can be partly derived from predictor response curves.

3. Results

3.1. Species Lists

3.1.1. Modelled Climate species

Table 3 shows a list of all climate species that were modelled for this thesis. The original list of climate species contained 161 distinct species and cultivars. These were mostly species originating from Southern or Eastern Europe. Of these 161 species, only 98 survived the downloading and cleaning process. Species with less than 100 occurrences left after data cleaning were not modelled. Eventually, not more than 47 climate species were modelled. Two species with more than 100 occurrences left after the cleaning process could not be modelled as none of the five model classes had a TSS-score over 0,7. Of all species that were modelled, 22 are observed to be at least moderately climate resilient for Flanders, based on the generated climatic suitability maps. These species are denoted in the last column of table 3. The original list of all climate species can be found in appendix 7.1.

Table 3: List of modelled climate species with their amount of occurrences after data cleaning. Species with less than 100 occurrences after data cleaning were not modelled. Species also present in the Traditional Species list are denoted in the 3rd column. Species that were observed to be at least moderately climate resilient for Flanders, are denoted in the last column.

Scientific name on GBIF	**Amount of occurences**	**Traditional species**	**Observed to be at least moderately climate resilient for Flanders**
Acer ginnala Maxim.	1,965		
Acer monspessulanum L.	7,439		
Acer opalus Mill.	4,003		
Acer rubrum L.	109		
Acer saccharinum L.	2,139	X	
Albizia julibrissin Durazz.	224		X
Broussonetia papyrifera (L.) Vent.	2,931		X
Carpinus orientalis Mill.	195		
Catalpa bignonioides Walter	3,885		
Cedrus atlantica (Endl.) Manetti ex Carriere	999		X
Cedrus deodara (Lamb.) G.Don	362		X
Cedrus libani A.Rich.	347		
Celtis australis L.	13,416		X
Cercis siliquastrum L.	7,921		X
Cornus mas L.	15,446		X
Corylus colurna L.	416	X	

Cotinus coggygria Scop.	14,283		X
Elaeagnus angustifolia L.	1,772		
Ficus carica L.	29,021		X
Fraxinus angustifolia Vahl	27,430	X	
Fraxinus ornus L.	2,969	X	X
Juglans nigra L.	839		X
Koelreuteria paniculata Laxm.	501		
Laburnum anagyroides Medik.	9,705		
Liquidambar styraciflua L.	148	X	X
Liriodendron tulipifera L.	389	X	
Mespilus germanica L.	7,469		X
Morus alba L.	1,416		X
Ostrya carpinifolia Scop.	2,342	X	X
Paulownia tomentosa (Thunb.) Steud.	4,719		X
Platanus hispanica Ten.	783	X	
Platanus orientalis L.	442		X
Prunus cerasifera Ehrh.	28,402	X	
Prunus domestica subsp. domestica	20,960		
Ptelea trifoliata L.	200		
Quercus cerris L.	2,920	X	X
Quercus frainetto Ten.	197		
Quercus ilex L.	20,001		X
Quercus pyrenaica Willd.	21,809		
Sorbus intermedia (Ehrh.) Pers.	33,879		
Sorbus latifolia (Lam.) Pers.	455		
Sorbus torminalis (L.) Crantz	20,975		X
Tamarix gallica L.	7,447		
Taxodium distichum (L.) Rich.	2,726		X
Tilia tomentosa Moench	240	X	
Ulmus laevis Pall.	5,077		
Ziziphus jujuba Mill.	2,090		X

3.1.2. Modelled Traditional species

Table 4 shows the list of all Traditional species that were modelled for this thesis. From the 14 original traditional species, only 4 survived the data downloading and cleaning process. The amount of occurrences that survived the cleaning process are shown in the second column. The last column shows the absolute frequency of the species in all three cities. The separate species list of each of the three cities, and the resulting compilated list can be seen in appendix 7.2 . None of the traditional species are observed to be climate resilient, based on the generated climatic suitability maps.

Table 4: List of Traditional Species with their total absolute frequency in Antwerp, Brussels and Ghent. Only four species were modelled, these are denoted in the last column.

Scientific name	**Amount of occurrences**	**Total Absolute Frequency**
Platanus occidentalis	16	56
Prunus serrulata	220	55
Salix pentandra	35,401	10
Tilia platyphyllos	17,877	1.315

3.2. *Quercus ilex*

The species *Quercus ilex* is used as a prototype for the climate species. It is a Mediterranean species with small leaves, conforming with the expected features of a possible climate species. Furthermore, it already has been planted on several locations in urban Flanders. With 20.001 occurrences left after the data cleaning process, it is an ideal species to explore the possibilities in SDM.

3.2.1. Model description

3.2.1.1. Input data

After downloading and cleaning the occurrence data of *Q. ilex* from GBIF, 20.001 occurrences remained. These occurrences are presence-only, so an equal amount of pseudo-absences were randomly generated over the entire geographical extent of Europe. These presences and pseudo-absences form the occurrence data on which the models were trained. A visual representation of the data can be seen in figure 1.

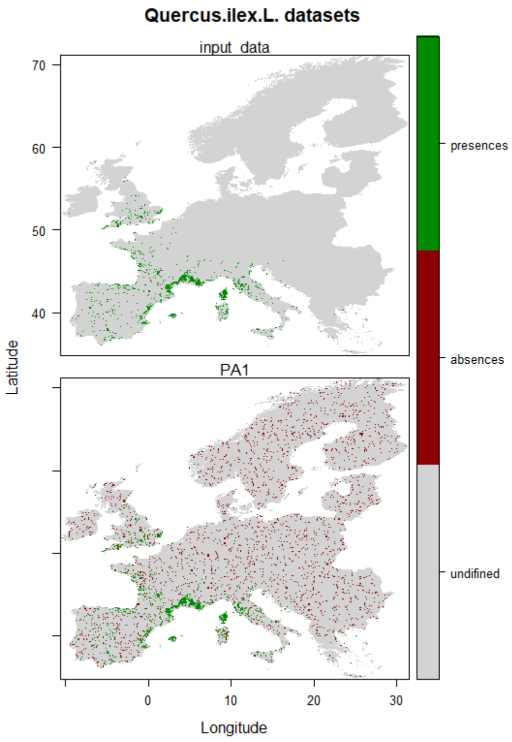

Figure 1: Input data of Q. ilex. The input data consists of presence data downloaded from the GBIF database and pseudo-absence data generated in the biomod2-package in R.

3.2.1.2. Evaluation

Cohen's Kappa, the True Skill Statistic (TSS) and the area under the relative operating characteristic curve (ROC) were used to evaluate the predictive power of the individual models and the ensemble model in a 20 % cross-validation. The results of the evaluations can be seen in table 5. Each metric is the mean of the 3 independent model runs. It can be seen that the ensemble model performs better than each of the individual models.

Table 5: Model evaluation of the ensemble model and individual models of Q. ilex. All metrics are a mean of three separate runs. The highest value for each metric is underlined.

	Model					
	Ensemble model	**MaxEnt**	**SRE**	**GAM**	**RF**	**ANN**
Kappa	<u>0.865</u>	0.749	0.594	0.782	0.842	0.769
TSS	<u>0.866</u>	0.752	0.590	0.784	0.842	0.771
ROC	<u>0.985</u>	0.900	0.795	0.959	0.980	0.963

3.2.1.3. Predictor Importance

The relative contribution of each predictor was evaluated for each of the individual models. A mean of the relative predictor importance across all three runs for all individual models can be seen in table 6. The relative importance is expressed as a percentage. Right away it is clear that 11^{th} bioclimatic variable has the largest contribution to the model.

Table 6: Relative predictor importance of all individual models of Q. ilex expressed in percentages. The presented result is the mean of the relative importance of the three runs made for each model.

	Mean	**Description**
Bio 1	7.50%	Annual mean temperature
Bio 2	2.61%	Annual mean diurnal range
Bio 3	3.31%	Isothermality
Bio 4	5.49%	Temperature seasonality
Bio 5	6.22%	Maximum temperature of warmest month
Bio 6	8.11%	Minimum temperature of coldest month
Bio 7	6.59%	Annual temperature range
Bio 8	1.54%	Mean temperature of wettest quarter
Bio 9	2.40%	Mean temperature of driest quarter
Bio 10	9.34%	Mean temperature of warmest quarter
Bio 11	19.05%	Mean temperature of coldest quarter
Bio 12	3.45%	Annual precipitation
Bio 13	2.07%	Precipitation of wettest month
Bio 14	6.04%	Precipitation of driest month
Bio 15	1.67%	Precipitation seasonality
Bio 16	2.13%	Precipitation of wettest quarter
Bio 17	4.00%	Precipitation of driest quarter
Bio 18	1.73%	Precipitation of warmest quarter
Bio 19	3.58%	Precipitation of coldest quarter

In table 6, the relative importance of all predictor variables for *Q. ilex* can be seen. In table 7, the top 5 of these predictors are ranked by relative importance. It can be seen that only temperature predictors are present in the top 5. Also, the mean temperature of the coldest quarter holds the largest importance in the models.

Table 7: Top 5 predictors for the climatic suitability to *Q. ilex*.

Bioclimatic predictor	**Relative importance**	**Short description**
Bio 11	19.05%	Mean temperature of coldest quarter
Bio 10	9.34%	Mean temperature of warmest quarter
Bio 6	8.11%	Minimum temperature of coldest month
Bio 1	7.50%	Annual mean temperature
Bio 7	6.59%	Annual temperature range

3.2.1.4. Predictor Response Curves

To gain insight in the relation between the climatic suitability for a species and certain bioclimatic predictors, predictor response curves were constructed. Figure 2 and 3 show the predictor response curves for the five bioclimatic predictors with the highest relative importance for *Q. ilex*. Figure 2 shows the response curves for the MaxEnt model, figure 3 shows the response plots for the Random Forest model. These two models were chosen based on the ecological interpretability of the models and the predictive performance of the models (table 5).

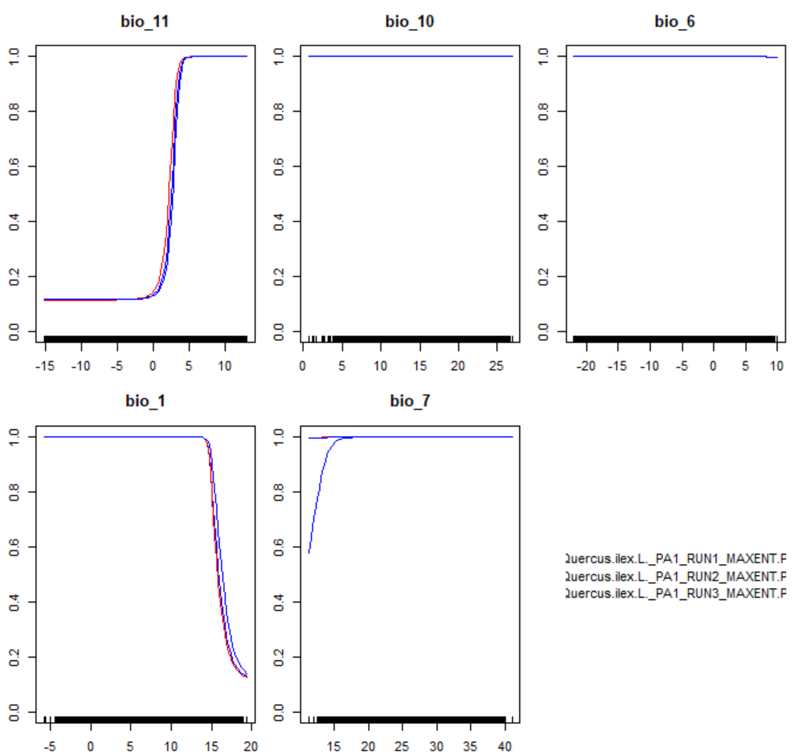

Figure 2: Predictor Response Curves of the MaxEnt model for Q. ilex.

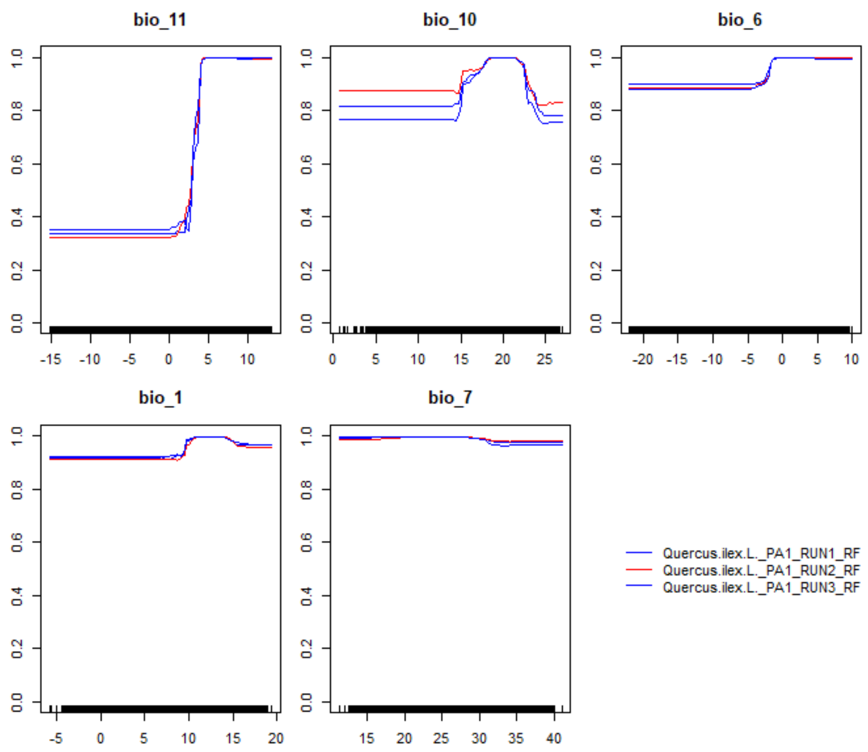

Figure 3: Predictor Response Curves of the Random Forest model for Q. ilex.

3.2.2. Climate projections on extent of Europe

The projected climatic suitability in each of the four scenarios for *Quercus ilex* on the extent of Europe can be seen in figure 4. The climatic suitability is the predicted chance of occurrence, based on the projected bioclimatic variables for that particular scenario. The climatic suitability ranges from 0 (no chance of occurrence) to 1000 (certainty of occurrence). Scenario 1 corresponds with SSP 2-4.5 in year 2050, scenario 2 with SSP 5-8.5 in 2050, scenario 3 with SSP 2-4.5 in 2100 and scenario 4 with SSP 5-8.5 in year 2100. The plots on the left, scenario 1 and 3, can thus be viewed as a timeline for the middle-of-the-road scenario. The plots on the right, scenario 2 and 4, can be seen as a timeline for the worst case scenario.

Each of the maps in figure 4 is a consensus of three distinct GCMs and an ensemble of the results of all individual models that had a TSS-score of 0.7 or higher. To illustrate the construction process, the individual models for each of the three GCMs in scenario 1 can be found in appendix 7.3. In section 7.3.1 one can see the results of each individual model, grouped per GCM. It can be seen that the individual models can show large discrepancies in results. Each of these individual models contribute to the ensemble prediction. The weight of each of the individual models in the ensemble models is based on its TSS. This results in a total of three ensemble-model predictions, one for each GCM. These three ensemble-model predictions for scenario 1 can be seen in appendix 7.3.2. The mean of these three forms a consensus prediction, which is the upper-left plot in figure 4.

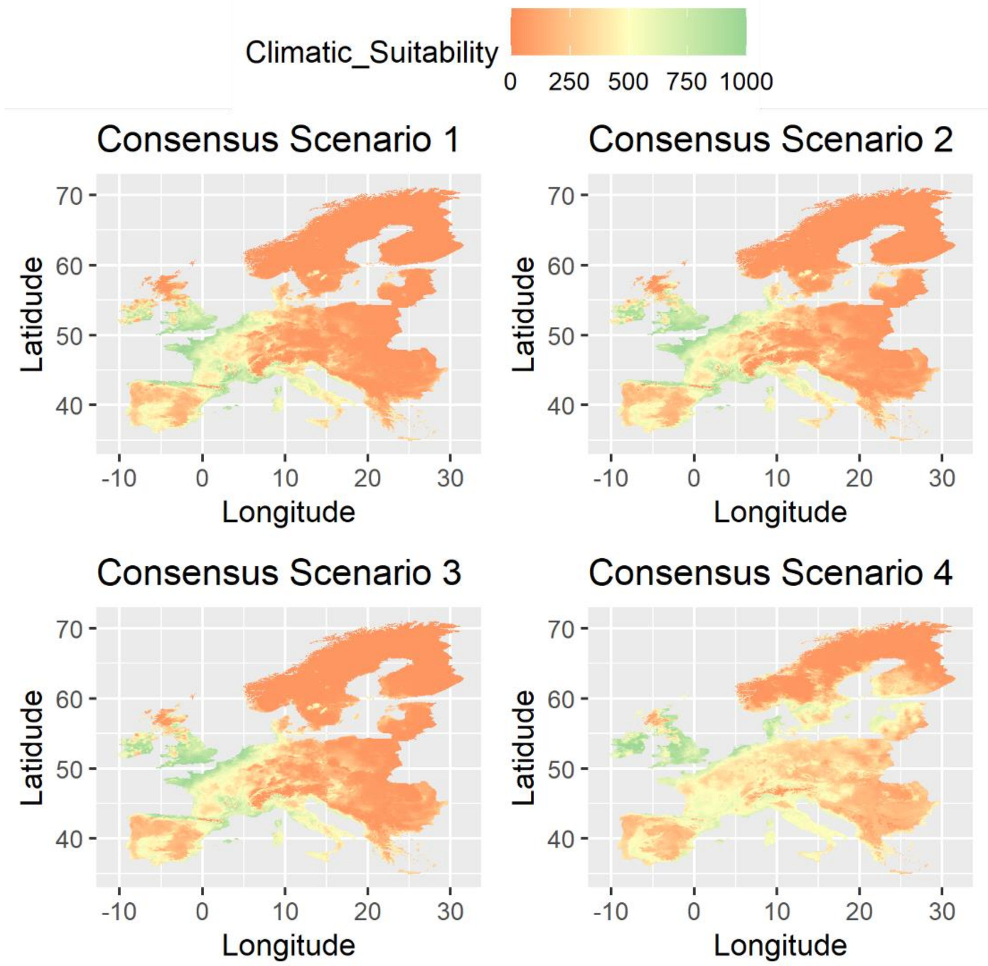

Figure 4: Consensus projections of the climatic suitability for Q. ilex on the extent of Europe. Scenario 1 and 3 represent a middle-of-the-road scenario for the year 2050 and 2100 respectively. Scenario 2 and 4 represent a worst case scenario for the 2050 and 2100 respectively.

3.2.3. Climate projections on extent of Flanders

To facilitate the evaluation of the climatic suitability for Flanders, the results were cropped to the extent of Flanders. The projected climatic suitability for each in the four scenarios for *Quercus ilex* on the extent of Flanders can be seen in figure 5. *Q. ilex* shows moderate to strong climate resilience for Flanders. The climatic suitability is highest in scenario 2 (middle-of-the-road scenario in 2100) and 3 (worst case scenario in 2050). It is lowest for scenario 4 (worst case scenario in 2100).

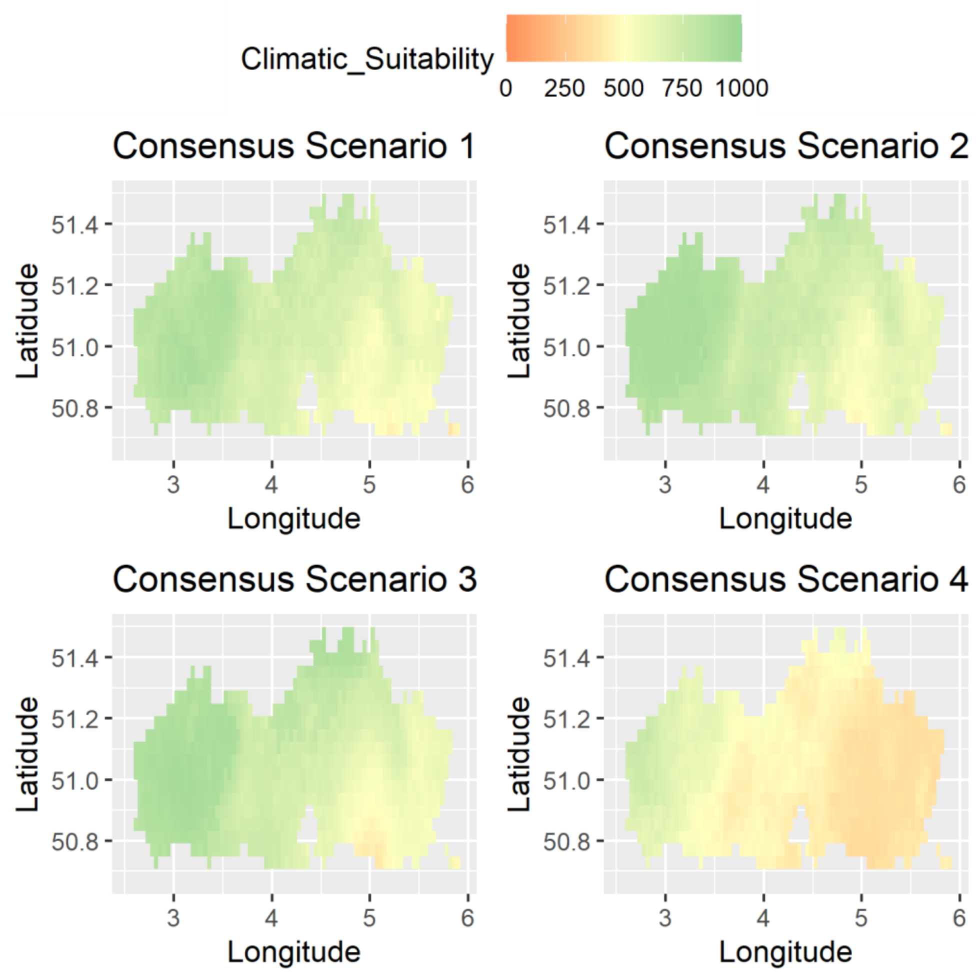

Figure 5: Consensus projection of the climatic suitability for Q. ilex on the extent of Flanders. Scenario 1 and 3 represent a middle-of-the-road scenario for the year 2050 and 2100 respectively. Scenario 2 and 4 represent a worst case scenario for the 2050 and 2100 respectively.

3.3. *Tilia platyphyllos*

Table 1 shows that *Tilia platyphyllos* is the most occurring traditional species used in Antwerp, Brussels and Ghent. The species is indigenous to Flanders. After data cleaning 17.877 occurrences still remained. It will be used as a protype for the traditional species.

3.3.1. Model description

3.3.1.1. Input data

After downloading and cleaning the occurrence data of *T. platyphyllos* from GBIF, 17.877 occurrences remained. These occurrences are presence-only, so an equal amount of pseudo-absences were randomly generated over the entire geographical extent of Europe. These presences and pseudo-absences form the occurrence data on which the models were trained. A visual representation of the data can be seen in figure 6.

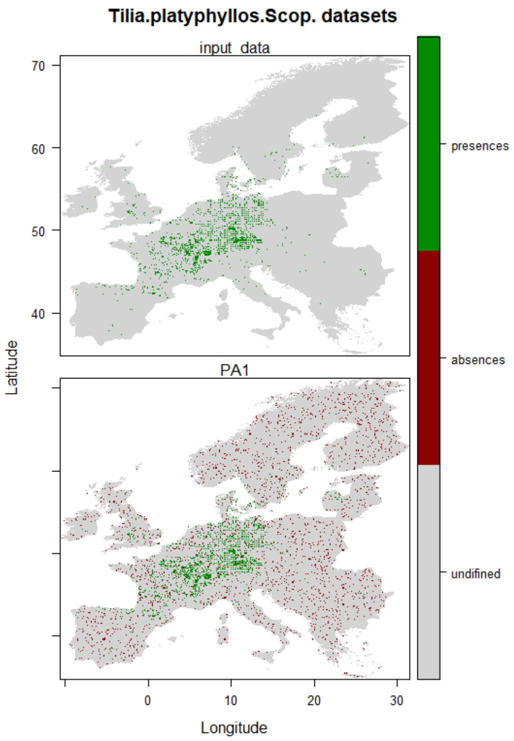

Figure 6: Input data of T. platyphyllos. The input data consists of presence data downloaded from the GBIF database and pseudo-absence data generated in the biomod2-package in R.

3.3.1.2. Evaluation

Cohen’s Kappa, the True Skill Statistic (TSS) and the area under the relative operating characteristic curve (ROC) were used to evaluate the predictive power of the individual models and the ensemble model in a 20 % cross-validation. The results of the evaluations can be seen in table 8. Each metric is the mean of the 3 independent model runs. It can be seen that the ensemble model performs better than each of the individual models.

Table 8: Model evaluation of ensemble model and individual models of T. platyphyllos. All metrics are a mean of three separate runs. The highest value for each metric is underlined.

	Model					
	Ensemble model	**MaxEnt**	**SRE**	**GAM**	**RF**	**ANN**
Kappa	<u>0.842</u>	0.693	0.553	0.712	0.769	0.705
TSS	<u>0.842</u>	0.694	0.552	0.712	0.769	0.705
ROC	<u>0.984</u>	0.916	0.776	0.921	0.948	0.896

3.3.1.3. Predictor Importance

The relative contribution of each predictor in the model was evaluated for each of the individual models. A mean of the relative predictor importance across all three runs for all individual models can be seen in table 9. The relative importance is expressed as a percentage. One can see that the relative importance for the model of *T. platyphyllos* (table 9) is distributed more evenly than for the model of *Q. ilex* (table 6).

Table 9: Relative predictor importance of all individual models of T. platyphyllos expressed in percentages. The presented result is the mean of the relative importance of the three runs made for each model.

	Mean	**Description**
Bio 1	7.00%	Annual mean temperature
Bio 2	4.59%	Annual mean diurnal range
Bio 3	4.98%	Isothermality
Bio 4	9.59%	Temperature seasonality
Bio 5	8.21%	Maximum temperature of warmest month
Bio 6	8.32%	Minimum temperature of coldest month
Bio 7	8.62%	Annual temperature range
Bio 8	0.96%	Mean temperature of wettest quarter
Bio 9	1.51%	Mean temperature of driest quarter
Bio 10	8.69%	Mean temperature of warmest quarter
Bio 11	5.61%	Mean temperature of coldest quarter
Bio 12	4.59%	Annual precipitation
Bio 13	2.14%	Precipitation of wettest month
Bio 14	2.11%	Precipitation of driest month
Bio 15	2.61%	Precipitation seasonality
Bio 16	3.66%	Precipitation of wettest quarter
Bio 17	7.99%	Precipitation of driest quarter
Bio 18	4.21%	Precipitation of warmest quarter
Bio 19	2.22%	Precipitation of coldest quarter

In table 9, the relative importance of all predictor variables for *T. platyphyllos* can be seen. In table 10, the top 5 of these predictors are ranked by relative importance. Similar to *Q.ilex*, we see no precipitation predictor in the top 5. For both species, the mean temperature of the warmest quarter is the second most important predictor. This predictor explains roughly nine percent of the variation in both species.

Table 10: Top 5 predictors for the climatic suitability to T. platyphyllos

Bioclimatic Predictor	Relative Importance	Short Description
Bio 4	9.59%	Temperature seasonality
Bio 10	8.69%	Mean temperature of warmest quarter
Bio 7	8.62%	Annual temperature range
Bio 6	8.32%	Minimum temperature of coldest month
Bio 5	8.21%	Maximum temperature of warmest month

3.3.1.4. Predictor Response Curves

To gain insight in the relation between the climatic suitability for a species and certain bioclimatic predictors, predictor response curves were constructed. These response curves were constructed only for the five predictors with the highest relative predictor importance. Figure 7 shows the predictor response curves of the MaxEnt model for *T. platyphyllos*. Figure 8 shows the predictor response curves of the Random Forest model for *T. platyphyllos*.

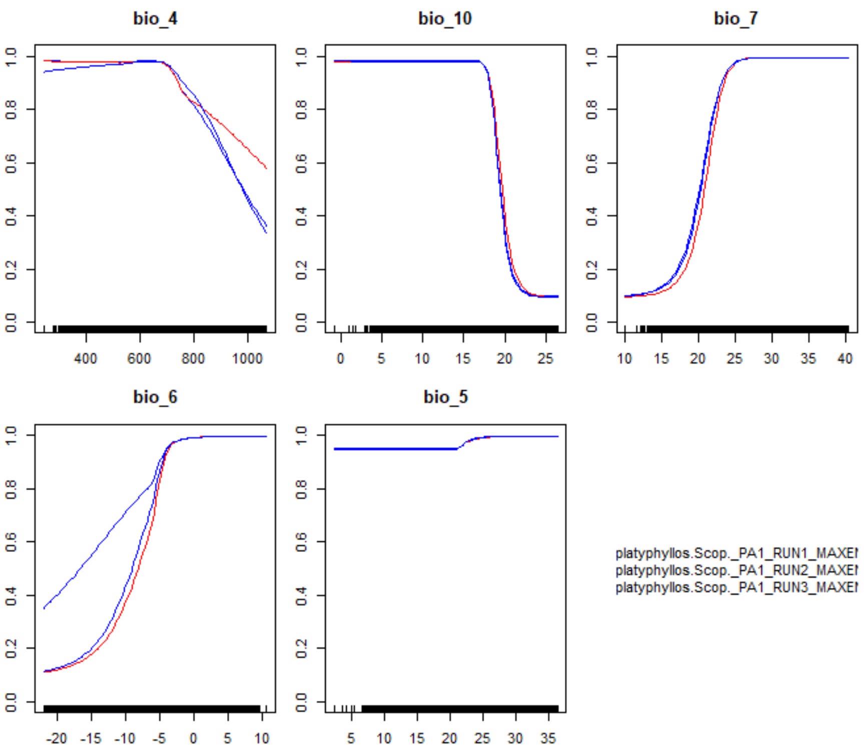

Figure 7: Predictor Response Curves of the MaxEnt model for T. platyphyllos.

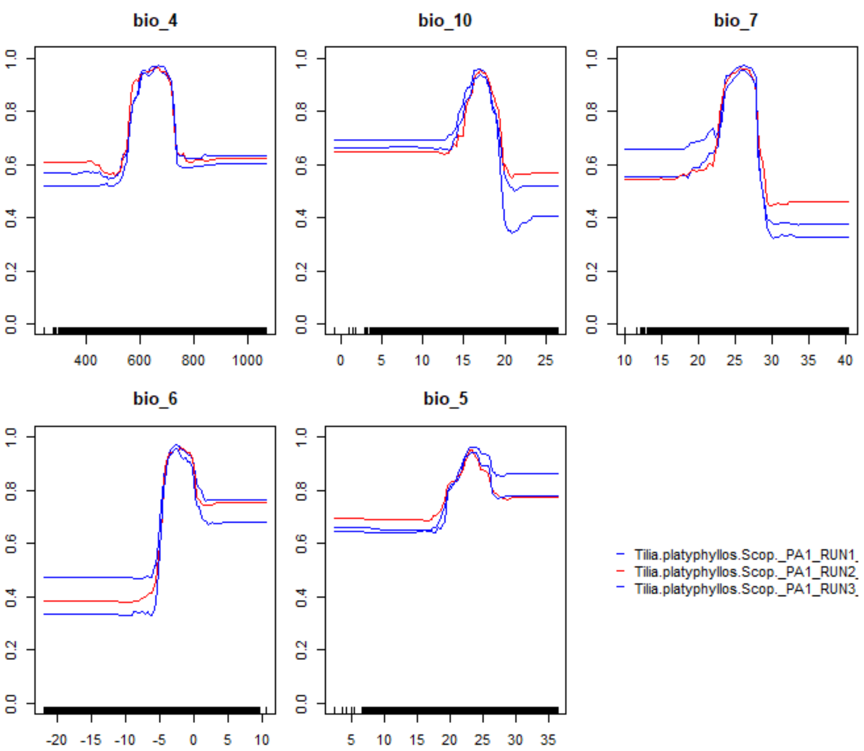

Figure 8: Predictor Response Curves of the Random Forest model for T. platyphyllos.

3.3.2. Climate projections on extent of Europe

The projected climatic suitability for each of the four scenarios for *Tilia platyphyllos* on the extent of Europe can be seen in figure 9. The climatic suitability is the predicted chance of occurrence, based on the projected bioclimatic variables for that particular scenario. The climatic suitability ranges from 0 (no chance of occurrence) to 1000 (certainty of occurrence). Scenario 1 corresponds with SSP 2-4.5 in year 2050, scenario 2 with SSP 5-8.5 in 2050, scenario 3 with SSP 2-4.5 in 2100 and scenario 4 with SSP 5-8.5 in year 2100. The plots on the left, scenario 1 and 3, can thus be viewed as a timeline for the middle-of-the-road scenario. The plots on the right, scenario 2 and 4, can be seen as a timeline for the worst case scenario.

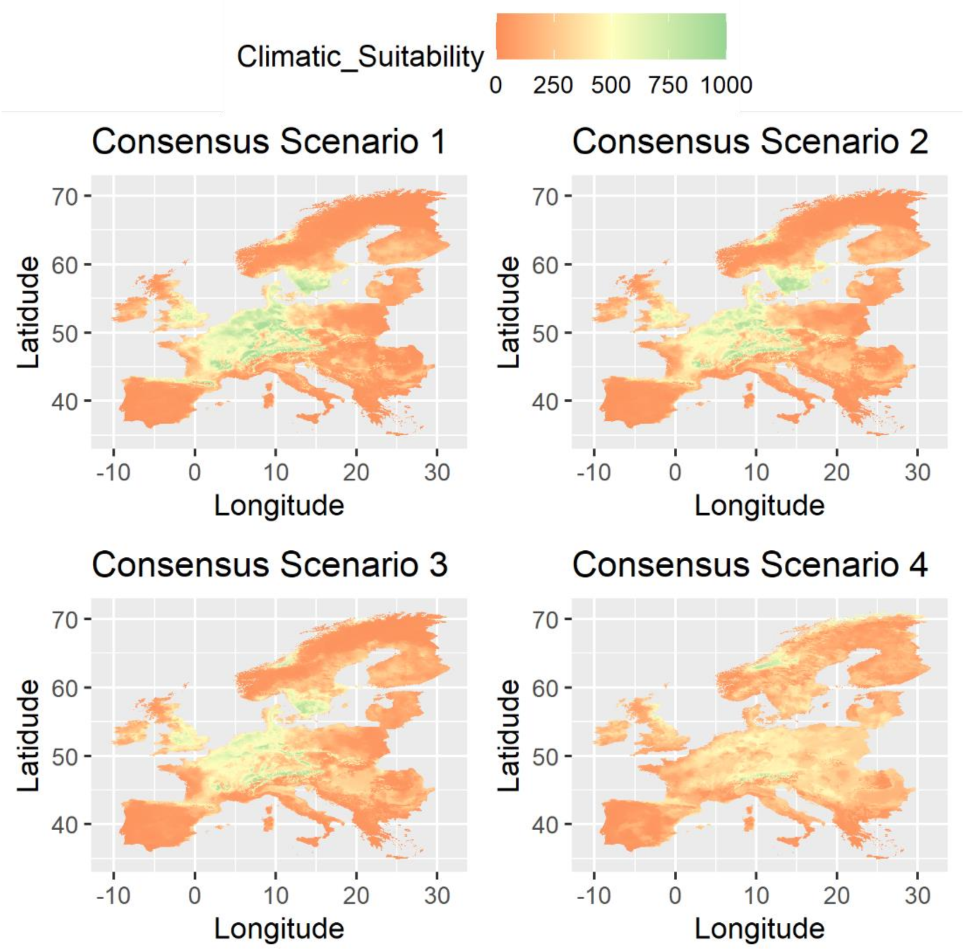

Figure 9: Consensus projections of the climatic suitability for T. platyphyllos on the extent of Europe. Scenario 1 and 3 represent a middle-of-the-road scenario for the year 2050 and 2100 respectively. Scenario 2 and 4 represent a worst case scenario for the 2050 and 2100 respectively.

3.3.3. Climate projections on extent of Flanders

To facilitate the evaluation of the climatic suitability for Flanders, the results were cropped to the extent of Flanders. The projected climatic suitability for each of the four scenarios for *Tilia platyphyllos* on the extent of Flanders can be seen in figure 10. *Tilia platyphyllos* shows a low climatic resilience for Flanders. The climatic suitability in Flanders for *Tilia platyphyllos* is highest in scenario 1 and lowest in scenario 4.

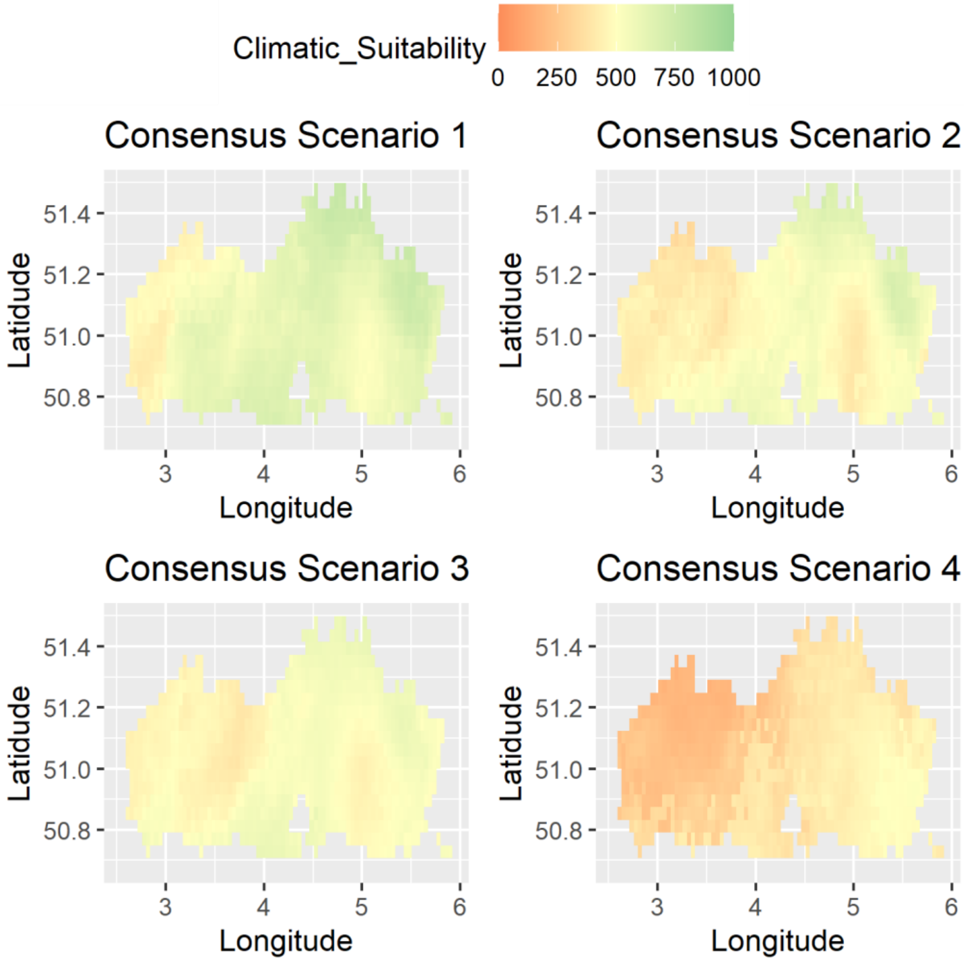

Figure 10: Consensus projections of the climatic suitability for T. platyphyllos on the extent of Flanders. Scenario 1 and 3 represent a middle-of-the-road scenario for the year 2050 and 2100 respectively. Scenario 2 and 4 represent a worst case scenario for the 2050 and 2100 respectively.

4. Discussion

The aim of this research is to quantify the suitability of the future urban climate of Flanders for different urban tree species. To ensure the urban applicability of the researched tree species, we only investigated trees which are known by experience to be applicable in urban areas. For this we invoked the practical knowledge of urban green managers and tree nurseries from Flanders. These knowledge users supplied a list of urban tree species which they believed to be potentially climate resilient. The climate resilience of the different proposed tree species were evaluated via Species Distribution Modelling.

4.1. Do we need Climate Resilient Tree species?

47 potentially climate resilient species were tested. 22 of these species were observed to be at least moderately climate resilient for Flanders, based on the produced results. Generally, Mediterranean species are most promising. Continental species are seen to be less climate resilient for Flanders. Urban green managers are thus advised to point their visor southward for potentially interesting species for urban areas in Flanders. Of all the modelled climate species, 11 species already have a tradition of being used in urban Flanders. Only 4 of these species were observed to be at least moderately climate resilient for Flanders.

Of all modelled exclusively traditional species, none were shown to be climate resilient. Trees that are already established will probably will be able to live out their expected lifetime. Individuals of traditional tree species that are planted presently or in the near future, will have a shorter lifetime than expected. This will be due to an increase in demand driven water stress because of the effects of climate change, strengthened by the Urban Heat Island.

It thus seems that the majority of trees currently present in urban Flanders are not climate resilient. More Mediterranean species will need to be used. When urban green managers plan to plant new trees in urban centres, they are strongly advised to use the addendum of this thesis to evaluate the climate resilience of tree species. Incorporating these results in the decision making process, might prevent large financial losses due to a deterioration in vitality of non-climate resilient trees in urban areas.

4.2. Comparing Climate and Traditional species

Table 7 shows insight in the ecology of *Q. ilex*. The importance of the predictors can only demonstrate the natural ecology of the species. In its natural environment, precipitation might not be a limiting factor. It will thus not show up in the top 5 most important predictions. But this does not necessarily mean that the same conclusion can be made for the urban environment. The limiting factors in the natural environment do not automatically correspond with the limiting factors in the urban environment. The urban environment can have a great impact on the hydrological dynamics within a tree, see section 1.2.2.

Except for the difference in which bioclimatic predictors are in the top 5 for *T. platyphyllos*, table 10 shows another distinct difference with the results for *Q. ilex* in table 7. The difference in relative importance between the first and the second most important predictor in table 9 is less than 1 %. While in table 10, there is a difference of one order of magnitude between the first and second most important predictor. This shows that the model of *T. platyphyllos* is less dominated by one predictor. The predictor response curves thus only allow for a less pronounced description of the species' ecology, compared to *Q. ilex*.

For both species, only temperature predictors are present in the top 5 most important predictors. From this we can gather the importance of temperature in determining the climatic suitability for a certain species. The Urban Heat Island effect can thus have a great impact on the vitality of urban trees.

Interpreting the response plots in figure 2, one can see that the MaxEnt model only shows a characteristic relationship with the 11^{th} and the 1^{st} bioclimatic predictor, the mean temperature of the coldest quarter and the annual mean temperature, respectively. The predictor response curve for the mean temperature of the coldest quarter (predictor 11) shows a clear bottom limit, showing *Q. ilex* is most suitable for soft winters. The response curve for annual mean temperature (predictor 1) shows *Q. ilex* has an upper limit for the mean annual temperature around 15 °C. In figure 3, the response curves for the mean temperature of the coldest quarter (predictor 11) and the minimum temperature of the coldest month (predictor 6) show a bottom limit for temperatures similar to the response curves in figure 2. Predictor 10, the mean temperature of warmest quarter, shows an optimal zone between 15 °C and 25 °C in figure 3.

Comparing to *Q. ilex*, *T. platyphyllos* shows a reversed relationship to bioclimatic predictor 10, the mean temperature of the warmest quarter. The climatic suitability for *Q. ilex* reacts neutral or slightly positive to a mean temperature of the warmest quarter that is higher than 17 °C. While a mean temperature of the warmest quarter above 17 °C has a distinct negative impact on the climatic suitability for *T. platyphyllos*. As the effect of the Urban Heat Island is largest in the warmest quarter, the relationship to this bioclimatic variable might be decisive in the measure of the climate resilience of a certain urban tree species. To confirm this hypothesis, an extensive analysis of the predictor response curves for an array of climate resilient species is needed.

It thus seems that the difference between climate resilient and non-climate resilient trees lies in their relationship to climatic temperature variables. Especially a rise in mean temperature of the warmest quarter. Which has a neutral or positive impact on the vitality of climate resilient trees, while it has a negative impact on the vitality of non-climate resilient trees.

4.3. How "Resilient" is Climate Resilient?

On figure 4, one can see the poleward migration of the climatic suitability for *Quercus ilex*, as was expected from the literature study. A similar pattern can be found for all modelled species. Figure 5 shows the climatic suitability of Flanders for *Quercus ilex* in 4 different scenarios. In scenario 4, one can see the core of climatic niche has already past Flanders, while Flanders is still in the core of the climatic niche in scenario 3. Another consistent result seen across all species, is the agreement in results of scenario 2 compared to scenario 3. This shows that a higher relative concentration in greenhouse gases will accelerate the poleward migration pattern. This implicates that when the worst case scenario would become reality, even most climate resilient trees would not be able to live out their urban life cycle. The poleward migration of the climatic suitability would become so rapid, that when a Mediterranean species is planted, the optimal climatic suitability would already be north of Flanders before the urban life cycle is completed.

Figure 9 and 10 show the climatic suitability for *Tilia platyphyllos* on the extent of Europe and Flanders, respectively. On figure 9 can be seen that in the year 2050 the core of the climatic niche lies north of Flanders, for both the middle-of-the-road and worst case scenario. In 2100, the climatic niche for *T. platyphyllos* has largely disintegrated. On figure 10, we can see a moderate climatic suitability for scenario 1. Scenario 2 and 3 show a moderately low climatic suitability. The climatic suitability for scenario 4 is low. The results in figure 9 and 10 do not include the Urban Heat Island effect. Combining this with the fact that figure 7 and 8 show that *T. platyphyllos* is sensitive to higher temperatures in the warmest quarter, the climatic suitability is even lower than shown on figure 9 and 10. We can conclude that *Tilia platyphyllos* is not climate resilient.

The indigenous tree species of Flanders will have a substantially diminished vitality when planted in an urban environment because of the mutually reinforcing effects of climate change and the Urban Heat Island. We will need to invoke Mediterranean species to render our urban tree stock more resilient to the effects of climate change. But even some of these Mediterranean species will not be suitable in the worst case scenario.

4.4. Impact of the Urban Heat Island effect

The need for bioclimatic agreement between the training data and prediction data in constructing SDMs became clear in an exploratory part of this research. As the focus lies on selecting species for urban areas, including atmospheric effects of urban areas would be ecologically relevant. This atmospheric effect would be the Urban Heat Island effect resulting in warmer and drier climates in urban areas (USA EPA, 2013).

VITO (Flemish Institute for Technological Research) constructed a climate model to incorporate the Urban Heat Island effect, named UrbClim. This model can generate temperature maps for present and future, on 100 m-scale which include the effects of the Urban Heat Island (De Ridder et al., 2015). Available UrbClim temperature maps of Flanders included a high, middle and low scenario for the average summer temperature for the periods 2019, 2020, 2030, 2050 and 2100. Figure 11 shows a temperature map generated by UrbClim in the high scenario for 2100.

Unfortunately, the integration of this data created no useable results. The problem was the lack of bioclimatic agreement. As both datasets are based on different modelling techniques, the genealogical distance between the WorldClim and UrbClim data was too large to interchange data from both datasets. The models were trained on WorldClim data and performed well on making predictions based on WorldClim data. But when one of the predictor variables, predictor 10, was swapped out with a temperature map generated by UrbClim to make predictions on the extent of Flanders, no useable results could be generated. This is because there is a structural difference between the temperature predictions of WorldClim and UrbClim. When UrbClim is integrated into the WorldClim data, the combinations of different predictor values did not match any of those present in the training dataset, resulting in a zero value of suitability across the entirety of Flanders. This issue illustrates the importance of bioclimatic consistency in SDM.

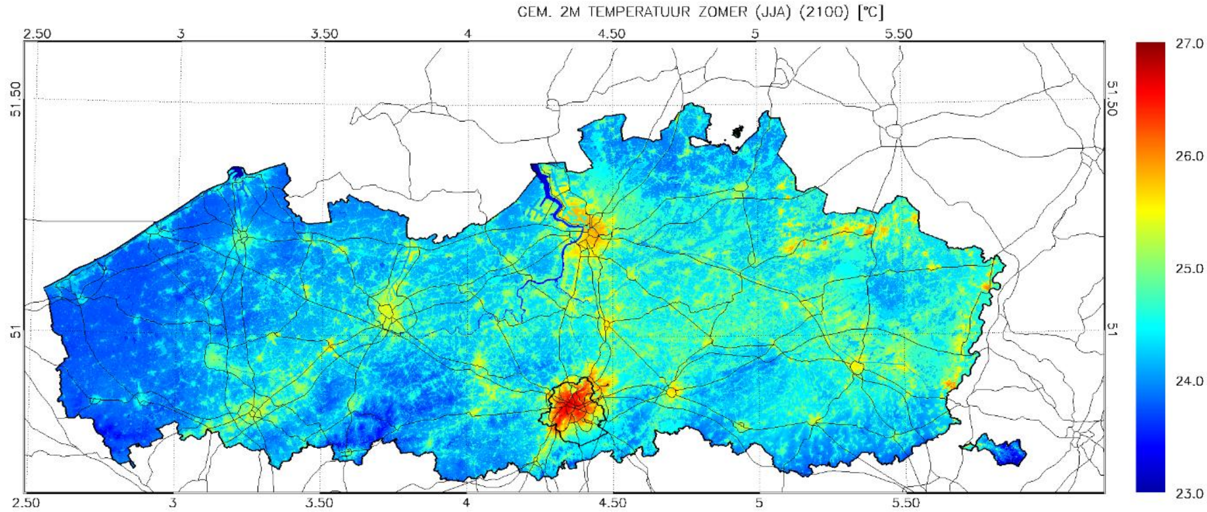

Figure 11: Average summer temperature for high scenario in 2100, modelled by UrbClim (data provided by prof H. Wouters).

Figure 11 also shows that strictness is necessary when interpreting the generated results. The scenario of the data in figure 11 match scenario 4 in the results generated in this thesis. On figure 11, it can be seen that an average summer temperature difference of as much as 4° C between rural and urban areas in Flanders is possible. This temperature difference can greatly affect the climatic suitability for tree species in urban areas. Especially because the mean temperature during the warmest quarter was the second most important bioclimatic predictor for both evaluated species (see table 7 and 10). The maps generated in this thesis do not account for the Urban Heat Island effect. One can see that figure 10 shows a low climatic suitability for *Tilia platyphyllos* in scenario 4. In reality, the climatic suitability of *T platyphyllos* in scenario 4 is even lower. As we are looking for climate resilient species for urban areas, the Urban Heat Island effect must be included. Figure 7 also shows the sensitivity of *T. platyphyllos* to a rise in the temperature of the warmest quarter. With this in mind, the generated results must be interpreted strictly, for both climate and traditional species.

4.5. Ensemble modelling

In table 5 and 8 it can be seen that the ensemble-model has a better predictive performance than each of the individual models separately, for all evaluation metrics. This demonstrates the power of the ensemble-modelling technique. In appendix 7.3 the results of the individual model projections of *Quercus ilex* in scenario 1 can be seen. The results of the individual models show large discrepancies. If only one model was to be used, this would be a reason for concern. While in ensemble-modelling, these discrepancies are the reason for a better predictive performance. The models complement each other which results in a better ensemble-prediction than any of the individual models could make on their own

The ensemble modelling method has proved useful in evaluating the climate resilience for an array of different species. It allowed for automatic model fitting through the chosen method of ensemble construction. It is possible that for the data of a certain species an individual model performed better than the ensemble model, but no one model will do so for all of the evaluated species. By invoking a diversity of model classes, a decent result for all species can be guaranteed. The different model classes complement each other.

However, some disadvantages of ensemble modelling have come forward. Looking at figure 2 and 3, it can be seen that while a certain predictor might have a distinct profile for one model class, it doesn't necessarily has one with all model classes. While predictor 10 shows a distinct optimal zone in figure 3, the climatic suitability is rather indifferent to predictor 10 in figure 2. If one wishes to select the predictors on which the model will be trained, this cannot be done optimally for all models. Certain models will have to accept the input of certain predictors, because they are important for other models. If models are based on different training data, they cannot be compared and an ensemble could not be constructed methodologically. Furthermore, one can only construct the predictor response curves for certain individual models and not for the ensemble model. Being able to generate predictor response curves for the ensemble model, and comparing these to those of the individual models, might deepen the insight in the species' ecology.

4.6. Knowledge Integration

Conventionally, the academic world creates knowledge and knowledge users apply this knowledge. When the created knowledge does not integrate practical conditions, or problems unforeseen by the academic world rise, the process restarts. In the case of this thesis, the academic world is presented by the researcher and the knowledge users are represented primarily by urban green managers. In the traditional academic approach, the researcher would compilate different lists and databases of similar academic research. The resulting species list would then be filtered and distilled until only species that fit the own research question remain. Results would be generated for the selected species and the results would be presented to the urban green managers in Flanders.

For this research urban green managers, tree nurseries, other researchers and urban green institutions were contacted to ask about their knowledge and their view on the subject of climate resilient urban tree species. That way, insight was gained in what is already known and what is not, which knowledge is already used and which is not. Urban green managers gladly pointed out gaps in their knowledge, and actively contributed to the effort to fill these knowledge gaps. This resulted in a collaborative research approach, with a mutual learning process. Tree nurseries reacted either enthusiastic and shared all of their knowledge, or defensive and being sceptic about sharing data openly. The latter is understandable, as their financial wellbeing could be at stake. Other researchers and institutions offered a guiding role, they were delighted to share their experiences and helped extending my limited network.

4.6.1. Constructing Species Lists

The most fundamental contribution of this approach was the construction of practically relevant species lists. Basing the species list on similar research would risk including species, which are not relevant in the practical world, or omitting species, which are of great interest to the knowledge users. In the traditional approach, the resulting lists would only be presented to the knowledge users after the research is finished. If species that are important or relevant to the knowledge users were not included, this problem would only arise after publication. Knowledge users are left with knowledge gaps, or the research should restart with an adapted species list. Because of the collaborative approach, the 22 species observed to be at least moderately climate resilient are known to be commercially available to urban green managers. By the traditional approach, the list of climate resilient species might contain species that are not available to urban green managers.

The lists with potentially climate resilient trees put forward by knowledge users were based on experience, natural species distribution and species ecology. This qualitative approach proved useful in generating a list of potentially interesting climate species. The different actors around the theme of climate resilient urban trees generally agree on the need for non-indigenous trees in urban areas. There is minor disagreement about the origin of this non-indigenous species. Most people involved agree on the use of European species. While some deem Eastern-European species most promising, others see great potential in Mediterranean species. This nuance in perception gives birth to a healthy discussion about the topic and forces green managers to inform themselves to make a sound selection of species. It thus aids in the generation of knowledge.

The list of traditional species was a result of the compilation of three tree inventories. Although many urban tree inventories exist, no central database unifies all of these inventories. To circumvent this problem, the three largest cities in the geographical area of Flanders were contacted directly. The three different inventories on which the traditional species list was based, did not always correspond in taxonomic resolution. Therefore, the absolute frequencies of the species list in section 7.2.2 offer a guiding role in ranking the popularity of the traditional species, rather than representing the exact amount of individuals for that species currently present in Antwerp, Brussels and Ghent. The collective traditional species list included 44 traditional species, of which 28 also already occurred in the climate species list. This shows that green managers are already aware of the problem concerning tree species and urban climate.

4.6.2. Different views

After taking several questionnaires, two things became clear. First of all, the terms “climate resilient urban tree species” or even “climate resilience” were not known by the majority of the interviewees. Rather the term “climate tree” was used. Secondly, it became clear that there was a distinct semantic discrepancy of the term “climate tree” between the different types of actors around the topic. Research institutions have a rather strict and abstract definition of the term, being trees that are resilient to climate change. The label of “climate tree” is thus dependant on your regional location, as different regions are effected differently by climate change. Tree nurseries have a more specified definition of the term. In general, tree nurseries interpret climate trees as trees that can withstand extreme weather events like heat waves, dry spells, floods, and freezing temperatures. As they will become more frequent in our regions due to climate change. The definition of this term can vary somewhat between different nurseries.

There is also a completely different view on the term “climate tree”. Local governments and urban green managers have a very general and more functional understanding of the concept. They generally describe climate trees as “trees that help to battle the effects of climate change”. This definition does not only include climate resilient trees, but all trees. This renders the term useless. The help trees offer take the form of supporting local biodiversity, carbon sequestration, and providing temperature buffering through shading and evapotranspiration. In se, every tree helps mitigating the effect of climate change. These mitigating effects grow with the dimensions, and thus age, of the tree. Climate resilient trees consequently help mitigate the climate on the long run, while non-climate resilient trees can only mitigate in the near future.

What a climate tree is, thus seems to depend on whom you ask. This frustrates some of the actors. But the biggest harm can be done by miscommunication or confusion. All of the actors have the same goal: to improve and secure the living quality in urban Flanders. The semantic discrepancy risks undermining that common goal. Although it is not generally accepted in the scientific world, the term “climate tree” is easy to understand. Even for people with no background in urban green whatsoever. It is a mode of communication between local governments and their citizens, to ensure that work is being done to secure the quality of living. It is a buzz word that allows smaller institutions and private companies to broadcast their environmental involvement, without a technical elaboration. Although it is not completely scientifically justified, the term has a social value.

The key in circumventing confusion done by the described semantic discrepancy is clear communication. Research institutions are advised to embrace the term “climate tree”, and propose and disseminate a correct definition. A scientifically justified explanation of the term “climate tree” should be offered in a document that is accessible and easy to understand. In this document, it should be explained that it is important to reserve the term “climate tree” only for climate resilient trees, rather than all trees tied to a project around climate change. Otherwise, we risk planting the wrong tree in the wrong place at the wrong time. The term climate tree should only be used to discriminate between climate resilient and non-climate resilient trees. This document should not only be able to reach urban green managers, but also local governments and private institutions with an ecological consciousness. That way, all actors have the same semantic tools to correctly describe the topic of the discussion. If the subject of the discussion is not clear for all parties, knowledge might be used incorrectly.

4.6.3. Tous ensemble

The proposed species lists that were compilated, were based on expertise, species ecology and natural species distribution. Knowledge users looked for species that were known to be applicable in urban areas. They then selected species which had their natural distribution in Southern and Eastern Europe. Species which were known to survive in hot and dry conditions were also added to the list. Although this method delivered certain species that show high climate resilience for Flanders based on the analysis performed in this thesis, some species on the climate species list showed to have relatively low climate resilience. This shows the importance of a quantitative analysis, like SDM, to make a decisive evaluation of the climate resilience of the species on the climate species list.

In conclusion, both knowledge users and knowledge creators benefitted from collaboration early on in the research process. It was a mutual learning process. The knowledge creator received practically relevant information and species lists. The knowledge users gained insight in the subject on one hand, and in the general approach on knowledge creation on the other hand. They also know now to look southward for new species, rather than eastward. They also received a, may it be rather limited, list of species which are available to them and can be assumed to be climate resilient. Just like for the approaches of the different model classes in the ensemble model, the approaches of the knowledge creator and users complemented each other.

4.7. Future prospects

While the performed research rendered numerous and useful results, much can still be done to broaden and deepen the knowledge around this topic. With less technical and temporal limitations, this research could conclude more generally applicable advice for urban green managers in Flanders. As a first example, generation of predictor response curves could be made for all species, instead of two prototype species. With this information, more insight can be gained in the ecology of climate resilient species. This would make it possible to have a more focused search for other possibly climate resilient species. Secondly, the data-downloading and -cleaning method could be revised to reduce the amount of species which were lost in the process.

Numerous ways exist to strengthen the robustness of the predictions. The amount of scenarios can be increased in two ways: evaluating a larger amount of SSPs and refining the temporal resolution of the scenarios. Another possibility is multi-source modelling. Where climate data could be downloaded from both WorldClim and CHELSA. The two separate predictions could then be compared, or be used to construct a consensus result. Also the amount of GCMs which are evaluated can be raised.

There are also different ways in which the predictive power of the models could be enhanced. By deleting the least important predictors, or by only preserving the most important predictors, the SDM can be fitted to a specific species. Different selecting tactics could be tested and through an iterative process, the most optimal selection of predictor variables can be determined for each species individually. Evaluating which selection of predictors would generate the most reliable results would not only improve the quality of the model, but would also allow for ecological insight on a species level. The same process can be done for the used models and the hyperparameters of these models. Also the impact of different pseudo-absence selection techniques can be explored to gain optimal performance for each of the species.

A more distant future prospect would be the inclusion of the Urban Heat Island effect in the predictions. The constructed models were too fickle to make sense of the UrbClim data when it was swapped with bioclimatic predictor 10, the mean temperature of the warmest quarter. There are two possible ways in which this problem could be solved. Either species distribution models need to become more flexible in accepting predictor data with low climatic consistency, or UrbClim data has to be rendered on the entire extent of Europe. That way, the UrbClim data could be included in the training data. While possible theoretically, both solutions still have large technical and practical obstacles to overcome. But when these are overcome, it should theoretically be possible to make predictions with a fine geographical resolution. Fine enough to make a distinction of species suitability to urban centres as opposed to urban periphery.

5. Conclusion

Climate change and the Urban Heat Island effect can have a large effect on tree vitality in urban areas, now and in the future. Both factors will contribute to an increased amount of water stress for urban trees. Especially the high vapour pressure deficit might cause tree deterioration through demand driven water stress, even for trees which were successfully used in urban areas before. The current urban tree stock of Flanders is not observed to be climate resilient. Of all the modelled possibly climate resilient species, 22 species were observed to be at least moderately climate resilient (see table 3 and appendix 7.1), based on the generated results. These are mostly Mediterranean species. Researchers and urban green managers are thus advised to point their visor southwards in the search for climate resilient urban tree species.

All actors around this topic in Flanders are advised to strive for open and clear communication with scientifically relevant terms. Only then can the common goal of liveable urban areas be achieved. In order to do so, there is a need for a central document and/or actor which gathers and coordinates all research around this topic. The term "climate tree" should be correctly defined as climate resilient trees, and the importance for this correct definition should be explained. Only then, fruitful discussion can contribute to new insights.

The produced results can guide green managers to make an informed decision about species selection, but knowledge users must be aware of the limits of these results. No species can be selected with an absolute certainty of success. Rather, one must cover the uncertainty of the future by selecting different species. As an ensemble of different species tends to stand the test of uncertainty with greater success than the strongest species alone.

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7. Appendices

7.1. Climate species list

This list contains all climate species that were put forward by the knowledge users. First, all species which were observed to be at least moderately climate resilient, based on the generated results, are listed. Then all modelled species for which the generated results did not a show a distinct climate resilience are shown, followed by all species that had occurrence data available on GBIF but were not modelled. Lastly, all species that had no data available on GBIF are given.

Scientific name	Cultivar	Data available on GBIF	Modelled	Amount of occurrence data	Observed to be at least moderately climate resilient
Albizia julibrissin Durazz.		X	X	*224*	X
Broussonetia papyrifera (L.) Vent.		X	X	*2.931*	X
Cedrus atlantica (Endl.) Manetti ex Carriere		X	X	*999*	X
Cedrus deodara (Lamb.) G.Don		X	X	*362*	X
Celtis australis L.		X	X	*13.416*	X
Cercis siliquastrum L.		X	X	*7.921*	X
Cornus mas L.		X	X	*15.446*	X
Cotinus coggygria Scop.		X	X	*14.283*	X
Ficus carica L.		X	X	*29.021*	X
Fraxinus ornus L.		X	X	*2.969*	X
Juglans nigra L.		X	X	*839*	X
Liquidambar styraciflua L.		X	X	*148*	X
Mespilus germanica L.		X	X	*7.469*	X
Morus alba L.		X	X	*1.416*	X
Ostrya carpinifolia Scop.		X	X	*2.342*	X
Paulownia tomentosa (Thunb.) Steud.		X	X	*4.719*	X
Platanus orientalis L.		X	X	*442*	X
Quercus cerris L.		X	X	*2.920*	X
Quercus ilex L.		X	X	*20.001*	X
Sorbus torminalis (L.) Crantz		X	X	*20.975*	X

Taxodium distichum (L.) Rich.		X	X	*2.726*	X
Ziziphus jujuba Mill.		X	X	*2.090*	X
Acer ginnala Maxim.		X	X	*1.965*	
Acer monspessulanum L.		X	X	*7.439*	
Acer opalus Mill.		X	X	*4.003*	
Acer rubrum L.		X	X	*109*	
Acer saccharinum L.		X	X	*2.139*	
Carpinus orientalis Mill.		X	X	*195*	
Catalpa bignonioides Walter		X	X	*3.885*	
Cedrus libani A.Rich.		X	X	*347*	
Corylus colurna L.		X	X	*416*	
Elaeagnus angustifolia L.		X	X	*1.772*	
Fraxinus angustifolia Vahl	‘Raywood'	X	X	*27.430*	
Koelreuteria paniculata Laxm.		X	X	*501*	
Laburnum anagyroides Medik.		X	X	*9.705*	
Liriodendron tulipifera L.		X	X	*389*	
Platanus hispanica Ten.		X	X	*783*	
Prunus cerasifera Ehrh.		X	X	*28.402*	
Prunus domestica subsp. domestica		X	X	*20.960*	
Ptelea trifoliata L.		X	X	*200*	
Quercus frainetto Ten.		X	X	*197*	
Quercus pyrenaica Willd.		X	X	*21.809*	
Sorbus intermedia (Ehrh.) Pers.		X	X	*33.879*	
Sorbus latifolia (Lam.) Pers.		X	X	*455*	
Tamarix gallica L.		X	X	*7.447*	
Tilia tomentosa Moench		X	X	*240*	
Ulmus laevis Pall.		X	X	*5.077*	
Acer buergerianum		X			
Acer campestre		X			
Acer cappadocicum		X			
Acer platanoides		X			
Alnus cordata		X			
Alnus subcordata		X			
Amelanchier arborea	‘Robin Hill'	X			
Amelanchier laevis	‘Ballerina'	X			

Amelanchier lamarckii		X	
Arbutus unedo		X	
Buddleja alternifolia		X	
Caragana arborescens		X	
Carpinus japonica		X	
Carya cordiformis		X	
Carya illinoinensis		X	
Carya ovata		X	
Castanea sativa		X	
Celtis occidentalis		X	
Cladrastis kentukea		X	
Clerodendrum trichotomum		X	
Corylus avellana		X	
Crataegus laevigata		X	
Crataegus monogyna		X	
Cydonia oblonga Mill.		X	*6.091*
Decaisnea fargesii		X	
Diospyros kaki		X	
Diospyros lotus		X	
Diospyros virginiana		X	
Elaeagnus commutata	'Zempin'	X	
Elaeagnus multiflora		X	
Elaeagnus umbellata		X	
Eriolobus trilobatus		X	
Euonymus europaeus		X	
Frangula alnus		X	
Fraxinus americana	‘Autumn Purple'	X	
Fraxinus pennsylvanica	‘Summit'	X	
Gleditsia triacanthos		X	
Gymnocladus dioicus		X	
Heptacodium miconioides		X	
Hippophae salicifolia		X	
Ilex aquifolium		X	
Juglans regia		X	
Juniperus communis		X	
Maackia amurensis		X	
Maclura pomifera		X	
Magnolia kobus		X	
Metasequoia glyptostroboides		X	
Morus nigra L.		X	*383*
Nyssa sylvatica		X	
Parrotia persica		X	

Phellodendron amurense		X
Picea orientalis		X
Pinus nigra		X
Pinus pinaster		X
Pinus pinea		X
Pinus sylvestris		X
Poncirus trifoliata		X
Populus tremula	‘Erecta'	X
Prunus padus	‘Albertii'	X
Pterocarya fraxinifolia		X
Pyrus calleryana		X
Quercus castaneifolia		X
Quercus coccinea		X
Quercus imbricaria		X
Quercus palustris		X
Quercus petraea		X
Quercus phellos		X
Quercus pubescens		X
Quercus robur		X
Quercus rysophylla	‘Maya'	X
Quercus suber		X
Quercus x hispanica		X
Quercus x turneri		X
Robinia pseudoacacia		X
Robinia viscosa		X
Sassafras albidum		X
Sorbus aria		X
Sorbus aucuparia		X
Sorbus thuringiaca		X
Styphnolobium japonicum	‘Regent'	X
Tamarix ramosissima		X
Tamarix tetrandra		X
Taxus baccata		X
Tetradium daniellii		X
Tilia cordata		X
Tilia henryana		X
Tilia mongolica		X
Tilia x europaea	‘Euchlora'	X
Ulmus minor		X
Ulmus parvifolia		X
Zelkova serrata		X
Acer x freemanii		
Acer x zoeschense		
Alnus x spaethii		
Carpinus betulus		

Celtis orientalis	
Cercis canadensis	
Crataegus x lavalleei	‘Carrierei'
Crataegus x persimilis	
Ginko biloba	
Ilex x meservae	
Langerstroemia indica	
Malus	‘Evereste'/'Red Obelisk'/'Red Sentinel'
Malus trilobata	
Morus alba	‘Fruitless'
Quercus bimundorum	‘Crimson Spire'
Quercus dentate	
Quercus texana	‘New Madrid'
Quercus x bimondorum	
Quercus x hispanica	'Lucombeana'
Quercus x kewensis	
Quercus x warei	‘Regal Prince'
Tilia x europaea	‘Pallida'
Ulmus	‘Columelle/Lobel'

7.2. Cities species lists

7.2.1. Antwerp

This table shows the absolute frequency of the 39 most abundant tree species in Antwerp. The data was downloaded from: https://stadantwerpen.maps.arcgis.com/apps/webappviewer/.

Species	**Frequency**	**Species**	**Frequency**
Acer campestre	42	*Ostrya carpinifolia*	41
Acer platanoides	266	*Parrotia persica*	59
Acer pseudoplatanus	114	*Platanus hispanica (x)*	241
Acer saccharinum	45	*Populus alba*	25
Aesculus hippocastanum	17	*Populus nigra*	69
Alnus spaethii (x)	38	*Prunus avium*	71
Betula pendula	60	*Prunus cerasifera 'Nigra'*	69
Carpinus betulus	117	*Prunus serrulata*	55

Castanea sativa	15	*Pyrus calleryana*	79
Crataegus laevigata	56	*Quercus cerris*	29
Fagus sylvatica	103	*Quercus petraea*	63
Fraxinus angustifolia	86	*Quercus robur*	125
Fraxinus excelsior	54	*Quercus rubra*	37
Fraxinus ornus	114	*Robinia pseudoacacia*	53
Ginkgo biloba	36	*Tilia cordata*	138
Juglans regia	9	*Tilia europaea (x)*	83
Liquidambar styraciflua	63	*Tilia platyphyllos*	107
Magnolia	44	*Tilia tomentosa*	37
Malus	54	*Salix pentandra*	10
Metasequoia glyptostroboides	10		

7.2.2 Brussels

This table shows the results of the tree inventory from Brussels. The data was attained through personal communication with Hans Dewandeler.

Species	**Frequency**	**Species**	**Frequency**
Acer campestre	227	*Ginkgo biloba*	220
Acer platanoides	543	*Liriodendron tulipifera*	252
Acer pseudoplatanus	201	*Magnolia kobus*	222
Aesculus hippocastanum	407	*Platanus xacerifolia*	1090
Carpinus betulus	579	*Pyrus calleryana*	289
Corylus colurna	197	*Quercus robur*	186
Fagus sylvatica	527	*Robinia pseudoacacia*	165
Fraxinus excelsior	491	*Tilia cordata*	391
Fraxinus ornus	247	*Tilia platyphyllos*	1208

7.2.3 Ghent

This table shows the results of the tree inventory for Ghent, performed by ANB (ANB, 2008).

Species	Frequency	Species	Frequency
Acer platanoides	140	*Platanus occidentalis*	56
Acer pseudoplatanus	168	*Prunus divers (mostly serrulata)*	77
Ailanthus altissima	52	*Quercus divers (mostly robur)*	78
Carpinus betulus	78	*Tilia divers (mostly europea)*	204
Crataegus monogyna	124		

7.2.2. Traditional species list

This list shows the compilation of the lists in sections 7.2.1, 7.2.2 and 7.2.3. It shows the species' scientific name and the total absolute frequency in all three cities. The third column denotes if the species was also present on the climate species list. None of the exclusively traditional species showed to be climate resilient.

Scientific name	Frequency	Possible climate resilient tree	Modelled	Amount of occurrence data
Acer pseudoplatanus	483			
Aesculus hippocastanum	424			
Betula pendula	60			
Carpinus betulus	774			
Fagus sylvatica	630			
Fraxinus excelsior	545			
Platanus occidentalis	56		X	16
Populus alba	25			
Populus nigra	69			
Prunus avium	71			
Prunus serrulata	55		X	220
Quercus rubra	37			
Salix pentandra	10		X	35.401
Tilia platyphyllos	1315		X	17.877

Acer campestre	269	X		
Acer platanoides	949	X		
Acer saccharinum	45	X	X	2.139
Alnus spaethii (x)	38	X		
Castanea sativa	15	X		
Corylus colurna	201	X	X	416
Crataegus laevigata	56	X		
Crataegus monogyna	124	X		
Fraxinus angustifolia	86	X	X	27.430
Fraxinus ornus	361	X	X	2.969
Ginkgo biloba	256	X		
Juglans regia	9	X		
Liquidambar styraciflua	63	X	X	148
Liriodendron tulipifera	252	X	X	389
Magnolia	266	X		
Malus	54	X		
Metasequoia glyptostroboides	10	X		
Ostrya carpinifolia	41	X	X	2.342
Parrotia persica	59	X		
Platanus hispanica (x)	1331	X	X	783
Prunus cerasifera 'Nigra'	69	X	X	28.402
Pyrus calleryana	368	X		
Quercus cerris	29	X	X	2.920
Quercus petraea	63	X		
Quercus robur	311	X		
Robinia pseudoacacia	218	X		
Tilia cordata	529	X		
Tilia europaea (x)	83	X		
Tilia tomentosa	37	X	X	240

7.3. Intermediate results *Quercus ilex* for scenario 1

7.3.1. Individual models

This appendix is dedicated to the illustration of the method of ensemble modelling. The construction process for the ensemble prediction of *Q. ilex* is presented here through intermediate results. The process is illustrated only for scenario 1, SSP2-4.5 in the year 2050. The predictions shown here are made by the models from which the ensemble model was constructed. Each model was ran three times. The intermediate results are grouped per GCM.

7.3.1.1. IPSL-CM6A-LR

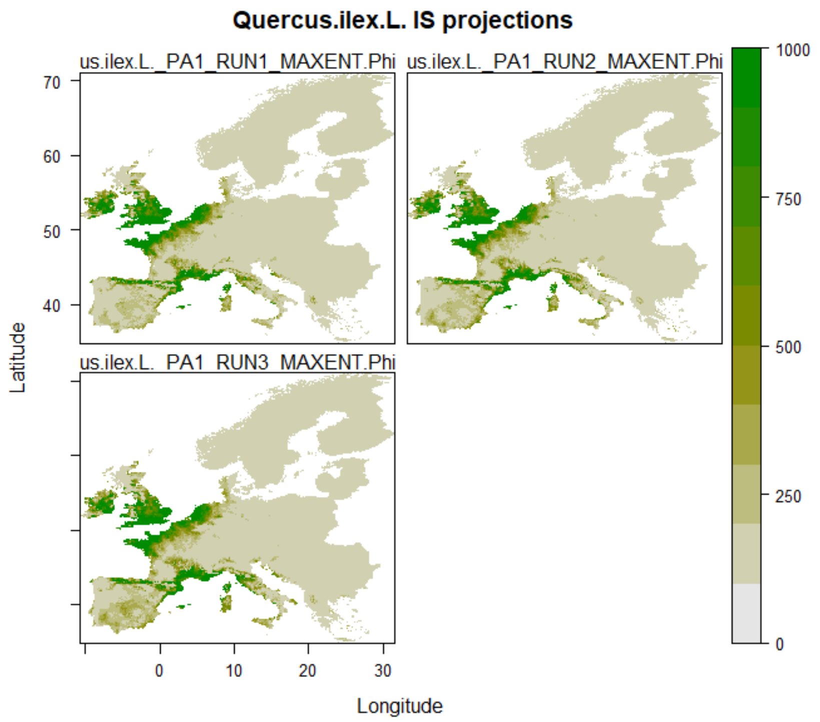

Figure 11: Predictions made by the MaxEnt model for Q. ilex in scenario 1 under GCM ISPL-CM6A-LR

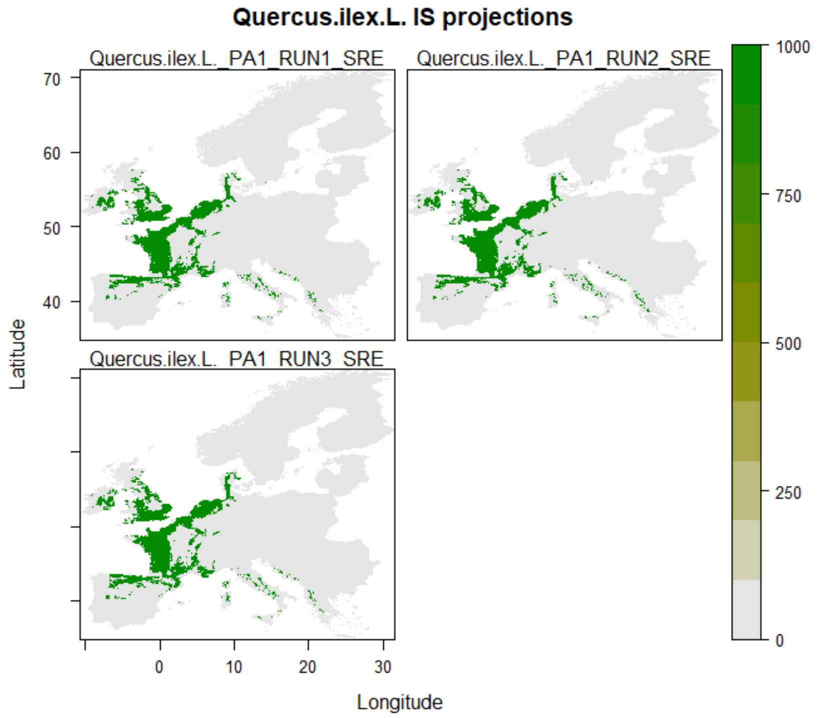

Figure 12: : Predictions made by the SRE model for Q. ilex in scenario 1 under GCM ISPL-CM6A-LR

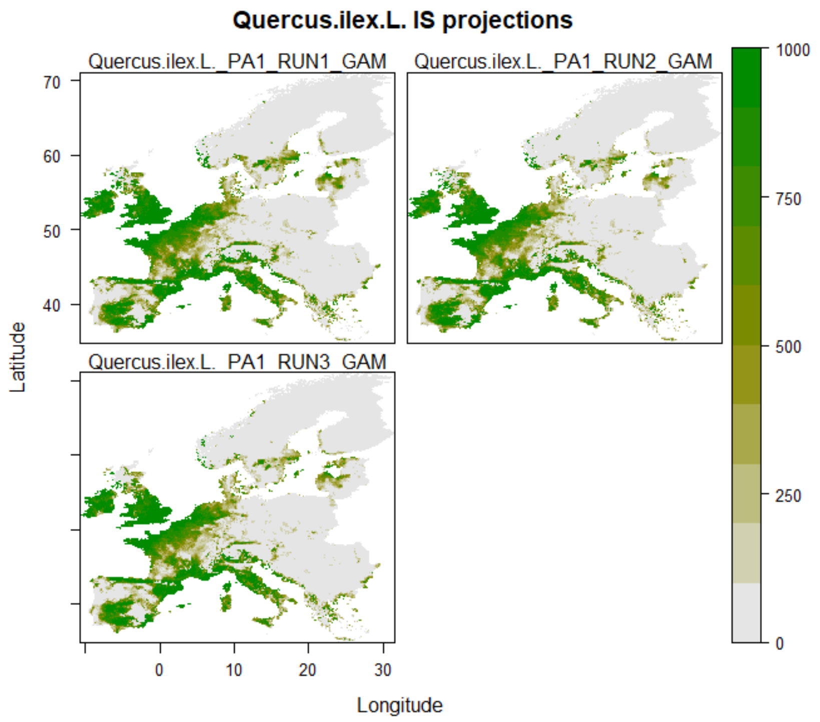

Figure 13: Predictions made by the GAM model for Q. ilex in scenario 1 under GCM ISPL-CM6A-LR

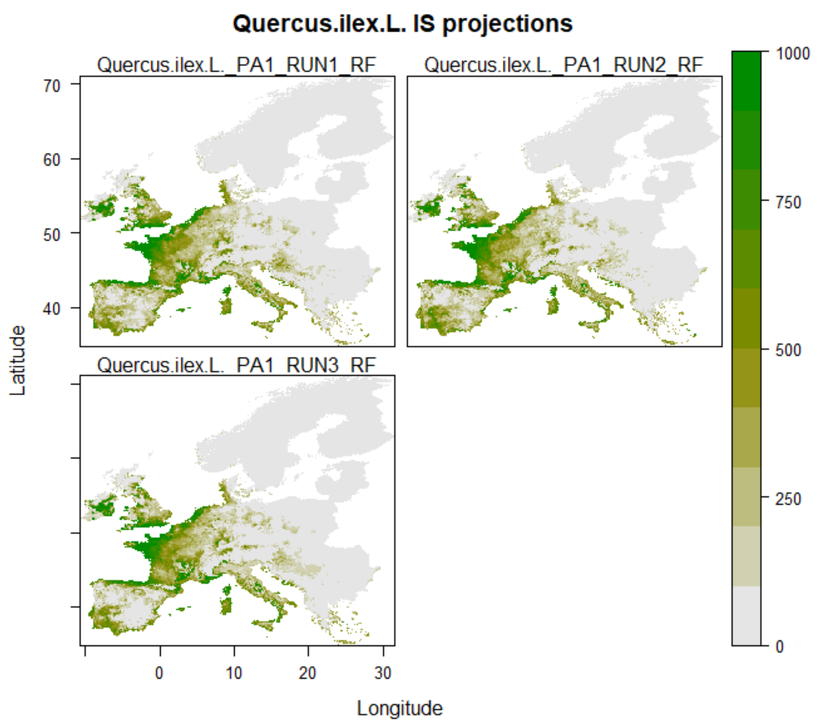

Figure 14: Predictions made by the RF model for Q. ilex in scenario 1 under GCM ISPL-CM6A-LR

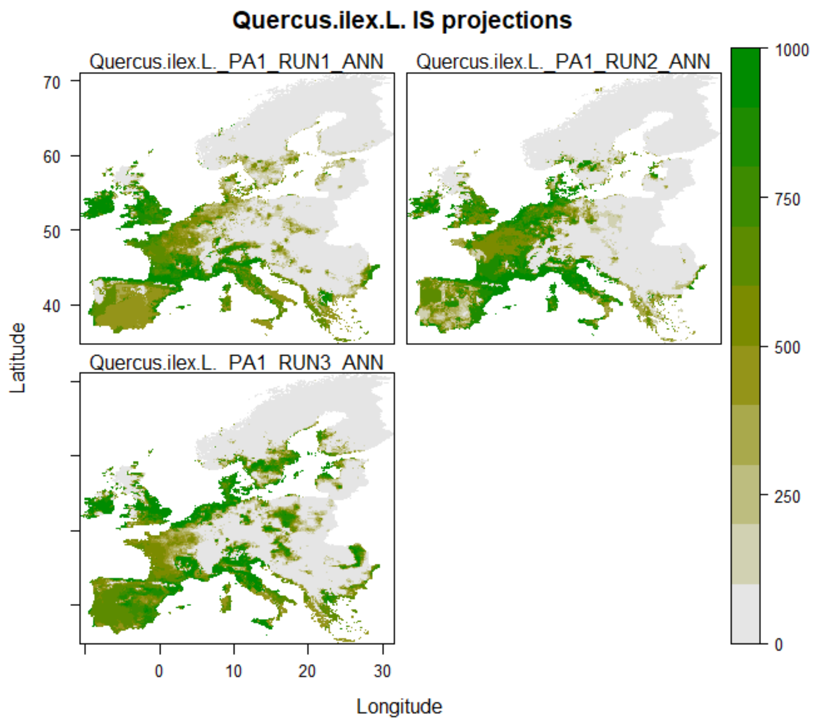

Figure 15: Predictions made by the ANN model for Q. ilex in scenario 1 under GCM ISPL-CM6A-LR

7.3.1.2. MIROC6

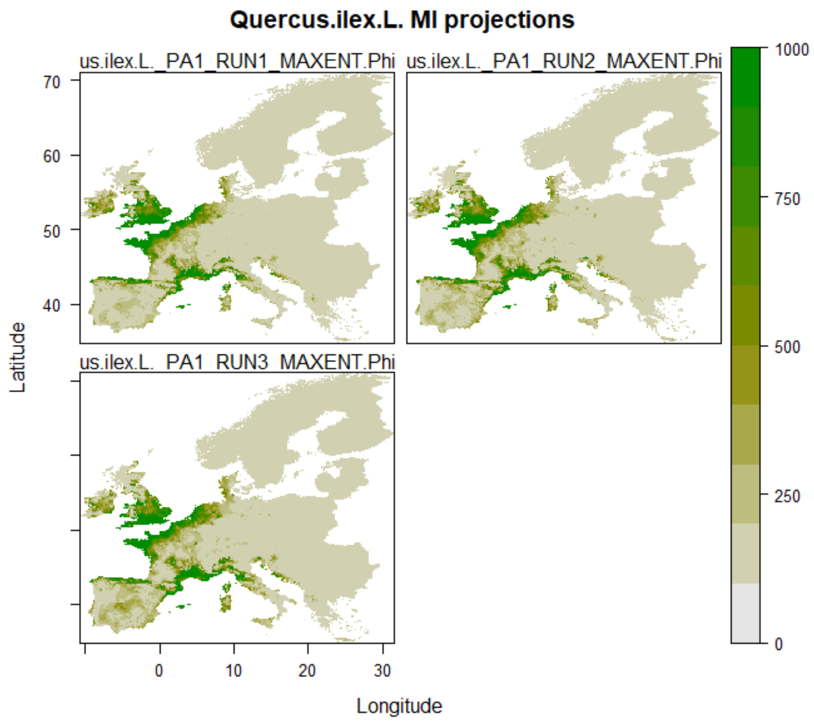

Figure 16: Predictions made by the MaxEnt model for Q. ilex in scenario 1 under GCM MIROC6

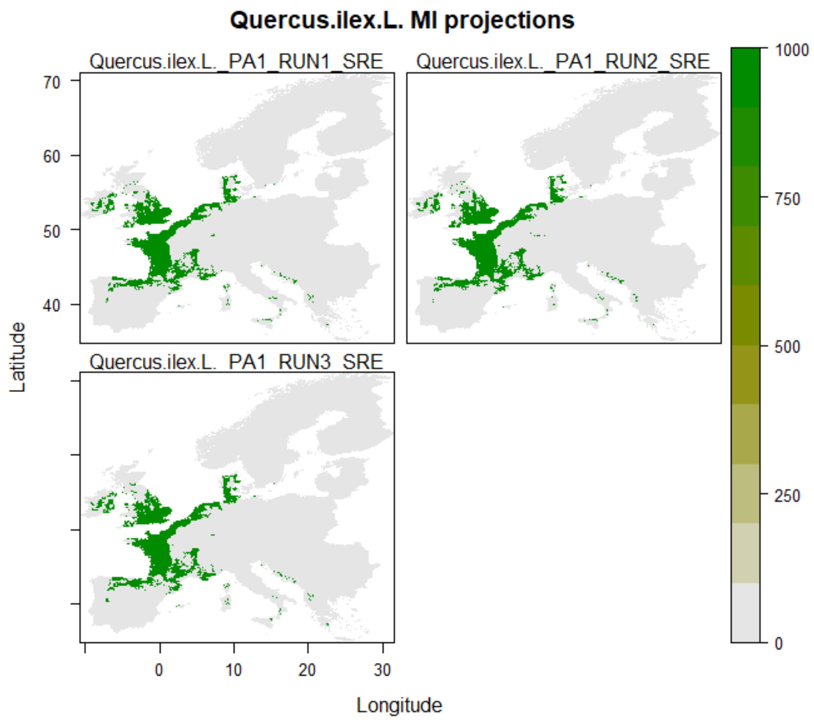

Figure 17: Predictions made by the SRE model for Q. ilex in scenario 1 under GCM MIROC6

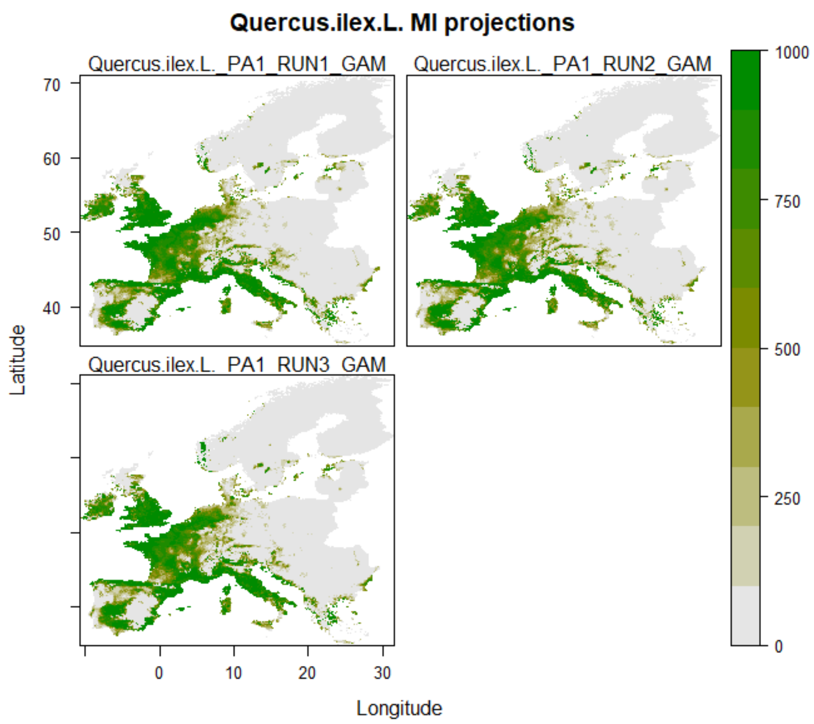

Figure 18: Predictions made by the GAM model for Q. ilex in scenario 1 under GCM MIROC6

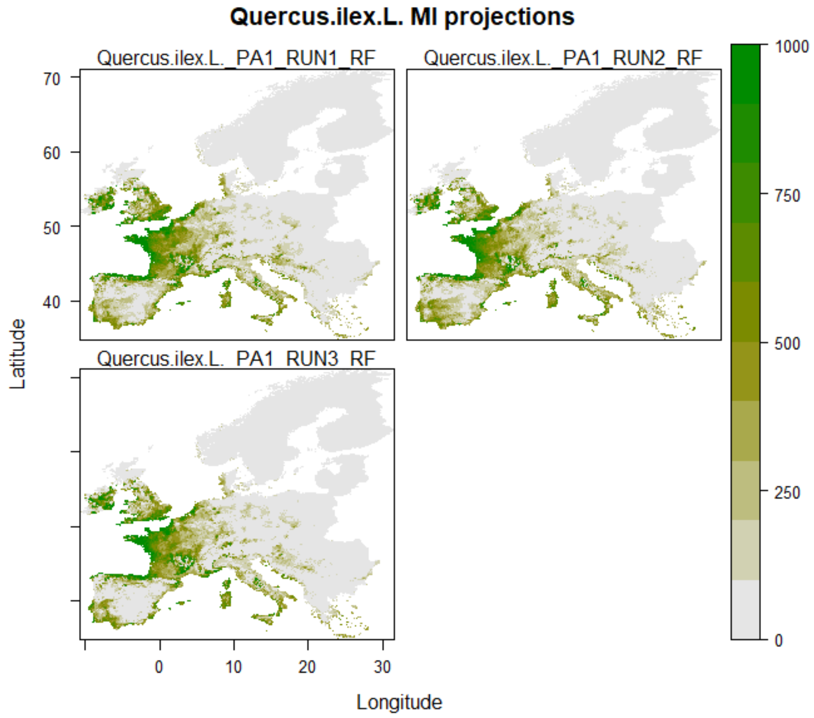

Figure 19: Predictions made by the RF model for Q. ilex in scenario 1 under GCM MIROC6

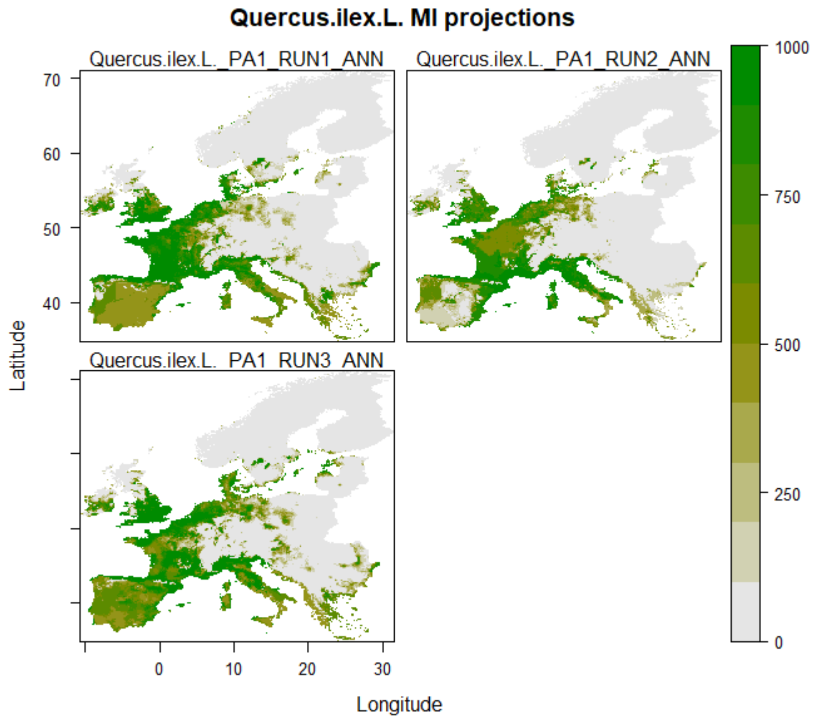

Figure 20: Predictions made by the ANN model for Q. ilex in scenario 1 under GCM MIROC6

7.3.1.3. CNRM-CM6-1

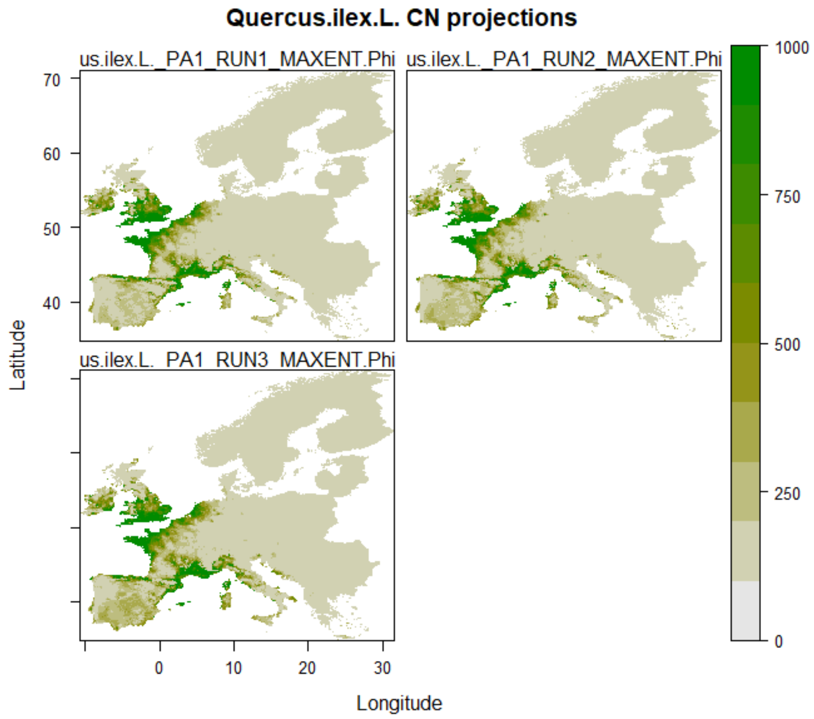

Figure 21: Predictions made by the MaxEnt model for Q. ilex in scenario 1 under GCM CNRM-CM6-1

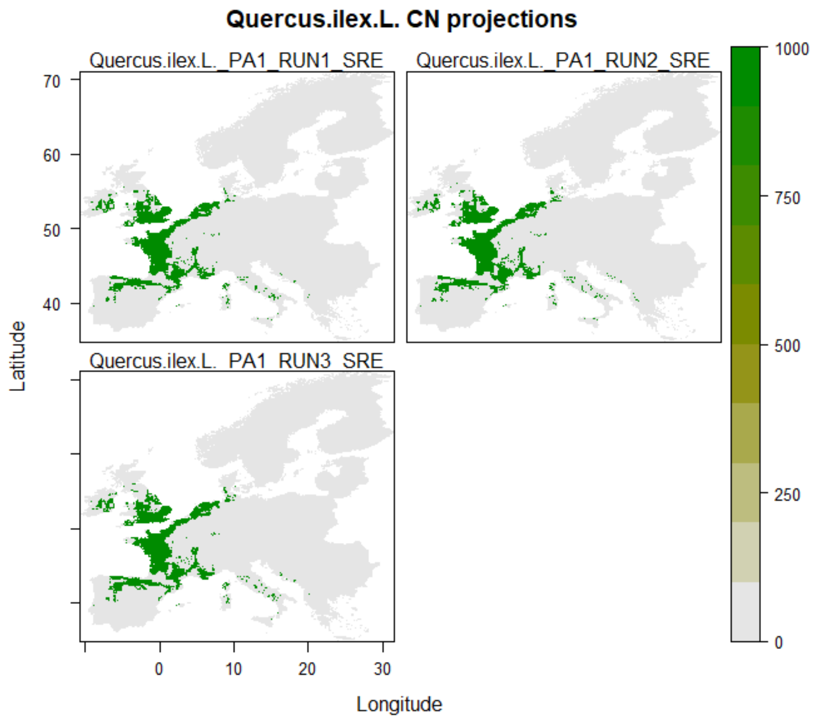

Figure 21: Predictions made by the SRE model for Q. ilex in scenario 1 under GCM CNRM-CM6-1

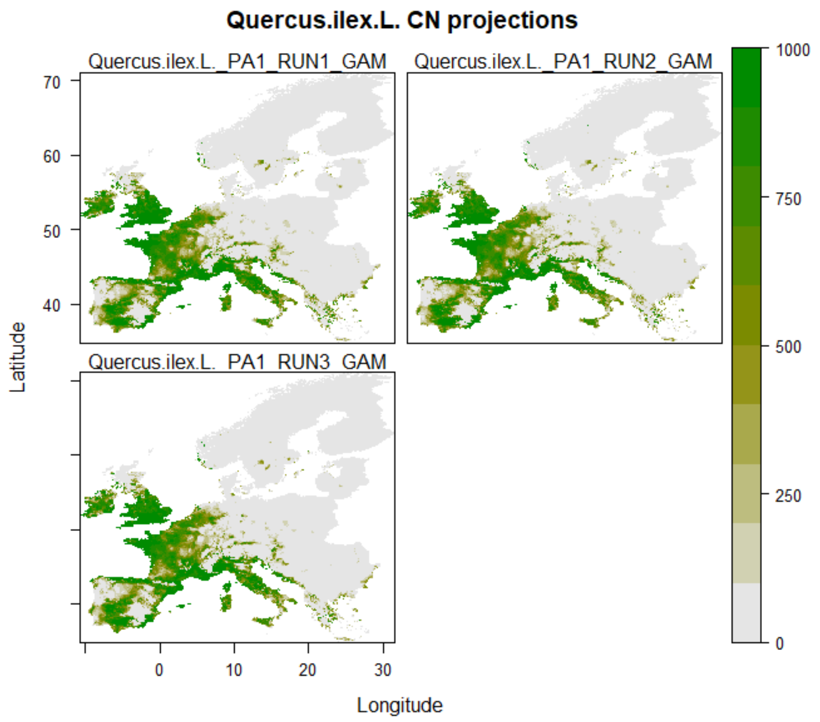

Figure 22: Predictions made by the GAM model for Q. ilex in scenario 1 under GCM CNRM-CM6-1

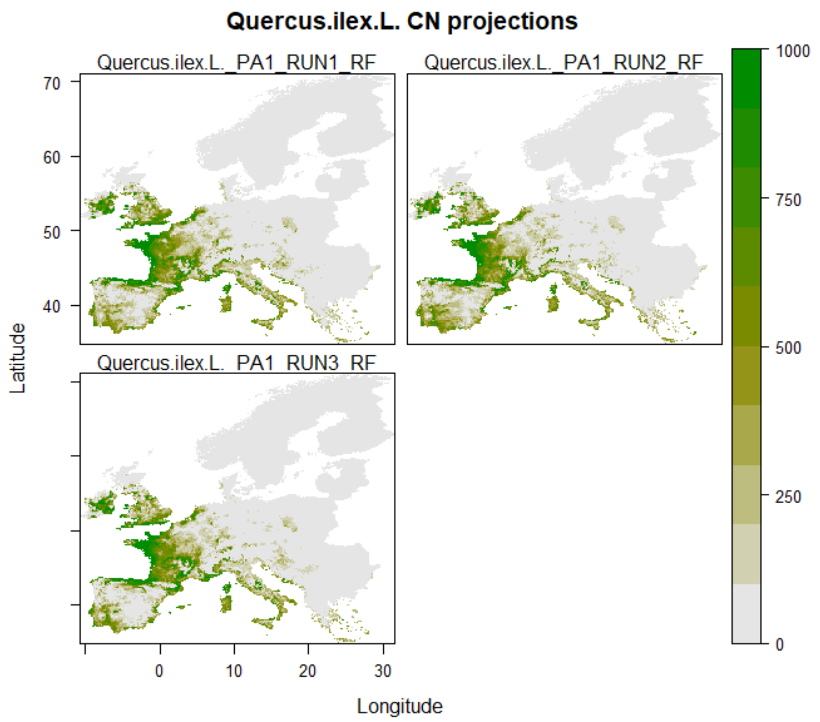

Figure 23: Predictions made by the RF model for Q. ilex in scenario 1 under GCM CNRM-CM6-1

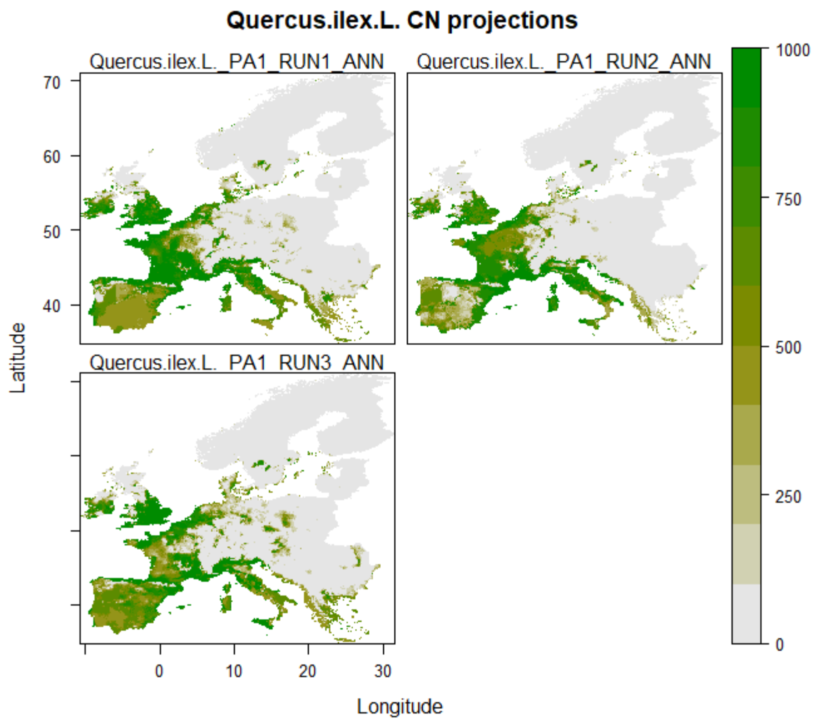

Figure 24: Predictions made by the ANN model for Q. ilex in scenario 1 under GCM CNRM-CM6-1

7.3.2. Ensemble model

The models that made the projections shown in section 7.3.1 were combined in the ensemble model projection. The ensemble model was constructed through weighted means. The weight of each individual model was determined by its TSS. A bottom limit of 0,7 was set for the TSS. The projections of the ensemble models are shown below, ordered by GCM.

7.3.2.1. IPSL-CM6A-LR

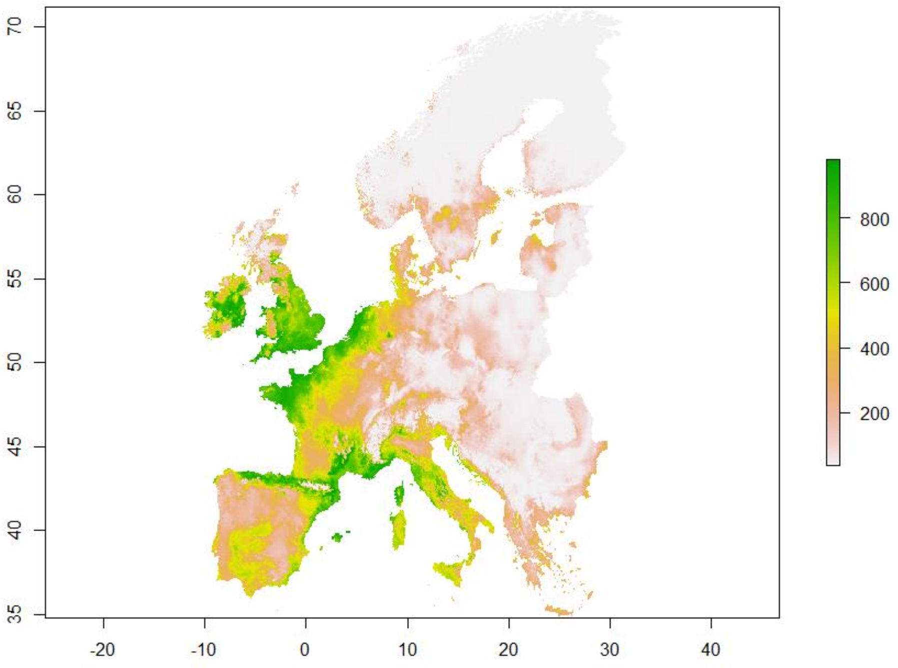

Figure 25: Predictions made by the ensemble model for Q. ilex in scenario 1 under GCM ISPL-CM6A-LR

7.3.2.2. MIROC6

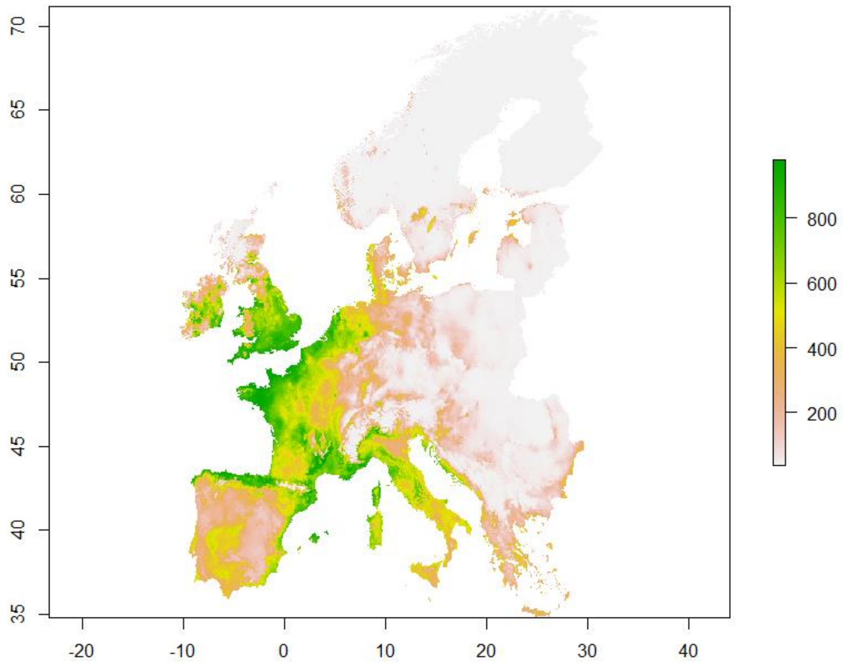

Figure 26: Predictions made by the ensemble model for Q. ilex in scenario 1 under GCM MIROC6

7.3.2.3. CNRM-CM6-1

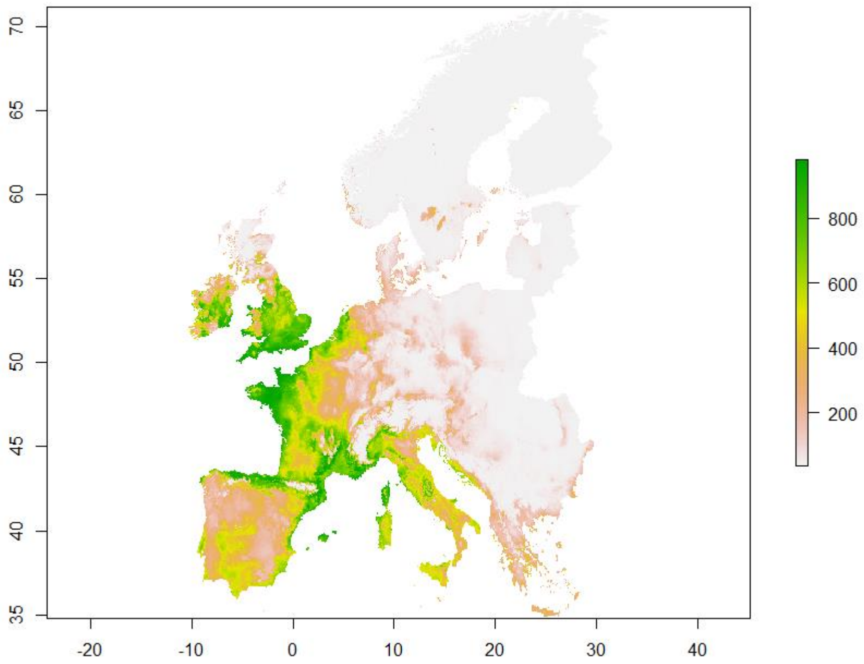

Figure 27: Predictions made by the ensemble model for Q. ilex in scenario 1 under GCM CNRM-CM6-1

7.3.3. Consensus

The ensemble predictions shown in section 7.3.2 were used to construct a consensus result. This consensus result is the mean of the prediction of the ensemble model for each of the three GCMs. Figure 28 corresponds with the upper left panel in figure 4.

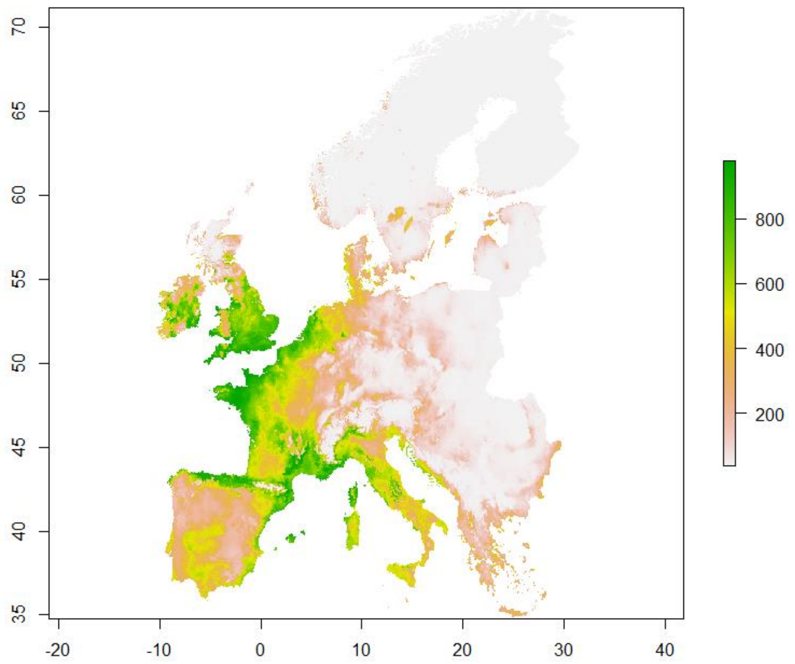

Figure 28: Consensus ensemble prediction for Q. ilex

Vulgarising Summary

Urban populations are growing worldwide, also in Flanders. These urban populations will suffer most from the effects of climate change and the Urban Heat Island. As one of the most urbanized regions in the world, these effects are of great concern to the people of Flanders. But increasing amounts of heat waves and dry spells will not only have an impact on the vitality of human urban inhabitants, but on urban trees as well. Trees already have a lot of challenges to overcome to be able to survive in urban areas. But trees that are planted in urban areas now or in the near future will have to be able to survive in the future urban climate of Flanders. This thesis is dedicated to evaluating the climate resilience of urban tree species.

To construct a list of potentially climate resilient urban tree species and traditional urban tree species, different actors of the urban green sector in Flanders were contacted. These actors were urban green managers, tree nurseries and different research institutions. Each of these actors put forward a list of potentially climate resilient urban tree species. These lists were constructed based on experience, species ecology and natural species distribution.

The results show that especially Mediterranean species with small leaves show great potential as climate resilient urban trees. Although the qualitative assessment of tree species provided a useful list of potentially climate resilient urban tree species, the quantitative analysis proved necessary. Some of the species on the potentially climate resilient species list showed not to be climate resilient after the quantitative analysis. The collaboration of the researcher with the actors in the practical field of the subject proved to be very useful to both parties.

The current landscape of climate resilient trees, or “climate trees” as they are called, is going through a metamorphosis. Different institutions are working around the subject in isolation, using different techniques and terms to study and discuss the same subject. These semantic discrepancies might cause confusion and miscommunication. A unification of semantics and methodology is prompted, so that all actors can contribute efficiently to the common goal of creating liveable urban areas for present and future generations.

Vulgariserende samenvatting

De stedelijke bevolking groeit wereldwijd, ook in Vlaanderen. Deze stedelijke populaties zijn het gevoeligst voor de effecten van klimaatverandering en het Stedelijk Hitte-eiland. Als één van de meest verstedelijkte regio's ter wereld, zijn deze gevolgen belangrijk voor alle Vlamingen. Maar toenemende hittegolven en droogtes zullen niet alleen een impact hebben op de vitaliteit van menselijke stadsbewoners, maar ook op die van stadsbomen. Bomen hebben al heel wat uitdagingen te overwinnen om te kunnen overleven in stedelijke gebieden. Maar bomen die nu of in de nabije toekomst in stedelijk gebied worden geplant, zullen daarbovenop ook nog het toekomstige stadsklimaat van Vlaanderen moeten trotseren. Deze thesis is gewijd aan het evalueren van de klimaatbestendigheid van stedelijke boomsoorten.

Om een lijst op te stellen van potentieel klimaatbestendige stedelijke boomsoorten en traditionele stedelijke boomsoorten, werden verschillende actoren van de stedelijke groensector in Vlaanderen gecontacteerd. Deze actoren waren groenbeheerders, boomkwekerijen en verschillende onderzoeksinstellingen. Elk van deze actoren stelde een lijst op van potentieel klimaatbestendige stedelijke boomsoorten. Deze lijsten zijn samengesteld op basis van ervaring, soortenecologie en de natuurlijke verspreiding van soorten.

De resultaten laten zien dat vooral Mediterrane soorten met kleine bladeren een groot potentieel hebben als klimaatbestendige stadsbomen. Hoewel de kwalitatieve beoordeling van boomsoorten een bruikbare lijst opleverde van potentieel klimaatbestendige boomsoorten, bleek de kwantitatieve analyse noodzakelijk. Een deel van de soorten op de potentieel klimaatbestendige soortenlijst bleek na de kwantitatieve analyse niet klimaatbestendig te zijn. De samenwerking van de onderzoeker met de actoren in het praktijkveld was voor beide kampen een leerrijke ervaring.

Het huidige landschap van klimaatbestendige bomen, of “klimaatbomen” zoals ze worden genoemd, ondergaat een metamorfose. Verschillende instellingen werken afzonderlijk rond het onderwerp en gebruiken verschillende technieken en termen om hetzelfde onderwerp te bestuderen en te bespreken. Deze semantische discrepanties kunnen verwarring en miscommunicatie veroorzaken. Een unificatie van semantiek en methodologie is nodig, zodat alle actoren efficiënt kunnen bijdragen aan het gemeenschappelijke doel om leefbare stedelijke gebieden te creëren voor huidige en toekomstige generaties.