Student thesis series INES nr 542

The future of urban trees – assessing the potential impact of climate change on urban tree populations in two European cities

Pia Elverich

2021
Department of
Physical Geography and Ecosystem Science
Lund University
Sölvegatan 12

Pia Elverich (2021)

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Master's degree thesis, 30 credits in *Physical Geography and Ecosystem Science*
Department of Physical Geography and Ecosystem Science, Lund University

Level: Master of Science (MSc)

Course duration: *January* 2021 until *June* 2021

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Pia Elverich

Master thesis, 30 credits, in Physical Geography and Ecosystem Science

Supervisor

Anna Maria Jönsson

Lund University Department of Physical Geography and Ecosystem Science, Lund University

Examiner

Cecilia Akselsson

Lund University Department of Physical Geography and Ecosystem Science, Lund University

Ben Smith,

Lund University Department of Physical Geography and Ecosystem Science, Lund University

Acknowledgement

First, I would like to thank my supervisor, Anna Maria Jönsson, who has been so dedicated in advising and supporting me during my work in times of distance. Both the scientific input and the regular feedback sessions were a great help for me to gain important input regarding my thesis and to stay motivated.

Furthermore, I would like to thank my friends and family who took numerous walks with me in nature to talk about my thesis and eliminate doubts.

I would especially like to thank Lukas for supporting and encouraged me all the time, despite the sometimes challenging spatial circumstances in which we both wrote our thesis.

Abstract

Due to climate change, cities are increasingly facing the situation of being exposed to more frequent and prolonged extreme weather events in the future, such as heat and droughts, which are exacerbated by urban heat island effects. The implementation of green infrastructure (GI) in the form of trees is seen as a possible adaptation measure to regulate the microclimate. However, there is an increased risk that both existing and future urban tree populations will suffer significantly from changing climate conditions. The aim of this study was to assess to what extent the current tree population in Berlin and Vienna will be threatened by heat and drought periods in the future and to what extent adaptation measures might become necessary. To this end, future climate-related heat and drought threats were investigated based on two emission scenarios (RCP 4.5, RCP 8.5) and selected climate indicators for both the near future (2021-2050) and the distant future (2071-2100). The heat and drought tolerance of trees was assessed based on a literature review. In addition, the exposure of categorised trees in relation to urban heat island (UHI) effects was investigated to identify particularly vulnerable locations and recurring patterns. The risk of extreme events (heat and drought) was found to increase in the future for both climate scenarios studied for both cities, especially in the distant future and at the beginning and end of the growing season. Of the urban tree species studied, the majority were classified as moderately sensitive and moderately tolerant. The distribution of highly sensitive trees within the city showed similar distribution patterns in the two cities with single hotspots in parks but different average UHI intensity exposures. It can be concluded that timely, targeted planning of GI adaptation measures is already essential for both cities to be able to provide adequate GI in the near, but especially in the distant future.

Keywords: *Physical geography, ecosystem analysis, climate adaptation, urban trees, green infrastructure; urban heat island effect, ecosystem services*

Contents

List of Abrreviations

CDF	-	Cumulative Density Function
ES	-	Ecosystem Services
GI	-	Green Infrastructure
NMHS	-	European National Meteorological and Hydrological Service
UHI	-	Urban Heat Island
UKCIP	-	UK Climate Impacts Program

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1. Introduction

Already now, and especially in the coming decades, the impacts of climate change are likely to affect people's lives despite attempted mitigation measures (Emmanuel and Loconsole 2015). Urban regions and cities are already looking for and implementing possible adaptation strategies, as urban environments are particularly at risk (Emmanuel and Loconsole 2015). This is because globally predicted rising temperatures and an increase in heat waves are expected to be even more pronounced in urban environments due to the development of urban heat islands (UHI) which are characterised by elevated temperatures in urban zones compared to surrounding areas and are mainly caused by urban land-use patterns (Ward et al. 2016; Hoegh-Guldberg et al. 2018).

Adverse impacts on health, as well as the general living conditions of the urban population, are triggered by extreme temperatures and heat waves, whereby already vulnerable groups such as children, older people and marginalised social groups are particularly affected (WorldBank 2011). Given the risks that extreme temperatures pose to humans, mitigating extreme climate conditions in cities is of key importance (Hoegh-Guldberg et al. 2018). Green infrastructure (GI) is one of the most communicated and promising approaches to adapt cities to new climate conditions. GI can mitigate negative consequences and thereby increase the resilience of cities to the growing risk of UHI developments (WorldBank 2011; Klemm et al. 2015; Zölch et al. 2016). Recently, the European Commission set in motion its new strategy on climate change adaptation to deal with future vulnerabilities, in which the importance of promoting GI in urban areas is highlighted (European Commission 2021).

Of the various possible GI vegetation types, trees are particularly in focus, as they provide a wide range of benefits and ecosystem services (ES) (Roy et al. 2012). This includes climate regulating services, such as microclimate regulation via efficient cooling of the nearby environment (Zölch et al. 2016). However, it is expected that general greening per se is not sufficient to reduce city temperatures, but that the targeted planting of e.g. trees at particularly heat-sensitive locations in the city is necessary (Zölch et al. 2016). Further, it has been shown that the provision of GI varies greatly between and even within cities, whereby poorer areas are often less well provided with GI compared to wealthier neighbourhoods (Hall et al. 2012). While GI, in general, has been shown to minimise the formation and impact of UHI, the focus in this study is on trees as part of the GI and their role as climate regulators.

One problem has recently become increasingly apparent, namely that already planted tree populations may have increasing difficulty in coping with new climatic conditions (Fahey et al. 2013). In the future, factors such as the heat and drought tolerance of different trees will thus be decisive for the successful growth and survival with a trend on the increased frequency of heat and drought events (Gillner et al. 2014). Especially because studies have shown that different tree species cope differently well with the changing environmental conditions in urban environments (Gillner et al. 2014; Stratópoulos et al. 2018).

While previous studies addressed the vulnerability of different tree species in the context of climate change in different regions of e.g., Germany (Brune 2016), the impact of climate change on the resilience and future vulnerability of existing tree populations in specific cities have so far not been addressed. Therefore, in this study, the possible effects of the climate change on the existing tree population are addressed for two European cities, Berlin, and Vienna to inquire how vulnerable they are and what adaptation measures will be necessary. The study was structured according to the UKCIP (UK Climate Impacts Program) Adaptation Wizard (UKCIP 2013), a tool for the development of adaptation measures, and the risk definition of the IPCC which consists of the assessment of vulnerability, exposure, and hazard (IPCC 2014).

This study aims to answer the following research questions:

1. To what extent will climate change, as depicted by RCP 4.5 or RCP 8.5, affect the occurrence of heat and dry spells in Berlin and Vienna?
2. To what extent will the most common urban tree species be affected by climate change (heat and drought) and what impact could this have on the green infrastructure within the two cities?
3. Which adaptation measures, to be carried out now and in the future, will likely be needed to support a vital urban tree population in the two cities?

2. Background

2.1 Urban heat islands

It is a widely accepted fact that the urban climate differs significantly from the climate of the surrounding areas. This is reflected in higher temperatures in the urban area compared to the surrounding areas, especially in the summer months. The phenomenon is known as an urban heat island (UHI) (Masumoto 2015). The UHI effect is mainly favoured by the particular characteristic structure of cities in terms of architecture, density, material, anthropogenic heat generation and often limited vegetation, which combined lead to changed absorption patterns of long and short waves radiation (Gillner et al. 2015a; Parsaee et al. 2019). Further, it is compounded by altered wind flow mechanisms that result in air being blocked instead of being able to flow (Parsaee et al. 2019). Generally, the cities location and size as well as land use distribution patterns play a crucial role in the context of UHI developments (Gillner et al. 2015a).

Great efforts are being made to prevent the development of UHI, as it has been shown to cause health problems and negatively affect the living comfort of the population in affected areas.

As temperatures continue to rise due to climate change, the risk of extreme events increases (IPCC 2012), leading to even more pronounced UHI developments and related health impacts on humans (Hoegh-Guldberg et al. 2018). Moreover, changes in those extreme summer events in central and southern Europe are expected to be even more pronounced than the general increase in mean temperature (IPCC 2013). Studies on the European heatwave in 2003 showed that about 40,000 additional deaths were related to the extreme temperature period, which mainly affected elderly people (Garcia-Herrera et al. 2010). It is, therefore, necessary to improve living conditions in cities by mitigating and adapting to climate change.

Several factors that influence the formation of UHI cannot be directly manipulated on short notice, including the climate itself and the cities' location. However, other areas can be modified through measures to counteract UHI and are consequently the responsibility of the city. One of these measures is the presence and provision of GI (Parsaee et al. 2019).

2.2 Urban trees as part of green infrastructure

The development and promotion of GI in cities are seen as a major tool for climate change adaptation due to the provision of various ecosystem services (ES) and benefits (European Commission 2021). ESs are commonly referred to as services provided by ecosystems that contribute to human well-being and are divided into three main groups: provisioning, regulating and cultural services. Regulating services are playing a very important role in the context of climate regulation in the urban context. These include services provided by vegetation such as regulating the microclimate by cooling the air, filtering the air of pollutants, regulating noise (MA 2005). As an example, a study for the city of Glasgow concluded that for the respective city, an increase of GI by 20% could decrease the local surface temperature by up to 2 °C. In addition, the increasing severe UHI effects would be limited to up to half the expected increase (Emmanuel and Loconsole 2015).

Tree components in GI are very popular as they provide a wide range of services and are especially profitable for cooling at a small scale by influencing local climates (Armson et al. 2012; Roy et al. 2012). As the ability of individual trees to provide certain services often depends on their phenotypic characteristics, different characteristics of different tree species lead to different potencies in the provision of ecosystem services (Rahman et al. 2019).

While short-lived parts of the GI can be quickly replaced and adapted, trees constitute the long-lived components of the GI. As they are designed to remain in place for an extended time, early selection of trees that have a good chance of survival in the changed future is recommended. By taking measures early on, unwanted effects such as tree death and the frequent need for replanting can be avoided (Banks et al. 2019).

Besides high temperatures and possible droughts, trees in urban environments must cope with a variety of other anthropogenic and natural influences. Urban imperviousness can be as high as 100% in some areas, creating difficult growing conditions, especially when combined with soil compaction or lack of water. Other influences can come from air and water pollution, the use of salt in winter months or human-caused destruction (Block et al. 2012).

As trees in the city have been shown to have a shorter lifespan compared to the natural environment, adaptation measures in the form of e.g. implementing new, better-adapted tree species could be realised within a short period without having to remove already planted GI, due to the ongoing need of regrowth and replacement of urban trees (Block et al. 2012).

2.2.1 Services

Trees contribute to the regulation and cooling of the microclimate through two main processes. The first is cooling through the provision of shaded areas (sensible heat flux) and the second is cooling through evapotranspiration (latent heat flux) (Rahman et al. 2019).

Trees provide a large part of their microclimatic regulation through canopy shading of their surroundings, which often lowers the air temperature by up to 2 degrees shaded by the tree canopy (Armson et al. 2012) and leads to a significantly cooler temperature perceived by humans (Armson et al. 2012; Block et al. 2012; Gillner et al. 2015a; Roloff 2016). Shading is due to the influence of trees on incoming solar radiation, as they contribute to regulating the ambient climate by interacting with solar radiation through absorption and reflection as well as transmission (Block et al. 2012; Roloff 2016). Several factors are crucial for the extent of shading, ranging from canopy height to leaf characteristics (species, size) and tree crown properties (Block et al. 2012; Rahman et al. 2019), whereby tree crown density has been shown to have the strongest influence on the provision of cooling in the context of physical plant properties (Rahman et al. 2019). The canopy density especially in deciduous tree species differs depending on the time of the year¸ therefore, leading to seasonal differences in the provision of the aforementioned services (Block et al. 2012). For deciduous trees, the shedding of the leaves also means that houses can easier be warmed by the incoming radiation in the winter months (Gillner et al. 2015a;Gillner et al. 2015b).

Another cooling effect provided by trees occurs when trees absorb parts of the incoming solar radiation. As one way to handle this increase in energy uptake, trees use transpiration to balance temperature. Water stored in the tree is converted to vapor with the spare energy and through the stomata of the leaves emitted to the environment and inducing a cooling (Block et al. 2012). Besides the direct effects of trees on local cooling by providing e.g., shaded areas and the associated positive effect on specific heat-related diseases in humans, they also contribute to mental and physical health in general across all seasons. Increased air quality through the filtering effect of trees also contributes to well-being (Roloff 2016), as the provision of habitats for several animal and plant species by trees, which are closely linked to biodiversity (Roy et al. 2012). Socially relevant are also the educational benefits and the aesthetic value of trees (Roy et al. 2012; Roloff 2016).

2.2.2 Disservices

However, when discussing different urban trees, the negative side effects caused by trees should not be ignored. One of the disadvantages that affect many people personally is the various pollens that can cause allergic reactions. In addition, aspects such as the danger from falling trees or damage from falling branches have to be taken into account, as well as, especially given climate change, the maintenance costs of urban trees (Roy et al. 2012; Roloff 2016). Meili et al. 2020 found that trees not only have cooling effects but can also contribute to warming if transpiration opportunities are inhibited. However, this phenomenon was not recorded for temperate cities. Which led to the assumption that trees contribute differently to cooling in different climatic zones, but in the case of temperate cities it can be assumed that they primarily have a warming effect in winter and a cooling effect in summer (Meili et al. 2021). For trees to provide the desired regulating and cultural services, special consideration should be given to species selection (Roy et al. 2012). Besides the respective ecological suitability, which is conditioned by the environment and aspects such as heat and drought tolerance of the species, aesthetic aspects can also be taken into account (Roloff 2016).

2.2 Climate-related stress factors for trees

Urban trees are exposed to a variety of influences, both natural and anthropogenic. Crucial climatic variables that significantly influence the success and health of trees are precipitation and temperature, e.g., in the form of drought periods (Gillner et al. 2014; Teskey et al. 2015).

2.4.1. Heat

In contrast to the predominantly negative effects of drought on the tree, increased temperatures do not necessarily have weakening effects, as they can stimulate growth (Arend et al. 2013). However, the extent to which increased temperatures positively influence growth depends strongly on the respective tree location. Since prevailing temperatures in colder climates can still restrict growth, it may be that warmer climates already represent the photosynthetic temperature optimum of the tree and increases have a growth-inhibiting effect (Arend et al. 2013). Nevertheless, high temperatures occurrences and periods can also have negative consequences in themselves. Damage can be observed at the molecular level as well as at the level of the leaf and the whole tree itself, albeit to varying degrees for different tree species. According to the study by Teskey et al. 2015, at the molecular level, photosynthesis in particular is negatively affected by extremely high temperatures (> 30 °C, mainly from 35 °C). (Teskey et al. 2015). While at the tree level, the damage is mainly expressed in the reduction of leaf area development and growth, associated with an increase in mortality. As high temperatures very often occur in combination with droughts, ultimately leading to increased evaporative demand, the pressure on trees sometimes often amplifies and damages increase (Stéfanon et al. 2014; Teskey et al. 2015). In general, the impact of heat or heat spells on tree species also strongly depends on other aspects such as the length of the extreme temperature period, water availability and the individual heat tolerance of the species (Teskey et al. 2015).

2.4.2 Drought

Droughts are often detrimental to trees as they reduce photosynthetic capacity and impair tree growth by limited water supply. Furthermore, the occurrence of water stress due to droughts can potentially limit the ability of trees to contribute to cooling, as evaporation is limited (Meili et al. 2021). Different tree species have developed different mechanisms to cope with drought stress, either by avoiding it or by tolerating it (Sjöman et al. 2015; Roloff 2016). According to Sjöman et al. 2015a, trees with an inherently greater drought tolerance are a better choice as urban trees for the future than those using the avoidance principle. This is because trees using the avoidance method are significantly more dependent on their environment to protect them against drought. For example, they respond by improving their water uptake with an extensive root system. Trying to reduce water loss is another strategy by stomatal closing or the falling of leaves (Roloff 2016). While trees applying tolerance mechanisms tackle the stress by enduring the heat by being able to maintain cell pressure through osmotic adjustment as well as continue photosynthetic processes and transpiration (Roloff 2016).

However, especially in cities, the soil depth and root capacity are often severely limited. Thus, adaptation mechanisms are further inhibited by the urban environment, making the trees more susceptible to heat as they cannot use their adaptation mechanisms (Sjöman et al. 2015). In contrast, trees with the tolerance coping mechanism are less dependent on environmental conditions such as rooting depth and are accordingly better equipped for urban environments (Sjöman et al. 2015).

2.5 Native vs. exotic tree species

There is a widespread consensus, e.g., in countries' sustainable development strategies, to support the planting of native tree species and to condemn the planting of exotic species. The main arguments for this are that native trees are better adapted to the given climatic conditions and that they provide better support for animals in native ecosystems (Sjöman et al. 2016).
However, the planting of better-adapted species, often not from native regions but areas with warmer climates, is generally considered a GI adaptation method, as they are partly considered to cope better with the increasingly harsh climatic conditions in urban areas (Hoyle et al. 2017).

Planting of exotic trees can however also pose a risk, as changing climatic conditions in particular increase the risk of exotic species becoming increasingly invasive, as they adapt quickly to new climatic conditions and are thus superior to native trees (Wang et al. 2017). Urban trees are particularly susceptible to exotic pests as they are located in a highly dynamic environment in terms of living organisms and materials (Paap et al. 2017). They are thus exposed to various possible sources of infection. Ultimately, they could also act as a potential transit point for pathogens into the surrounding ecosystems. Sjöman et al. 2016, on the other hand, advises not to make the mistake of generally considering exotic tree species as harmful to urban GI and categorically excluding them from planting. He argues that newly introduced species do not automatically have to be invasive, and that the location of individual trees is decisive in determining whether species behave invasively or not. Furthermore, invasive species can be problematic in terms of conservation aspects, while still being able to provide ecosystem services such as climate regulation (Roman et al. 2021).

The decision on whether to promote native or exotic species thus depends heavily on the location. It also depends on whether the respective area contains sufficient native species that can survive under the new climatic conditions and thus continue to fulfil advantages over exotic species, e.g. in providing resources for native animals (Sjöman et al. 2016).

2.6 Previous Studies

The issue of increased risk from extreme urban conditions such as UHI is widely discussed in scientific literature, as are the possible measures to implement GI to mitigate negative impacts for the population (Block et al. 2012; Klemm et al. 2015). Specifically, regarding trees as part of GI, the studies have focused on the total amount of ecosystem services provided by urban trees in specific cities, incl. the provisioning capacities of specific species (Baró et al. 2014; Scholz et al. 2016; Rahman et al. 2017; Stratópoulos et al. 2018; Rahman et al. 2019; Pace et al. 2021). Frameworks have been developed to locate areas within a city with a high need for increased plant cover and to develop planting strategies (Bodnaruk et al. 2017), as well as the analysis of future habitats and suitable climatic zones for common tree species (Kim et al. 2020). Impacts on specific tree species in urban environments in the context of climate change and their response to e.g. drought stress is also widely studied (Gillner et al. 2014). In addition, a study by Radhakrishnan et al. 2019 addresses the question of generating criteria and frameworks for selecting trees that are best adapted to specific urban and regional climates in the future and thus suitable as urban trees. Others focus on the development of indicators to summarise and present the advantages and disadvantages of individual tree species (Speak et al. 2018).

Less discussed are the potential impacts of climate change on GI in specific cities depending on their prevailing plant species composition. There is also less discussion of differences between possible future scenarios and their impacts on GI for specific cities. The comparison between GI vulnerability risk and adaptation needs between cities and regions is also not often addressed. Brune 2016 analysed and compared the possible impacts of future climate on trees in different regions in Germany.

3 Methodology

The UKCIP Adaptation Wizard tool, which was created to develop possible adaptation measures, first analyses the current vulnerabilities of a project, followed by the possible future vulnerabilities or risks and possible adaptation strategies (UKCIP 2013). Using this structure, the possible impacts on the tree population in the two cities were analysed to draw conclusions about possible adaptation measures.

The analysis and the presentation of the results were further subdivided into the three categories of the IPCC risk definition, hazard, vulnerability, and exposure (IPCC 2014). To investigate the possibility of current and potential hazards to trees in each city, an indicator-based climate analysis was conducted for two scenarios (RCP 4.5 and RCP 8.5). As the future climate depends on various factors that cannot be predicted with certainty, such as the rate of greenhouse gas emissions, two different climate scenarios were analysed. In this way, possible future developments were mapped, and the possible range, variability and uncertainties presented (IPCC 2013; Sanderson and Knutti 2012). In addition, a literature review was conducted to investigate the vulnerability of dominant trees to heat and drought, and exposure was assessed by analysing the location of trees within the city in relation to UHI formation.

3.1 City selection

For the analysis of the urban tree vulnerability of different capital cities, Berlin and Vienna were chosen. The cities differ in terms of population size and areal extent. However, both cities have a high average population density - Berlin (4.120/ km²) (Berlin 2020) and Vienna (4.600 people/ km²) (Himpele 2020). Although the population density does not necessarily have a direct impact on the formation of UHIs and the associated living conditions, it can have a strong indirect influence on their formation by affecting factors, such as the degree of sealing (Tang et al. 2017). Both cities are located in the "Cfb" climate, defined as a warm temperate, fully humid climate with warm summers, according to the Köppen-Geiger Climate Classification (Kottek et al. 2006; Brugger and Rubel 2013).

The focus of this paper was on the individual cities and their risk, however, similarities and differences will be highlighted, as the study focuses on the vulnerability of trees and possible climate impacts on the existing and possible future urban tree population. Differences and similarities were discussed in terms of risk, as well as mitigation and possible adaptation measures.

3.2 Climate data & analysis

For the analysis of the prevailing and future climate vulnerabilities for the two chosen cities, three different climate data sources were applied. Two of them, the station data and gridded E-OBS dataset, were used to put the EURO-CORDEX scenario data results for the reference period in relation to the observed data and to get an overview over the current climate in the respective cities. The reference period for all datasets applied in this study was set for 1991-2020. In addition, the scenario analysis was divided into the near future (2021-2050) and the distant future (2071-2100), to be able to make statements about possible adaptation measures and their urgency. Whereby a 30-year period was selected, as this being the shortest period to provide statistical information about the climate variables (Hennemuth et al. 2013). In addition, climate data analysis was further refined and broken down to the months of April to September in order to make statements about the impact on the growing season (Rötzer and Chmielewski 2001).

For the analysis of the annual and monthly climate data (maximum temperature and total precipitation) besides the calculation of basics descriptive statistics, depending on the variances of the compared datasets, a homoscedastic or heteroscedastic, unpaired, two-tail t-test statistical analysis, with a set significance level < 0.05, was conducted Additionally, the correlation coefficient was calculated. Further, a calculation of the correlation coefficient and cumulative density function (CDF) was conducted. Quantile mapping is a common method used for the correction of possible biases in simulation data to observed data (Maraun 2016). In this case, the quantile mapping method was only used as a comparison tool between datasets to analyze how well the different datasets represented observed data and in which areas under- or over-represented values were mapped.

All climate data analysis was conducted with Matlab R2020a and Excel, while the tree inventory analysis was conducted with ArcGISPro.

3.2.1 Station observed climate data

To assess the extent to which the E-OBS and scenario data reflect on- site point measurements, station data for the average, maximum temperature and total precipitation amounts for both cities were analysed for the reference period 1991-2020 from station data within each city.

For Berlin, the station selected from the ECA&D datasets was Berlin-Mitte, located in the centre of Berlin (ECA&D 2020b). This station was chosen as it represents a heavily sealed and populated district, probably representing the more extreme temperature values for Berlin. It was decided to use the blended dataset as the non-blended one showed too many missing values. Since different urban areas differ greatly in their structure, it can be assumed that the station data are not representative for all areas of Berlin.

For Vienna, the ECA&D datasets were insufficient as the dataset did not cover the period until 2020. Consequently, official temperature and precipitation data from the city of Vienna were used, which was available in monthly resolution for the required period (Stadt Wien 2020a).

3.2.2 E-OBS-gridded dataset

The E-OBS dataset (Copernicus 2020) was a gridded dataset with a daily resolution covering the European area. Its basis was formed by the compiled and aggregated data received from the entries of the European Climate Assessment & Dataset (ECA&D) project network. The European National Meteorological and Hydrological Services (NMHSs) was the main data source besides several other institutions. The dataset covered the period from 1950 to the present with a daily temporal resolution (Cornes et al. 2018; Copernicus 2019). For this study, the reference period 1991-2020 was analysed and the most recent version of the dataset was used (v22.0e) and compared with the reference period of the station dataset to determine to what extent the E-OBS data represented the station data values and could thus be used in the further analysis. The missing months for 2020 were completed by the additional monthly 2020 datasets provided. The number of extracted grid cells was chosen to cover the city areas as accurately as possible with a horizontal resolution of 0.1° x 0.1° (Berlin 4x3 grid cells and Vienna 2x3 grid cells).

3.2.3 Bias-Adjusted EURO-CORDEX climate scenario dataset

To represent the regional climate conditions in the near and distant future as accurately as possible, it was useful to take regional climate model outputs as the data source. For the analysis of future climate conditions, the daily bias-adjusted EURO-CORDEX dataset (GCM: MPI-M-MPI-ESM-LR, RCM: RCA4) (is-enes 2020) for the EUR-11 zone was used.

The EURO-CORDEX datasets come prepossessed and downscaled from the CIMP 5 results (enes 2016; HZG 2020) which is why they are used in this study to make statements about regional processes and changes. The strength of the global climate models and their outputs (CIMP5) was that they are able to represent global processes. Thus, they can model the changes in global circulation that occur, for example, due to changes in the Earth's greenhouse gas budget. In contrast, regional climate models have the strength of being able to incorporate important site information, such as topography etc., much more accurately due to their higher spatial resolution (Giorgi 2019). For the analysis of the Representative Concentration Pathways (RCP) 4.5 and 8.5, bias-adjusted EURO-CORDEX- data was selected. The EURO-CORDEX dataset, covering the European area, has a spatial resolution of 0.11 degrees (~12km). The simulations are downscaling the CIMP5 long-term experiments, driven by the different RCPs. The simulations are covering a period from 2006-2100 (HZG 2020).

In this work, two RCP scenarios, the RCP 4.5 (medium emission scenario) and RCP 8.5 (high emission scenario) were analysed to represent a range of possible future developments (van Vuuren et al. 2011; Sanderson and Knutti 2012; IPCC 2014). Whereby, RCP 4.5 corresponds to a radiative forcing of 4.5 W/m^2 (~650 ppm CO_2 equivalent) by 2100 and the RCP 8.5 to a radiative forcing of 8.5 W/m^2 (~1370 ppm CO_2 equivalent) by 2100 (van Vuuren et al. 2011). To ensure the representability of the scenario data, values for the mean annual maximum temperature as well as mean annual total precipitation were compared with the E-OBS data for the reference period. In addition, the values of the reference period of the respective analysed scenario were used for the further analysis, as differences in the reference period between the scenarios already occurred from 1991- 2020.

3.3 Climate Indicator

Precipitation and temperature are among the most important climate parameters to be analysed when making statements about the suitability of different tree species (see Section 2.2). To ensure an efficient data analysis for both cities and both scenarios, meaningful climate indicators were selected and analysed (Tab. 1). Furthermore, also the indicator analyses were separated into the near (2021-2050) and distant future (2071-2100).

All indicators (Table 1) were calculated for the period 2021-2100 as well as for the 30-year periods of near future (2021-2050) and the distant future (2071-2100) for the month April -

September. In order to obtain a complete overview of the extent of an extreme event or hazard, the frequency of the occurrence, average duration (intensity) and changes in the average maximum duration (intensity) were examined (Goodess 2013). T- tests were conducted to point out significant differences between various dataset for the reference period (1991-2020) and are presented in the results section. The results were considered to be significantly different from a value < 0.05. Additionally, the correlation coefficient was calculated.

In this study, two scenarios and time periods were described in terms of frequency and severity of heat and dry spells. The climate projections are associated with model and scenario uncertainties (Sanderson and Knutti 2012). While the scenarios represent possible climate futures, there could be a global temperature increase that is above, between or below the two scenarios. A statistical analysis comparing the two scenarios was therefore not performed.

Table 1: Climate Indicators – definition of climate indicators representing heat and dry periods

CATEGORY	INDICES	DEFINITION
Maximum Temperature	Maximum temperature	Average maximum temperature (° C)
Heat	1. Average no. of occurring heat spells per year 2. Average duration of heat spells 3. Average max. duration of heat spell (most extreme event per year)	Heat spell: days with max Temp. ≥ 30 ° C (≥ 3 consecutive days)
Precipitation	Precipitation sum	Total amount of precipitation (mm)
Drought	1. Average no. of occurrence of dry spells per year 2. Average duration of dry spells 3. Average max. duration of dry spell (most extreme event per year)	Dry spell: days < 1mm (≥ 5 consecutive days)

3.3.1 Heat indicator

The average maximum temperature was calculated both annually and monthly to get an overview of the climate change signal. In general, if sufficient water supply is provided, temperatures > 40 °C for a short limited time do not pose a problem for trees (Teskey et al. 2015). However, as heat spells and water deficits often occur together and increase the stress, the temperature threshold for the trees is often even lower (Stéfanon et al. 2014; Teskey et al. 2015). A threshold for hot days at ≥ 30 °C, similar to the definition for hot days by DWD, 2020a, was therefor used. Furthermore, Fenner et al. 2019 analyzed the impact of the definition of heat -wave on the long-term analysis results in the region of Berlin -Potsdam. They found that heat-wave definitions based on T mean instead of T max better accounted for the UHI effect, as these also include night-time temperatures. However, as the focus of this study was on the vulnerability of urban trees due to high-temperature periods and less on the effects that UHI effects might have on urban population health, the choice for the heat-wave definition was a static temperature threshold and T max was used for the calculation. Static thresholds generate results indicating when the absolute temperature is passing the threshold and does not refer to a specific long-term reference period (Fenner et al. 2019). In addition, a heat spell was defined as a period of ≥ 3 consecutive days or more, equal and or above the threshold of ≥ 30 °C (DWD 2020a, DWD 2020b).

3.3.2 Drought indicator

For the precipitation analysis, the annual and monthly sum according to the ECA&D (2020) "RR" indicator was analyzed representing the total amount of precipitation (mm). To analyze the drought the annual and the monthly number of consecutive days < 1mm was analyzed according to the definition of the ECA&D (2020a) "CDD" indicator. A dry spell was defined as a period of ≥ 5 consecutive days below the threshold of 1 mm (Jacob et al. 2014).

3.4 Literature review and tree inventory analysis

For obtaining data on trees in the cities, tree inventories are useful as they are often part of the tree management of cities. As a tree monitoring tool , they provide important information on individual tree stands, like the tree species (Östberg et al. 2018). To obtain an overview of the different proportions of tree species within the cities, the respective tree registers were reviewed. General information on the respective tree inventories is presented in Table 2.

Table 2: Tree inventory data information for Berlin and Vienna

City	Inv. No. Tree	Last updated	Areas trees
Berlin	565.363	21.12.2020	Street, Public
Vienna	202.116	15.04.2020	Street, Public

In the first step of the analysis, the 10 most common tree species of each city were filtered out at the time of the last inventory update. As the categorisation and naming of tree species within and between the analysed tree stands is not uniform, in some cases subspecies were named, but in other cases only the family name was displayed, such as *Tilia spec.* In this case, an exact subspecies assignment was no longer possible and could influence the overall statistics of the species distribution. This problem occurred once within the top 10 tree species for Berlin with the example mentioned. The *Tilia spec*. trees with missing subspecies were excluded. However, three species of *Tilia spec.* are still present among the top 10 species for Berlin. Thus, the distribution of the dominance of Tilia species within the data area is still represented. In addition, the extent to which the most widespread species are of native or exotic origin was investigated.

Subsequently, for each of the previously filtered tree species, a literature review was carried out on species-specific heat and drought tolerance to assess the potential vulnerability. Other properties, such as winter hardiness, waterlogging tolerance, or salt tolerance were not examined. The review focused on published existing drought and heat tolerance classifications and databases and was complemented by a tolerance categorisation based on it.

The final classification of heat and drought tolerance was developed based on the literature review and oriented at the categorisation by Brune 2016. As the definitions and thresholds for heat and drought tolerance vary greatly between publications, the results are only comparable to a limited extent. For this reason, a categorical scale was retained for the assessment of the drought tolerance to make an overall assessment for the respective tree species. The species were categorized into four categories (Table 3) according to their mean value (see Appendix 1 and 2). To keep the classification of drought and heat tolerance separate, the classification of heat tolerance was only highlighted in the case of deviations from the assessment of drought tolerance in the analysis.

Finally, the exposure of the tree species in the different tolerance groups was analysed in terms of distribution and density within the city and in terms of the UHI intensities to which they are exposed on average. The UHI dataset applied in this study represented the average UHI intensity for the summer month June, July, and August (JJA) for the period 2008- 2017 (EEA 2020a).

Table 3: Categorization for the drought tolerance assessment based on the literature review (more detail in Appendix 1)

	Category	**Very sensitive**	**Moderately sensitive**	**Moderately tolerant**	**Very tolerant**
Drought tolerance	Value	≤2	<3	≥3	≥ 4
	Color				

4 Results

To investigate the extent of possible hazards in the form of changing climate conditions as well as heat and dry spell occurrences, the first part analyses the climate data of the respective city. Subsequently, the potential vulnerability of the dominant tree species of the city is shown based on the literature review and classified into tolerance categories. To investigate the exposure of the trees within the city, the trees previously divided into tolerance categories are examined in terms of UHI intensity and distribution within the city.

4.1 Berlin

4.1.1 Point measurements (1991-2020) vs Gridded observed data (1991-2020)

4.1.1.1 Daily maximum temperature & heat spells

For the annual mean maximum temperature in the reference period 1991-2020 for Berlin, the E-OBS data displayed a very good representation of the station data (Fig.1). The E-OBS data did not differ significantly from the station data (*t(56)=0.1, p=0.9*) and therefore, in combination with a correlation value of 1, represented the prevailing climate of the city of Berlin for the reference period very well. The cumulative density function (CDF) for the individual months (April-September) also showed a very good representation of the station data by the E-OBS data (Fig. 1) and according to the t-test no significant difference for any of the month. It could be concluded that the climate during the reference period was well represented by the E-OBS dataset and could thus be referred to for comparison purposes in the further course of the elaboration.

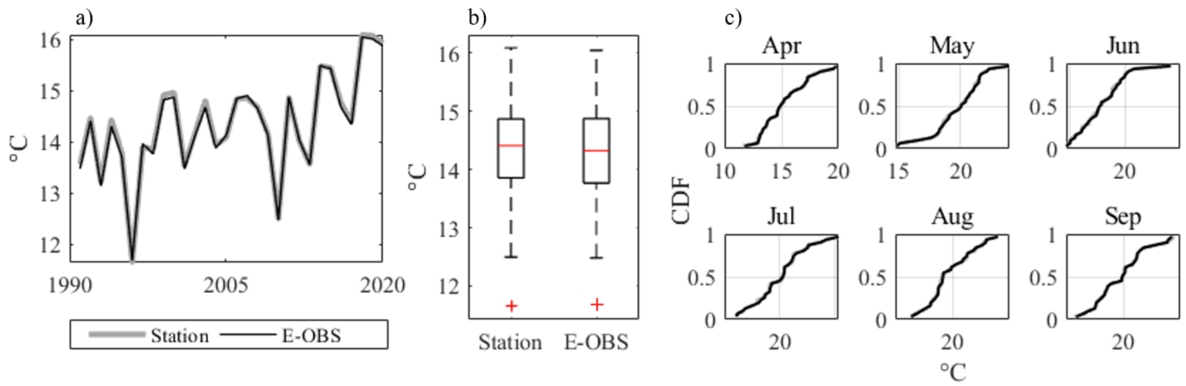


Figure 1: Comparison of mean annual maximum temperature for 1991-2020 for station and E-OBS data (a, b) and CDF for the month April - September for station and E-OBS data (c) for Berlin.

Overall, a mean annual maximum temperature of 14.3 °C was observed for the reference period by the E-OBS data. Furthermore, the reference period from 1991-2020 showed an average occurrence of 1.4 heat spells per year from April to September. The average length was 4.2 days and the mean maximum length 7.3 days.

4.1.1.2. Cumulative precipitation & Dry spells

The mean annual total precipitation for Berlin showed no significant difference between station and E-OBS data for the reference period (*t(56) =1, p=0.32*) (Fig. 2). The correlation of the dataset was 1, ensuring the same trend. Overall, the E-OBS data showed slightly higher values, but this finding could be neglected due to non-significance.

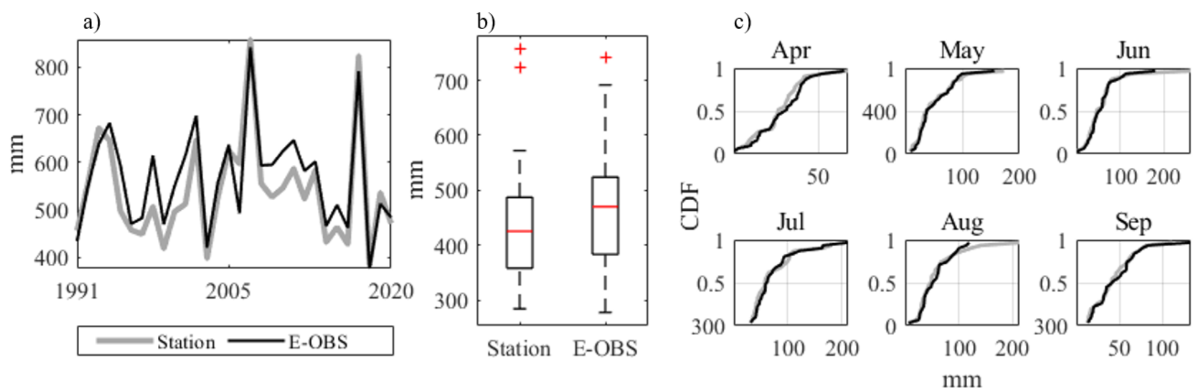


Figure 2: Comparison of total mean annual precipitation sum for the reference period 1991-2020 for station and E-OBS data (a, b) and CDF for the month April -September for station and E-OBS data (c) for Berlin

The analysis of the individual months (April- September) also showed a good representation of the station data by the E-OBS data. Only in August did the station data show slightly higher density for high precipitation sums but no significant difference *(t(56)=0.2,p=0.84).* The other months displayed no significant difference. The annual total mean precipitation according to the E-OBS dataset was 567 mm for the reference period 1991- 2020. In addition, there were an average of 9.6 dry spells per year for the months April to September with an average length of 9.4 days and an average maximum length of 19.5 days

4.1.2 Gridded observed data (1991-2020) vs. Modelled climate data (1991-2100)

4.1.2.1 Daily maximum temperature

The comparison of the E-OBS dataset and the respective scenario datasets for the average annual maximum temperature in the reference period (Fig.3) showed no significant differences for the reference period, (RCP 4.5: *t(57) = 1.1, p= 0.31*, RCP 8.5: *t(57) = 0.4, p= 0.7*). The mean annual maximum temperature values were therefore well represented for the reference period by both scenarios. However, the correlation values for both scenarios were low (RCP4.5: *0.37*, RCP 8.5: *0.31*), indicating that the overall annual maximum temperature was well represented, but that there were limitations in representing the exact temporal temperature pattern. For the months April to September, the CDF showed only minor differences in the distribution of temperature values between the E-OBS data and the reference period of the climate model data for the monthly mean maximum temperature (Fig. 3). Furthermore, the t-test showed no significant difference for either scenario for any of the months. Overall, however, the climate model data represent the E-OBS data well.

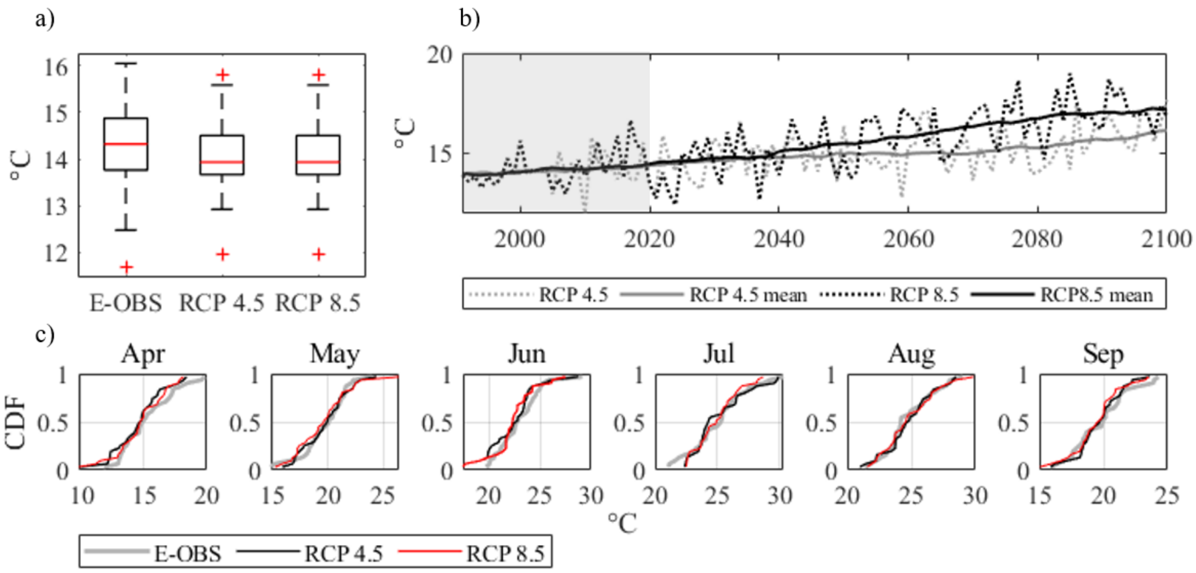


Figure 3:Comparison of annual and monthly average maximum temperature for E-OBS, RCP 4.5 and RCP 8.5 data for the reference period (a) and the CDF for the month April -September for E-OBS and scenario data (c) for Berlin. Overall development of scenario data until 2100 (b). Reference period highlighted in grey.

The scenario projections for the mean annual maximum temperature (Fig. 3, Tab. 4) showed a steady increase in the coming century for both RCP scenarios. While RCP 4.5 projected an overall increase of 1 °C, RCP 8.5 displayed an overall increase of 1.6 °C compared to the reference period (Tab. 4). Both scenarios showed a weaker increase, but of similar magnitude, in the near future (RCP 4.5: 0.6 °C, RCP 8.5: 0.5 °C), while a stronger increase was projected towards the end of the century 2071-2100 (RCP 4.5: 1.5 °C, RCP 8.5: 2.7 °C), being more pronounced for RCP 8.5.

Table 4: Development of annual mean maximum temperature for RCP 4.5 and RCP 8.5 -Berlin. Δ temp represents the difference between scenario value and the value of the reference period of the respective scenario (1991-2020).

	RCP 4.5		RCP 8.5	
Time period	°C	Δ TEMP.	°C	Δ TEMP.
Ref. Period	14.09		14.23	
2021-2100	15.11	1.02	15.86	1.64
2021-2050	14.75	0.66	14.77	0.54
2071-2100	15.59	1.50	16.96	2.73

4.1.2.2 Cumulative precipitation

The average total precipitation per year showed no significant difference when comparing the E-OBS data and the scenario data for the reference period (RCP 4.5: *t(57)= 0.9, p=0.34*; RCP 8.5: *t(57)=0.08, p = 0.9*), although the correlation values of the data sets were low (RCP4.5: *0.32* & RCP 8,5: - *0.15*). The analysis of the individual months showed a stronger occurrence of high values for April compared to the E-OBS data, especially in the RCP 8.5 scenario, however, no significant difference (*t(58)=-1.4, p=0.14*) (Fig.4). In July, the trend reversed, and the scenario data showed lower values more often than the E-OBS data. No significant differences were shown for any month (Fig. 4).

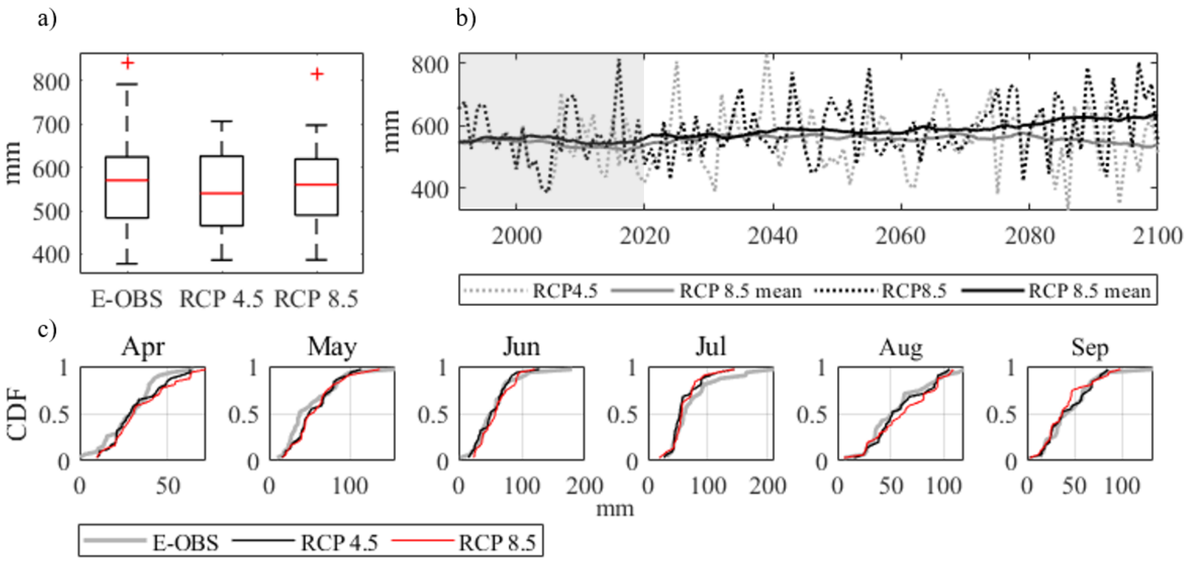


Figure 4:Comparison of annual and monthly average total precipitation sum for E-OBS, RCP 4.5 and RCP 8.5 data for the reference period (a) and the CDF for the month April -September for E-OBS and scenario data (c) for Berlin. Overall development of scenario data until 2100 (b). Reference period highlighted in grey.

Both scenarios projected a slight increase in total precipitation per year for the coming century, with RCP 4.5 showing a smaller overall increase of 3.2 % than RCP 8.5 with 5.3 % (Tab.5). While RCP 4.5 indicated a slightly larger increase in precipitation in the near future (+4.9%) and a slightly smaller increase in the distant future (+2.5%), RCP 8.5 demonstrated the opposite trend. The near future showed almost no change (+1.85 %), but the distant future showed a very strong change (+11.3 %).

Table 5 Development of annual mean precipitation sum for RCP 4.5 and RCP 8.5 -Berlin. %-change represents the %-change between scenario value and the value of the reference period of the respective scenario (1991-2020).

	RCP 4.5		**RCP 8.5**	
Time period	mm	%-change	mm	%-change
Ref. Period	542.39		561.75	
2021-2100	559.70	3.19	591.33	5.27
2021-2050	568.69	4.85	572.17	1.85
2071-2100	556.06	2.52	624.93	11.25

4.1.3 General trends in occurrence of heat and dry spells (2021-2100)

For the course of the century, 2021-2100 heat spells were predicted to increase for both scenarios, with strongest changes displayed for the distant future. Slightly higher mean values for the average occurrence per year with 2.8 times were shown for RCP 8.5 compared to RCP 4.5 with 2.6 times. Also, for the average duration and average maximum duration, RCP 4.5 showed smaller overall values with respectively 2.7 days and 7.4 days for 2021-2100. RCP 8.5 displayed values of 5.8 days for the average duration and 9 days for the average maximum duration for 2021-2100. However, RCP 4.5 in total displayed a stronger increase for the average maximum duration (+2.7 days), while RCP 8.5 increased stronger for the average length (+1.9 days). The average occurrence of dry spells per year for the months April – September (2021-2100) showed a slightly stronger increase for RCP 4.5 with + 0.5 times leading to an average number of 9.1 occurrences per year, while RCP 8.5 predicted an increase of + 0.1 times leading to an average of 9 occurrences per year. The average duration and average maximum duration showed similar values for 2021-2100 for both scenarios with respectively 8.7 days average duration and 16.7 days average maximum duration. Despite the overall small changes, significant monthly changes in the occurrence of droughts could not be ruled out, as fluctuations may have resulted from both increases and decreases in frequency and length over time.

4.1.3.1 Average annual frequency of heat and dry spells

Compared to the reference period, both RCP scenarios showed stronger absolute and percentage changes in the frequency of occurrence of heat and dry spells (April-September) in the distant future and less in the near future (Fig. 5). Nevertheless, some noticeable changes were already evident in the near future. For RCP 4.5, the largest percentage increase in the occurrence of heat spells per year occurred in May +0.03 (+100%), and the largest absolute increase was displayed in the summer months of July +0.4 (+63%) and August +0.4 (+87%). In addition, an increase of +0.1 heat spells per year occurred in September, while none occurred in the reference period. Dry periods increased most in percentage and absolute terms in June +0.2 (+15%) and August +0.3 (+18%), which indicates that August was affected by an increase in the frequency of both types of periods. RCP 8.5 also showed slight changes in the frequency of heat spells in the near future. Just as in RCP 4.5, May was affected by the strongest percentage increase +0.1 (+100%), while June and July showed the same increase in occurrences per year in absolute terms of +0.1, but the percentage increase was smaller (June +60%, July +15%). Regarding the changes in dry spells for RCP 8.5, April +0.4 (+24%) and August 0.2 (+15%) were particularly affected. As no positive changes in the occurrence of dry spells were predicted for these months, no month showed a joint increase in both periods.

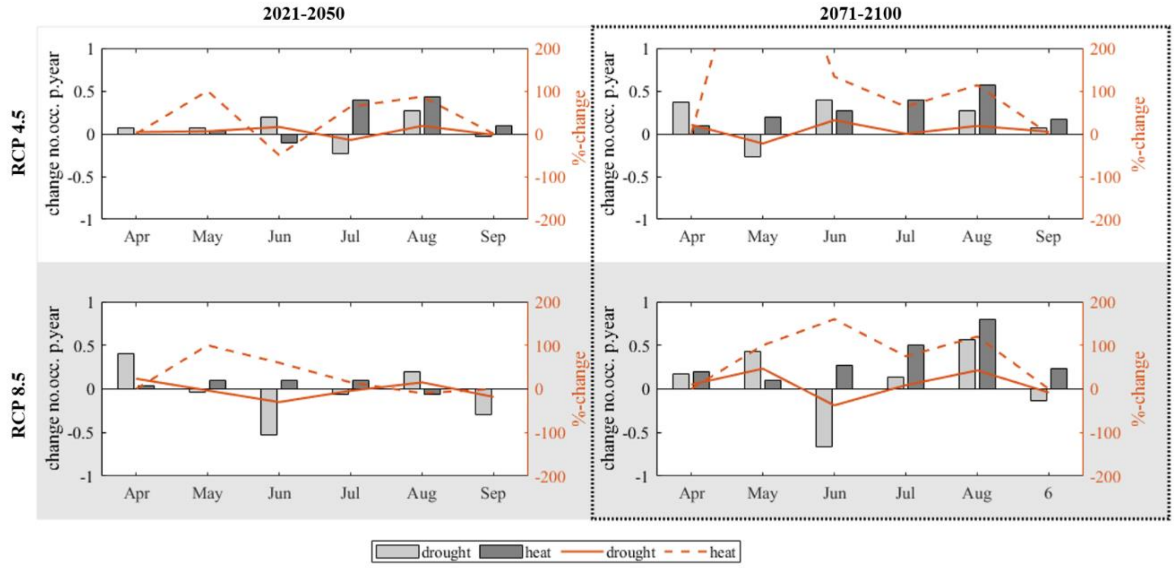


Figure 5: Absolute and %-change of average number of occurrences of drought and heat spells for the month April – September (2021-2100) compared to the reference period for both scenarios. Top: RCP 4.5, Bottom: RCP 8.5

** Value 600% for RCP 4.5, May, 2071-2100*

In the distant future, both scenarios showed an intensification of the increases in heat spells, which was expressed by an increase in all months, with the strongest absolute increases in the summer month. In absolute terms, RCP 8.5 was more affected than RCP 4.5 in the summer months, with the largest absolute increases in June + 0.3 times, July +0.5 times, and August +0.8 times. However, RCP 4.5 displayed a distinctive percentage increase of heat spell occurrence in May (+600%). Changes in dry spell frequency were dominant in the RCP 4.5 scenario in April +0.4 times (+21%), June +0.4 (-31%) and August +0.3 (+18%). This means that especially June and August were affected by a joint increase of both parameters. For RCP 8.5, it was mainly May +0.4 times (+46) and August +0.6 (+42%) that showed an increase in dryness, whereby August was thus particularly affected by a joint increase in both periods.

4.1.3.2 Average length of spells

For both scenarios, changes in the average length of heat spells occurred more pronounced in the distant future than in the near future and showed larger increases in absolute values in RCP 8.5 (Fig.6). Nevertheless, the changes, in the near future, in the length of heat spells in the RCP 4.5 scenario were +1.5 days (+43%) in August and + 4 days in September. The length of the dry spells increased only in August by 0.6 days (+7%). In RCP 8.5, changes in the length of heat spells already occurred in the near future in all months except June and September. Dry spells showed slight increases in May by +0.5 days (+7%) and in July by +1 day (+13%).

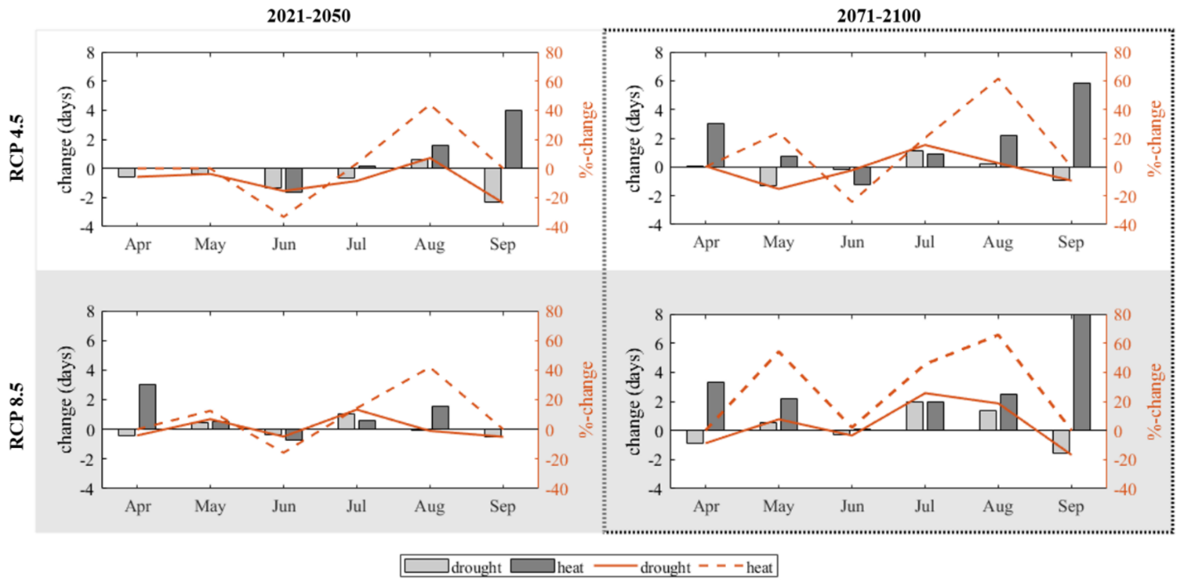


Figure 6: Absolute and %-change of average length of drought and heat spells for the month April – September (2021-2100) compared to the reference period for both scenarios. Top: RCP 4.5, Bottom: RCP 8.5

In the distant future, heat spells were strongly affected in RCP 4.5 as all months except June showed an increase. May displayed an increase of 0.7 days (23%), July of 0.9 days (+20%) and August of 2.2 days (+61%). In addition, April showed an increase of + 3 days and September an increase of +5.8 days, while no heat spells occurred in the reference period. For the distant future, changes in RCP 4.5 in the length of droughts were only detectable in July by 1.2 days (+15 %). For RCP 8.5, changes in the length of heat spells in the distant future were also more extreme compared to the near future, increasing in all presented months except June. April with 3 days and September with 8 days showed a strong increase, similar to RCP 4.5 but more pronounced. The remaining months also showed a greater increase in length than in RCP 4.5 for this period, with May increasing by 2 days (+54%), July by 2 days (+45%) and August by 2.5 days (+65%). Overall, July and August were particularly affected by a combined increase in both periods, with dramatic increases in heat pressure at the beginning and end of the season.

The distant future in RCP 8.5 was characterized by longer dry periods in July by 2 days (+25%) and in August by 1.4 days (+18%) compared to the reference period.

4.1.3.3 Worst event - Maximum spell length

In the near future the changes in the average maximum length of dry spells followed the same trend for RCP 4.5 as the changes in the average length, however, in August, the average maximum length of dry spells rose by 2 days (+20%) (Fig. 7). Additionally, also the average maximum length of heat spells increased by 2.6 days (+72%) in August. Furthermore, September's average maximum duration for heat spell increased by 4 days. Overall, the month towards the end of the analyzed period were stronger affected by an increase in average maximum length of spells. For RCP 8.5 the average maximum duration of heat spells in the near future, also changed according to the average changes for duration, e.g., in April by 3 days, July by 0.8 days (+18%) and August by 2.3 days (+60%). Changes in the average maximum duration of dry spells were predominant observed in July by 1.6 days (+17%) the trend was in line with the trend in the average duration of dry spells.

Changes for RCP 4.5 for the average maximum duration in the distant future were predominantly apparent for dry spells in July and August, which respectively rose by 1.5 days (+16%) and 1.2 days (11%). whereby heat spells showed distinctive changes in April by 3 days, July by 1.6 days (+32%) and August by 3.4 days (+93%). The changes displayed for drought and heat spells for the distant future for RCP 8.5 showed a similar pattern as well as similar values as the average trend in changes in the duration. With the highest increases in for drought in July by 3 days (+30%) and August by 2.5 days (30%) and for heat spells in all months, but especially in September by 8 days.

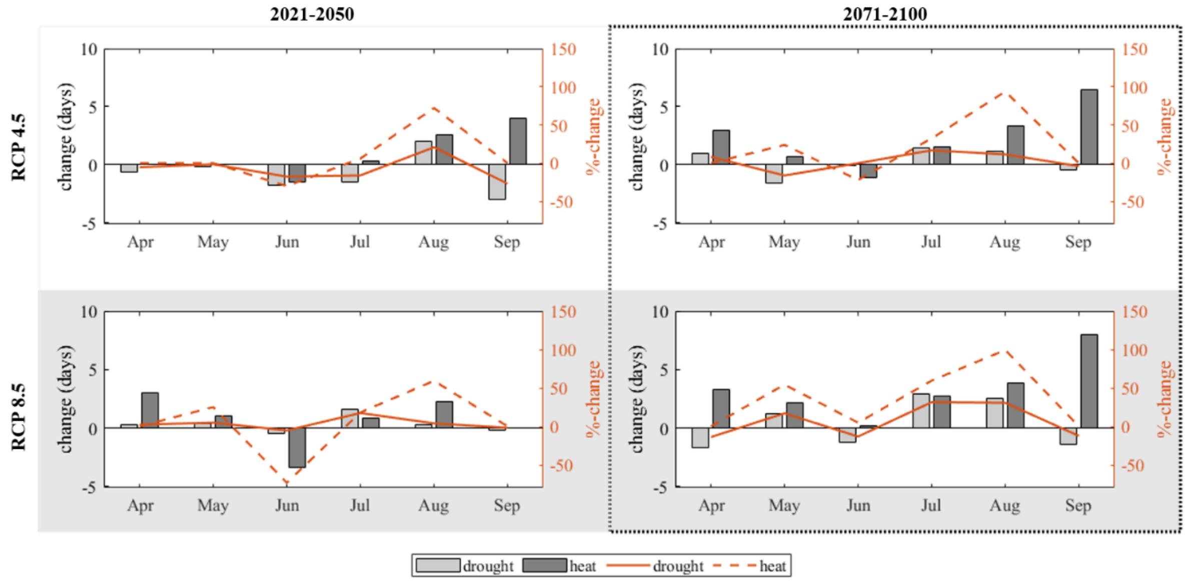


Figure 7: Absolute and %-change of average maximum duration of drought and heat spells for the month April – September (2021-2100) compared to the reference period for both scenarios. Top: RCP 4.5, below: RCP 8.5

4.1.4 Tree inventory analysis

The most common tree species in the city of Berlin according to the tree inventory were *Acer platanoides* (12%) and *Tilia cordata* (11%). Within the 10 most common tree species, 3 exotic species are contained, accounting for a total share of 11% (Tab.6.; Appendix 1, 2).

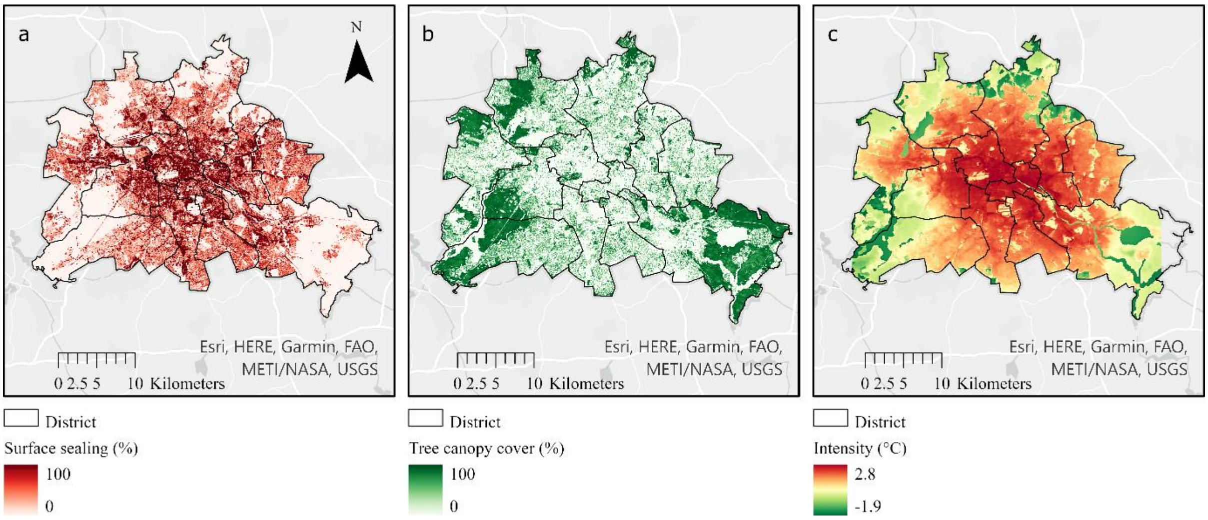
Table 6: Overview of the tree inventory literature review for the 10 most common tree species in Berlin. D = Drought tolerance (very sensitive ●, moderately sensitive ●, moderately tolerant ●, very tolerant ●), H = Heat tolerance (low ●, middle ●, high ●)

	Berlin	Origin	Share (%) of total pop.	D	H
Bot. name	*Acer platanoides*	native	12		
	Tilia cordata	native	11		
	Quercus robur	native	6		
	Tilia intermedia	hybrid	5		
	Platanus acerifolia	exotic	5		
	Betula pendula	native	4		
	Aesculus hippocastanum	exotic	3		
	Acer pseudoplatanus	native	3		
	Tilia platyphyllos	native	3		
	Robina pseudoacacia	exotic	3		
	Total		55		

Overall, 60% of the analyzed trees belonged to the moderately tolerant group, 34% to the moderately sensitive group and just 6% to the very sensitive group. No tree species was ranked as very tolerant. The drought tolerance does not automatically allow statements to be made about the heat tolerance of the tree species. For Berlin, however, it could be stated that all at least moderately tolerant species coped moderately well with heat and only moderately sensitive and very sensitive species showed only a low tolerance to heat.

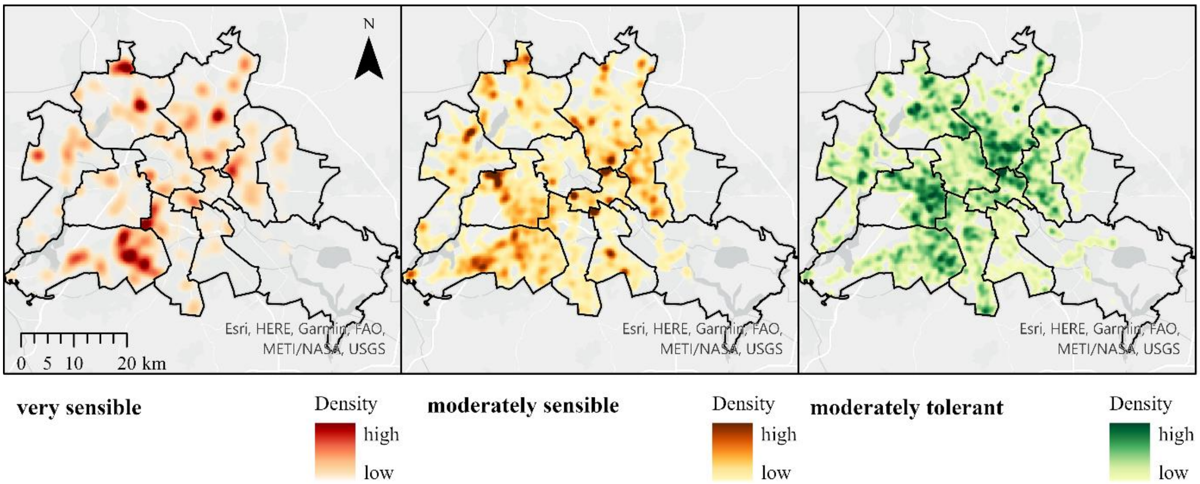
4.1.5 Exposure to UHI

Map 1 displayed the extent of land sealing in 2018, the extent of tree canopy cover in 2018 and the UHI intensity for the period 2005-2017. In Berlin, visual and statistical correlations between different land uses and UHI intensity within the urban area could be identified (Map. 1). Thus, urban core areas with a high degree of sealing (Map 1a) displayed higher UHI intensity values than peripheral areas (Map1c) (correlation coefficient: 0.7). Conversely, areas with high tree cover density (Map 1b) displayed considerably lower UHI intensity values (correlation coefficient: -0.3). Areas with more vegetation, therefore, demonstrated considerably lower UHI intensities than sealed areas for the Berlin case.



Map 1: Berlin- a) extent of surface sealing, b) tree canopy cover density c) urban heat island intensity (JJA) (Figure created from data source: EEA 2018a, EEA 2018b;EEA 2020a, ESRI 2020b)

The different trees assessed in the tolerance categories displayed different distribution and density patterns within the city (Map 2). The very sensitive trees were strongly concentrated in certain hot spots, which was also caused by their overall lower quantity. On average, the trees classified in the very sensitive category on average displayed UHI intensities for the summer month (JJA) of 1.5 in the areas they were located in (Table 7).



Map 2: Tree density distribution for the four different drought tolerance categories for Berlin based on the literature review-based categorization

For the moderately sensitive categorized trees, a more extensive distribution over the entire city area could be observed, with a few small hotspots. Trees in this category were also exposed to average UHI intensities of 1.5. Similar patterns could be seen for the moderately tolerant trees, which represented the highest total number. These show higher density values distributed around the city center and are on average exposed to the highest UHI intensity (1.6). In addition, the average year of planting of the trees became steadily younger from the very sensitive category (1964) to the moderately sensitive (1967) and moderately tolerant class (1974).

Table 7: Frequency, UHI intensity (∅) and planting year (∅) for the drought tolerance categories for Berlin

Tolerance Category	Frequency	UHI intensity (∅)	planting year (∅)
Very sensitive	18621	1.5	1964
Moderately sensitive	110201	1.5	1967
Moderately tolerant	183532	1.6	1974
Very tolerant	-	-	-

4.2 Vienna

4.2.1 Point measurements (1991-2020) vs Gridded observed data (1991-2020)

4.2.1.1 Maximum temperature & heat spells

The average annual maximum temperature values for the station and E-OBS data of the city of Vienna (Fig. 8) did not differ significantly for the reference period (*t(56)=0.3,p=0.77*). In addition, the course of the data series showed a correlation of 1. The observation and comparison of the CDF curves for the average monthly values of maximum temperature also indicated that the station data values were very well represented by the E-OBS data series during the growing season from April to September, supported by no observed significant difference between the datasets. The E-OBS data thus represented the station data very well and was used for comparisons in the further course of the work.

The mean annual maximum temperature for Vienna according to the E-OBS dataset was 15.4 °C. for the reference period. The average number of heat spells occurring in the months April to May in the reference period was 2.3 times per year for Vienna. The average length was 4.6 days, and the average maximum length was 10.3 days.

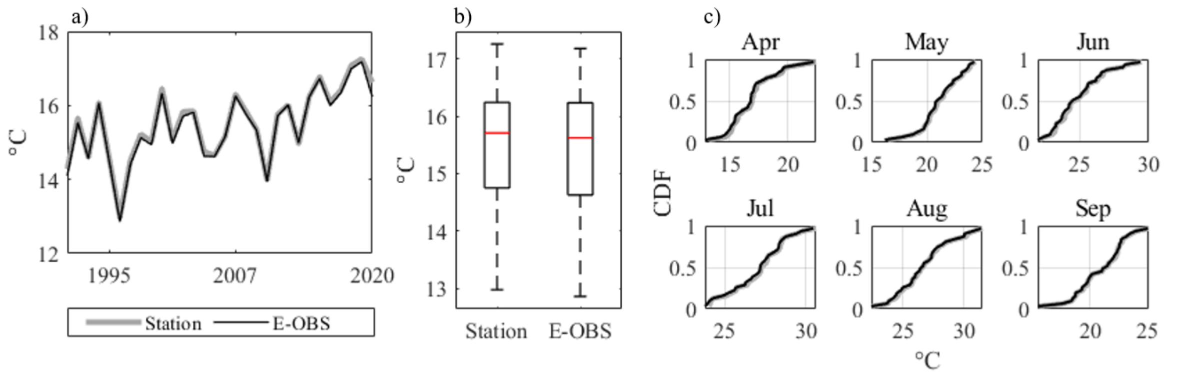


Figure 8: Comparison of mean annual maximum temperature for 1991-2020 for station and E-OBS data (a, b) and CDF for the month April - September for station and E-OBS data (c) for Vienna

4.2.1.2. Cumulative Precipitation & dry spells

The analysis of the annual precipitation sum for the reference period for station and E-OBS data for Vienna showed that these were significantly different according to the t-test carried out (*t(56)=2.4, p=0.01*), but still showed a very high correlation (0.97) (Fig. 9). Overall, the E-OBS data regularly showed a 10% higher annual total precipitation sum compared to the station data, explaining the significance difference between the datasets, but displayed the same course over the reference period and therefore a high correlation value. This can be clearly seen in the representation of the course of the annual precipitation sum for station and E-OBS data in Fig. 10.

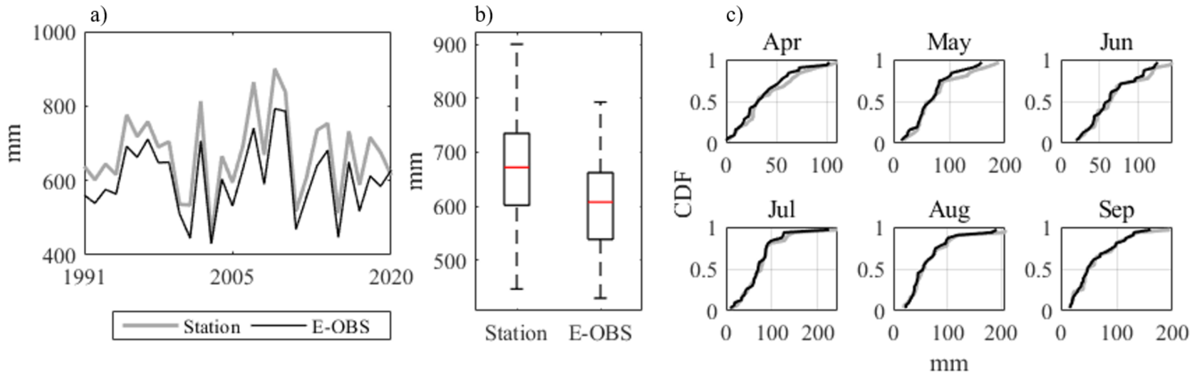


Figure 9: Comparison of total mean annual precipitation sum for the reference period 1991-2020 for station and E-OBS data (a, b) and CDF for the month April -September for station and E-OBS data (c) for Vienna.

However, the CDF for the months April to September showed a very good fit and no significant difference, leading to the assumption that differences in precipitation sum between station and E-OBS data mainly occurred in the remaining months of the year.

The average annual precipitation sum according to the E-OBS dataset was 605 mm. In Vienna, dry spells were recorded for the month April – May for the reference period. The average occurrence per year was approx. 10.5 times. And the waves had a length of 8.5 days with an average maximum length of 26 days.

4.2.2 Gridded observed data (1991-2020) vs. Modelled climate data (1991-2100)

4.2.2.1 Daily Maximum temperature

For the mean annual maximum temperature, the RCP 4.5 data were found to not deviate significantly from the reference period (*t(57)=2, p=0.05*),but displayed a very low p-value, whereas the RCP 8.5 values did not (*t(57)=1, p= 0.3*) (Fig.10). Both scenario datasets showed a similar correlation compared to the E-OBS data (*0.47* and *0.62*). The average monthly maximum temperature for the months April differed significantly for both scenarios from the E-OBS data (RCP4.5*: t(58)=2.1, p=0.03;* RCP 8.5*: t(58)=2.5,p= 0.02*). June displayed a frequencies of lower temperature values in the scenario data compared to the E-OBS data (Fig.11), but no significant difference. Overall, the average maximum temperature in the month from April-September were represented well, except for April.

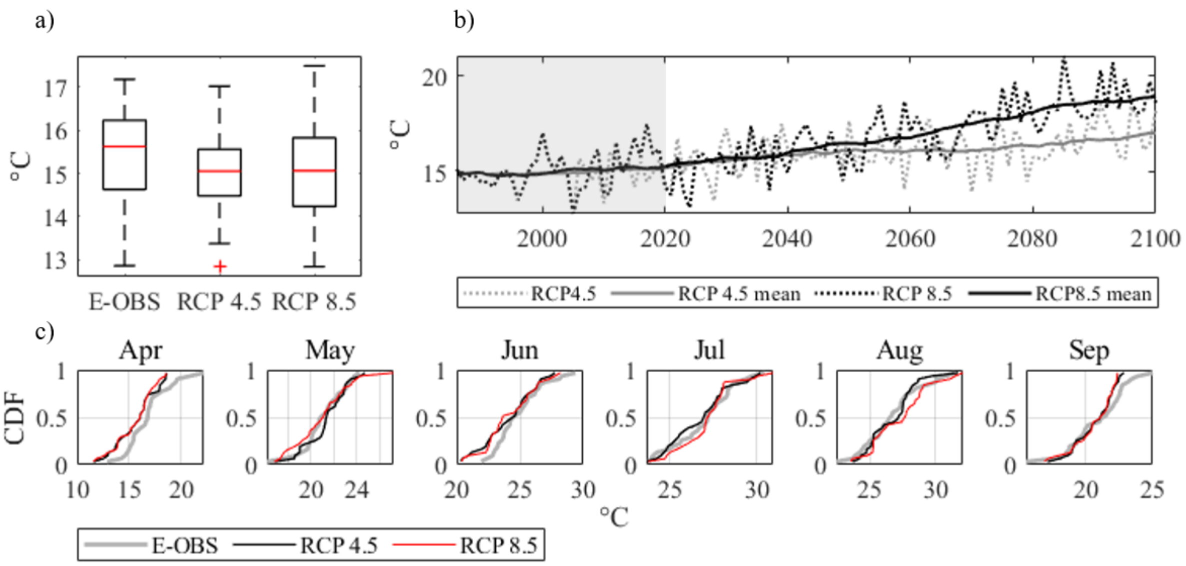


Figure 10: Comparison of annual and monthly average maximum temperature for E-OBS, RCP 4.5 and RCP 8.5 data for the reference period (a) and the CDF for the month April -September for E-OBS and scenario data (c) for Vienna. Overall development of scenario data until 2100 (b). Reference period highlighted in grey.

Both scenarios predicted an increase in mean annual maximum temperature over the total course of the century, with RCP 4.5 estimating an average increase of 1.2 C and RCP 8.5 an increase of 1.9 °C. For both scenarios, there was a steady increase towards the end of the century, with RCP 8.5 particularly increasing in the distant future from 2071 (+3.4 °C) (Table 8).

Table 8: Comparison development annual mean maximum temperature for the scenarios - Vienna. Δ temp represents the difference between scenario value and the value of the reference period of the respective scenario (1991-2020).

	RCP 4.5		**RCP 8.5**	
Time period	°C	Δ TEMP.	°C	Δ TEMP.
Ref. Period	14.96		15.15	
2021-2100	16.18	1.21	17.06	1.91
2021-2050	15.85	0.88	15.75	0.59
2071-2100	16.6	1.63	18.5	3.36

4.2.2.2 Cumulative precipitation

The comparison of the E-OBS data and the scenario data in the reference period for the annual precipitation sum shown in Fig. 11 displayed a low p-value for RCP 4.5 ($t(57)=1.7, p= 0.08$). The RCP 8.5 values did not differ significantly ($t(57)=0.9$, $p= 0.39$). A closer look at the monthly values also showed that especially in May and July low p-values (0.19, 0.16) were recorded for both scenarios. In September, the RCP 4.5 differed significantly from the E-OBS data ($t(48)=2.5, p= 0.01$), as the precipitation totals were displayed significantly lower (Fig.12). It can therefore be assumed that the precipitation totals were predicted too low in September, especially for RCP 4.5 compared to the E-OBS data. The other month displayed no significant difference.

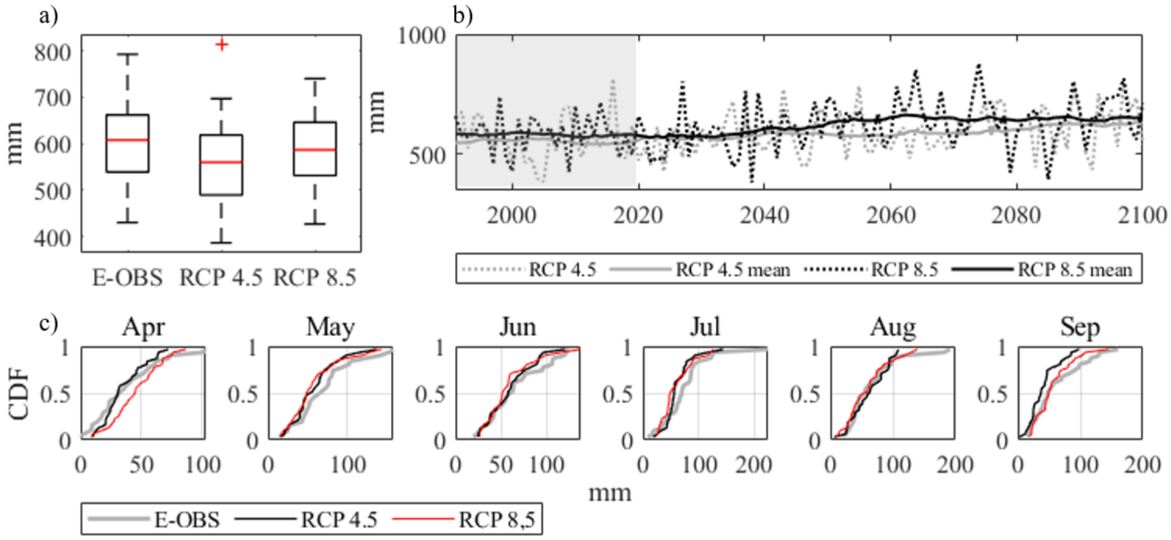


Figure 11: Comparison of annual and monthly average total precipitation sum for E-OBS, RCP 4.5 and RCP 8.5 data for the reference period (a) and the CDF for the month April -September for E-OBS and scenario data (c) for Vienna. Overall development of scenario data until 2100 (b). Reference period highlighted in grey.

Overall, a slight increase in annual precipitation was predicted for the city of Vienna by both RCPs (Table 9). Over the course of the century, RCP 4.5 showed an increase of 5% and RCP 8.5 of 7%. Distributed over the different periods, RCP 4.5 showed no change in precipitation in the near future but a strong increase over the further course of the century by 11%. RCP 8.5, on the other hand, forecasted a steady increase in precipitation distributed over the periods an increase of with 11.5 % for the distant future.

Table 9: Comparison development annual total precipitation for both scenarios -Vienna. %-change represents the %-change from scenario value to the value of the reference period of the respective scenario (1991-2020).

	RCP 4.5		**RCP 8.5**	
Time period	mm	%-change	mm	%-change
Ref. Period	561.8		585.5	
2021-2100	591.3	5.27	627.2	7.12
2021-2050	572.2	1.85	585.8	0.04
2071-2100	624.9	11.2	652.9	11.5

4.2.3 General trends in occurrence of heat and dry spells (2021-2100)

Regarding the occurrence of heat spells, both the occurrence and the changes in the average length and the average maximum length, for both scenarios diaplayed stronger changes in the distant future. RCP 4.5 showed a smaller average number of occurences per year predicted for 2021-2100 with 4.4 occurrences, while RCP 8.5 displayed 4.9 occurrences per year for that period. The average duration of heat spells displayed values of 6.4 days for RCP 4.5 and 6.7 for RCP 8.5. The average maximum length rose to 11.1 days for RCP 4.5 and 13 days for RCP 8.5.

The changes for dry spells were rather small, with stronger changes in the distant future. Dry spells showed on average no changes in the average number of occurenes per year for the month April- September and stayed at 8.9 times per year for RCP 4.5 and 10.1 times per year for RCP 8.5 which led to RCP 8.5 representing the E-OBS data value of 10.5 times per year for the reference period better. Also, the changes in average length (RCP 4.5: + 0.3 days, RCP 8.5: +0.8 days) and average maximum length (RCP 4.5: +1 days, RCP 8.5: +2.5 days) were more pronounced in the distant future and for RCP 8.5.

4.2.3.1 Average annual frequency of heat and dry spells

For Vienna, changes in the frequency of heat and dry spells for both scenarios were found to occur more pronounced in the distant future and less in the near future (Fig.12). Interestingly, the RCP 8.5 scenario showed considerably lower total and percentage changes in the occurrence of heat spells than RCP 4.5 in the near future. Thus, the months June +0.4 times (+162%), July +0.3 (+28%), August +0.5 (+51%) and September +0.13 (+400%) showed more marked increases in frequency than in RCP 8.5, where only June +0.2 (+54%) and August +0.4 (+30%) showed an increase. Also, in the occurrence of dry periods, April +0.4 (+23%) and thus the beginning of the study period and August +0.13 (+10%) were affected in RCP 4.5, while RCP 8.5 was particularly affected in September +0.4 (+25%). Only RCP 4.5 displayed a month, August, that was affected by a significant increase in the frequency of both periods.

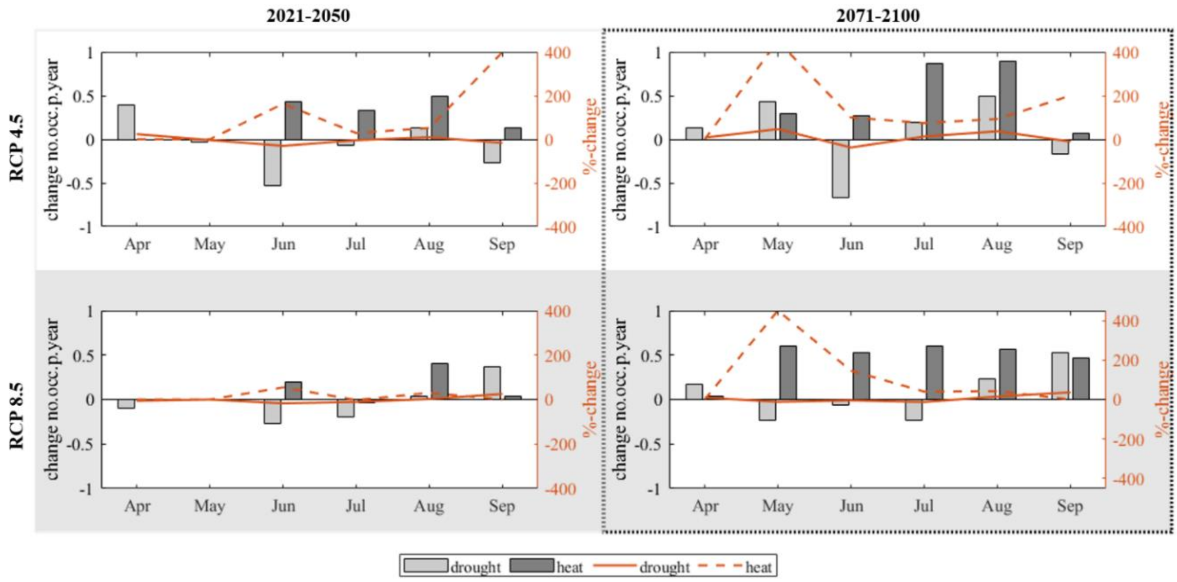


Figure 12: Absolute and %-change of average number of occurrences of drought and heat spells for the month May – September (2021-2100) compared to the reference period for both scenarios.

Top: RCP4.5, down: RCP 8.5

** Value 450 % for RCP 4.5, May, 2071-2100*

The distant future displayed more extreme changes for both period types. The frequency of heat spells for RCP 4.5 increased in the majority of months. In absolute terms, this was particularly the case in July and August with an increase of 0.9. In percentage terms, however, the increase was greatest in May (+400%), June (+100%) and September (+200%). May, July and August showed the strongest risk of a combined increase in heat and drought. The result indicated an increase in the frequency of dry spells in all months presented, except June. Whereby May (+450%) and August (100%) were particularly affected by an increase in average number of occurences. While in the RCP 4.5 scenario for the distant future a concentration of the increase in occurrence was particularly in the months of May, July and August, RCP 8.5 displayed a very pronounced increase in all months except April with May (+450%), June (145%), July (+40%) and August (+42%). In the distant future, changes in the frequency of droughts were also less extreme than for RCP 4.5, with only September showing a large increase in both the total number (+0.5 times) and percentage (+36%) of events per year. August and September were particularly affected by a combined change in heat and dry periods.

4.2.3.2 Average length of spells

For the near future RCP 4.5 displayed no major changes for the duration of heat spells in spring, but from July onwards there was an increase in average duration of almost 2 days for each remaining month, representing a percentage increase of 40-60% (Fig.13). Few changes in the average length of the dry spells were predicted, expect for July by 1 day (+15 %). July, therefore, was predominantly exposed to an increase in both periods. For RCP 8,5 the average length of heat spells also increased but less regularly distributed over the months as in RCP 4.5, but particularly pronounced in September with an increase of 4 days compared to the reference period, where no heat spells occurred at this time of year. A strong increase in the length of dry spells was already evident in the near future, especially in the early months of April by 1.2 days (12%) May by 1.3 days (18%), June 0.6 days (+8%) and September by 1.7 days (+21%). therefore June, but especially September was exposed to an increase in both spell types.

For RCP 4.5 changes in the duration of the heat spell were even more extreme in the distant future. On the one hand, May and June showed an increase in length, and on the other hand, the increase in July (+66%) and September (+144%), describing an increase of almost 4 days, was much more pronounced than at the beginning of the century. Changes in the length of dry spells were described, especially in July by almost 2 days (+31%) and in August by 1.6 days (+12%), while the length in April and September decreased slightly on average. Especially in July there was a joint increase of dry and heat spells, but also May and August were affected. The average heat spell length increased in all presented months for RCP 8.5 in the distant future. April with an increase by 4 days was particularly affected. The summer months of July and August, as well as September also showed an extreme increase in the average length of at least 4 days. The distant future continued to display an intensification of dry spells at the beginning of the season, similar to the near future, and an increase in the average length of about 2 days in July. Especially in April, May and July, the average length of both periods increased together.

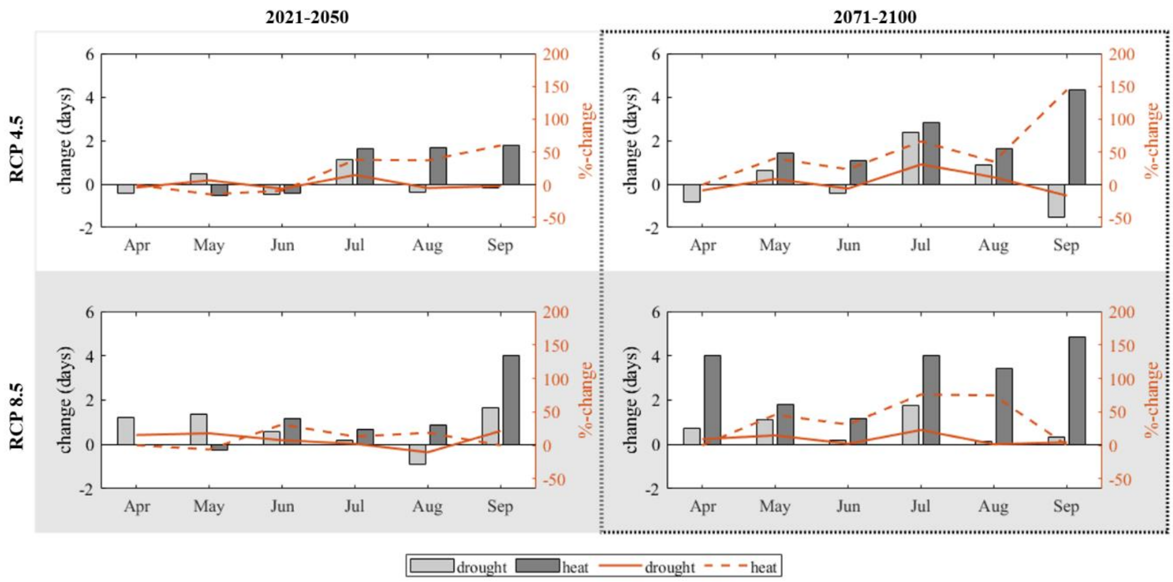


Figure 13: Absolute and %-change of average length of drought and heat spells for the month May – September (2021-2100) compared to the reference period for both scenarios.

Top: RCP4.5, down: RCP 8.5

4.2.3.3 Worst event - Maximum spell length

For the near future, the RCP 4.5 results for the changes in average maximum duration showed values that were close to the change in mean duration presented earlier (Fig.14). The situation was different for the heat spells, which already at the beginning of the century showed even more extreme values for the change in maximum duration than for the general mean length of the heat spells. Thus, the duration in July and August increased by 2.6 and 3 days, respectively, which corresponded to 50 and 62 %. September also showed a strong increase of 2.3 days (75 %). For RCP 8.5 the projections for the changes in average maximum duration for the period 2021-2050 displayed a similar trend to the changes in average duration for dry, as well as heat spells.

For RCP 4.5, the same pattern occurred in the distant future, with the changes in maximum length of the dry spells again showing similar values to the changes in mean duration. In addition, the heat spells displayed even more extreme changes in mean maximum length compared to the change in average duration, e.g., July with 5.2 days (100%) and September with a change of 4.3 days (133%). For RCP 8.5, the maximum duration of heat spells in the distant future also showed a further increase in the maximum length. This was particularly pronounced in July, August and September, where the average maximum duration of heat spells increased to 8 and 6 days respectively.

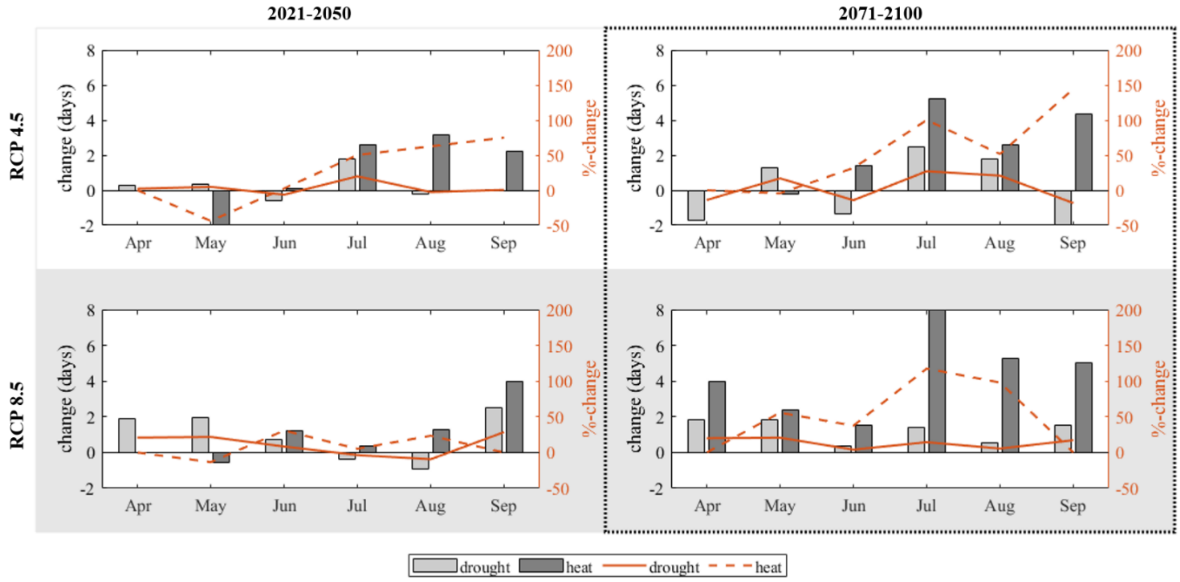


Figure 14: Absolute and %-change of average maximum duration of drought and heat spells for the month May – September (2021-2100) compared to the reference period for both scenarios.

Top: RCP4.5, down: RCP 8.5

4.2.4 Tree inventory analysis

The ten most common tree species, roughly present 52% of the total city tree population for Vienna. According to the tree inventory was *Acer platanoides* (14%). Already the second most common tree was defined as exotic according to the literature review (*Aesculus hippocastanum*) with 6%. In total, exotic tree species account for 17% of the 10 most common tree species (Tab. 10, Appendix 1,2).

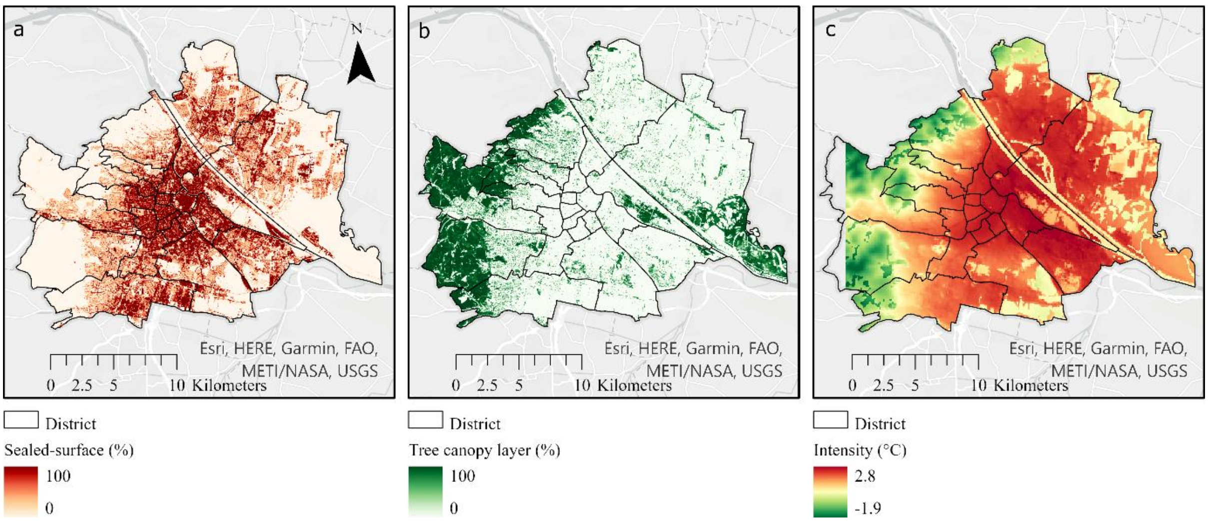
Overall, 8% are characterized as very tolerant, 52% as moderately tolerant, 23% as moderately sensitive and 17% as very sensitive. For Vienna, the analysis of the heat tolerance of the trees also showed that all trees that were at least moderately tolerant were also able to cope moderately well with heat. The majority of moderately sensitive to very sensitive tree species also showed low heat tolerance, but there were exceptions. *Populus nigra*, for example, was very sensitive to drought but only moderately sensitive to heat. *Robinia pseudoacacia* and *Fraxinus excelsior* were also moderately sensitive to drought but tolerated heat well. Thus, of the trees in Vienna, only 2 species were classified as sensitive to heat.

Table 10: Ten most common tree species in Vienna ordered by share and tolerance ranking. D = Drought tolerance (very sensitive ●, moderately sensitive ●, moderately tolerant ●, very tolerant ●), H = Heat tolerance (low ●, middle ●, high ●)

	Vienna	Origin	Share (%) of total pop.	D	H
Bot. name	*Acer platanoides*	native	14	moderately tolerant	middle
	Aesculus hippocastanum	exotic	6	very sensitive	low
	Tilia cordata	native	6	moderately tolerant	middle
	Fraxinus excelsior	native	5	moderately sensitive	middle
	Pinus nigra	native	4	very tolerant	high
	Acer pseudoplatanus	native	4	moderately sensitive	low
	Acer campestre	native	4	moderately tolerant	high
	Platanus acerifolia	exotic	4	moderately tolerant	high
	Robina pseudoacacia	exotic	3	moderately sensitive	high
	Populus nigra	native	3	very sensitive	middle
	Total		53		

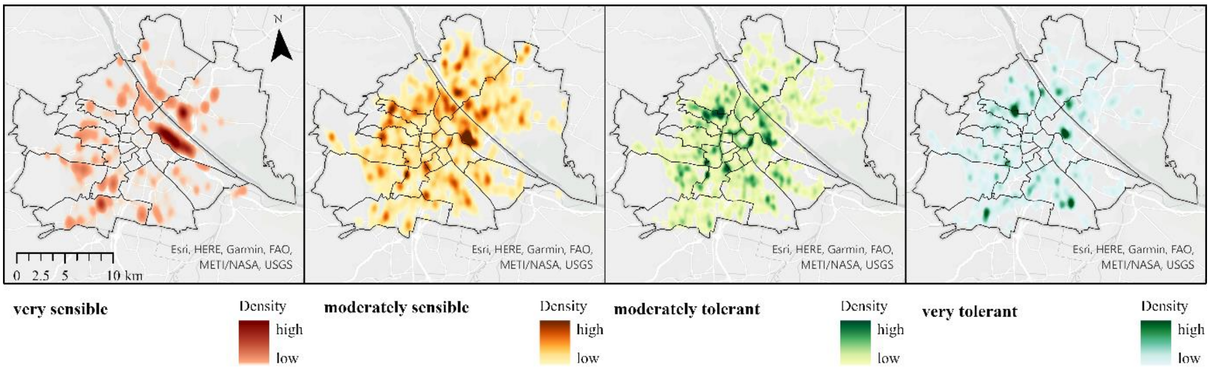
4.2.5 Exposure to UHI

Map 3 presents the extent of sealed surfaces, the amount of tree canopy cover as well as the urban heat island intensity for the city of Vienna. Patterns like those in the previous analysis of Berlin can be visually and statistically identified (Map 3). Thus, heavily sealed, often inner-city areas show markedly higher UHI intensities for the summer month (JJA) than areas with lower sealing levels (correlation coefficient: 0.6). In addition, areas with a high degree of tree canopy cover presented lower UHI intensity values, like seen in the western part of Vienna (Map 3) (correlation coefficient: -0.5).



Map 3: Vienna- a) extent of surface sealing, b) extent of tree cover canopy, c) urban heat island intensity (JJA) (Figure created from data source: EEA 2018a, EEA 2018b, EEA. 2020a, Stadt Wien 2020c)

In Vienna, too, the distribution and density of trees in the individual tolerance categories varied. The vulnerability of tree species showed that the second most dominant tree species was categorised as very sensitive *(Aesculus hippocastanum)* making, together with the moderately sensitive trees, for 32% of the total tree population. As the distribution of the very sensitive trees in the city suggests, they were particularly localised in certain hot spots, such as park areas (Map 4). However, it appeared that other cohesive structures within the city are also affected. The moderately sensitive trees, also due to their total quantity, were distributed over the entire urban area, with individual hotspots that partly already occur with the sensitive species.



Map 4:Tree density distribution for the four different drought tolerance categories for Vienna based on the literature review-based categorization

The moderately tolerant trees were just as strongly distributed in total number as the two aforementioned categories together but show only a few hotspots and are relatively evenly distributed over the entire urban area. Both moderate categories were, on average, exposed to the highest UHI intensity. The very tolerant trees, on the other hand, were again more frequently found in certain hotspots, and they too are not distributed over the entire cityscape. Overall, the sites of the very tolerant trees showed on average the lowest UHI intensity (1.7), while the two moderate classes showed the highest (1.9), the very sensitive category displayed the value (1.8) (Table 11). The average year of planting became steadily younger from the very sensitive category (1960), to moderately sensitive (1980), moderately tolerant (1984) and very tolerant (1988).

Table 11: Frequency, UHI intensity (Ø) *and planting year* (Ø) *for the drought tolerance categories for Vienna*

Tolerance Category	Frequency	UHI intensity (Ø)	planting year (Ø)
Very sensitive	11.600	1.8	1960
Moderately sensitive	15.731	1.9	1980
Moderately tolerant	32.254	1.9	1984
Very tolerant	9.683	1.7	1988

5. Discussion

5.1 Hazard - Climate analysis

The climate analysis showed that in the recent past (1991-2020), both cities had been exposed to heat and drought events. Further, the analysis of the RCP 4.5 and RCP 8.5 scenario demonstrated an increase in annual mean maximum temperature and a slight increase in annual total precipitation sum for both cities, whereby Vienna showed a stronger increase compared to the reference period for both variables than Berlin. The comparison with E-OBS data indicated that the climate model data (reference period) showed that overall temperature values were better represented than the precipitation data. However, the precipitation total was sufficiently represented, as both data sets did not differ significantly from the E-OBS data.

Total precipitation for both cities may according to Jacob et al. 2014 increase to a similar extent for both scenarios (RCP 4.5 and RCP 8.5) for the distant future (2071-2100), by 15 -25 % compared to the reference period, 1971-2000. The results in this study showed that while Vienna displayed an increase of 12 % for this period in both scenarios, Berlin only showed an increase for RCP 8.5 of 11.5 %, but not in RCP 4.5 (3 %). This was possibly due to differences in the climate model data or reference period values.

5.2 Changes in heat and dry spells

The mean monthly maximum temperature and precipitation values showed no significant difference compared to the E-OBS data For Berlin. The same applies to Vienna expect for April, where the values for the maximum temperature differed significantly for both scenarios and September were the RCP 8.5 scenario values differed significantly from the E-OBS dataset. Despite this, the overall representation was therefore good.

Clear differences between the RCPs, as well as the time periods investigated (near and distant future) regarding the frequency and severity of heat and dry spells, were shown for both cities for the month April – September. It could be demonstrated that the average frequency per year and severity of these extreme events indicated more pronounced changes in the distant future (2071-2100) and were overall stronger for RCP 8.5 than RCP 4.5 which is in line with the results by a study by Jacob et al. 2014. The overall increasing risk of heat waves across Europe, but especially the stronger impact on Vienna compared to Berlin, are further supported by the results of a study by Smid et al. 2019, which states that the increase in the occurrence of heat waves runs along a European gradient from south to north-east.

For both cities and scenarios, the distant future is likely to be associated with an increased frequency of heat spells during the summer months June, July, and August. This trend has already been detected for Berlin for the period of 1893 to 2017, in a study comparing different heat wave definitions by Fenner et al. 2019. The majority of the definitions with a static threshold identified a concentration of heat waves in the months of June, July and August. In the future the impact of heat spells might be further increased by increased drought spells as precipitation is mainly predicted to increase in the autumn and winter month and not in summer for the study areas (EEA 2019). An analysis of various compound events by (Ridder et al. 2020) identified heat waves in combination with dry days, as the compound event with the highest occurrence risk for Europe for the period 1980-2014, particularly frequently in August and September.

In this study, the analysis of climate model data showed that heat events in the future were accompanied by an increase in the occurrence and length of dry spells, leading to a higher probability of multiple stressors. Europe is likely to experience an almost 50 % increase in the occurrence of compound events consisting of hot and dry events for 2055-2090 (RCP 8.5) compared to 1950-1999 (Wu et al. 2021).

Additionally, it should be emphasised that Berlin showed a particular increase in the average durations of heat spells in April and September in the distant future for both scenarios, i.e., located towards the beginning and end of the growing season (Rötzer and Chmielewski 2001) Unlike Berlin, Vienna did not show a concentration of more frequent heat waves in summer and longer ones in spring and autumn, but an increase in both phenomena over the entire period under consideration (May-Sep). Accordingly, warmer, and more extreme temperatures at the end of the century may occur more regularly at the beginning and end of the growing season. This can be problematic as it might lead to phenological changes like an earlier budburst, unfulfilled chilling requirements (Fu et al. 2012), longer periods of flowering or autumn phenomena like second flowerings (Luterbacher et al. 2007). However, Fu et al. 2012 showed that these impacts are highly dependent on the tree species investigated. They concluded that temperature impacts might outcompete negative effects by decreasing chilling days. The extent to which climate variability affects the phenology of trees has, however, not yet been sufficiently researched (Reyer et al. 2013).

5.3 Vulnerability

For both cities, the majority of the ten most dominant species were classified as moderately tolerant and moderately sensitive and less in the extreme categories, very sensitive or very tolerant.

For Vienna overall, more tree species were characterised towards more extreme categories of the tolerance spectrum (17% as very sensitive and 15% as very tolerant). However, interestingly both cities displayed 40 % of the analysed tree in the categories very and moderately sensitive combined. According to the conducted literature review, in both cities, the exotic species did not show a predominantly better tolerance towards drought compared to endemic species. However, they often showed better values for heat tolerance in relation to their drought tolerance.

No qualitative values for heat or drought tolerance could be generated, only qualitative defined ranges in which the trees were categorised. Thus, despite the review of various studies, literature reviews and online databases, there is still uncertainty and inconsistencies as to what extent a specific tree species shows tolerance to environmental influences like drought and heat (Banks et al. 2019). In most rankings for drought and heat tolerance, only one tolerance category or value for the whole year for a tree species is given, although studies have already found seasonal variability in these tolerances for some species throughout the year (Banks et al. 2019). This suggests that the specific timing of dry spells is crucial for the survival of tree species such as *Betula pendula* (Hannus et al. 2021) and should be more thoroughly analysed. Regarding the possible selection of trees species, a high drought and heat tolerance in both spring and summer would therefore be preferred, especially if spring drought is expected. It is difficult to predict to what extent and how quickly plants can adapt to new climatic conditions, as these can promote changes in the susceptibility and tolerance of a species (Reyer et al. 2013).

In this study the tree species itself were analysed, but no assumptions about the provenance origin of the planted trees could not be made. However, several studies have shown that the drought or heat tolerance of a species is not necessarily the same for all genotypes (Percival et al. 2006; Sjöman et al. 2015; Banks et al. 2019). Furthermore, a study by Viger et al. 2016 identified for *Populus nigra* that the more southern genotype, commonly exposed to dry conditions, had higher adaptive capacity compared to genotypes of the same species from more northern and wetter sites.

This allows to conclude, that the selection of species should not only be concentrated on the species itself but the origin of the genotypes and subspecies. As indicated by the results of the literature review regarding heat and drought tolerance, many native species may not have the necessary tolerances to survive successfully in the future (Appendix 1, 2). Taking different genotypes into account could offer an opportunity regarding the conservation goal of specific species within the urban environment despite a changing climate.

5.4 Exposure

For both cities, similar patterns were observed regarding the distribution of the trees categorized as very sensitive, as these trees were often found in specific hotspots within the city, including parks (particularly pronounced in Vienna) and thus less spread over the entire urban area. Trees in the moderately tolerant categories showed a more widespread distribution within the cityscape in Berlin, most likely also due to the considerably higher absolute number of trees in this category for Berlin.

In addition, trees of all categories in Berlin were exposed to lower average UHI intensities than in Vienna. Considering the results of the climate analysis, this would mean that the already higher average temperatures in Vienna and an additionally stronger UHI development could create even more adverse conditions at the locations of the sensitive trees and increase the stress level even more, particularly at street level. As influences like salt contamination, air pollution and poor water supply due to modified infiltration ways, are probably less extensive in areas with higher urban alteration (Reyer et al. 2013), very and moderately sensitive trees located in park areas can thus be assumed to be less affected by further anthropogenic influences affecting tree health compared to street trees.

Despite the rising annual mean temperatures and even more severe conditions due to UHI developments, the heat and drought tolerance ranking does not imply that specific tree species will not survive. Urban spaces are generally not comparable with natural environments, especially because of the anthropogenic maintenance that is taking place. The survival of the trees therefore depends largely on the amount of care that is given to them according to Yang 2009 as optimal distribution rages can be expanded by it. For Berlin and Vienna, this would mean that in the long run there is a trade-off between less tolerant tree species with high maintenance standards, e.g., in the form of water consumption, and better adapted species that require less maintenance, but may no longer correspond to the original appearance of the park area or street. In case of exotic species trade-offs regarding biodiversity and possible plant diseases have to be taken into account. In the case of sensitive trees in park areas, trees in combination with grass areas are especially useful, as shaded grass areas are even cooler than shaded concrete areas, which further promotes the adaptation needs and support of trees in these areas (Armson et al. 2012).

In both cities, the age structure of the different categories indicated that very sensitive trees were the oldest, with average planting year in the 1960s. The rather high age of the trees could be interpreted as a possibility to replace them in the near future successively with better-adapted species as soon as they show signs of decay.

5.6 Adaptation

Regarding possible adaptation measures required in the respective cities to support a vital tree population, it can be stated that both cities have in common that they will be affected by more and frequently longer periods of heat regardless of the climate scenarios, but especially in the distant future. In addition, depending on the scenario, dry spells will occur more frequently and last longer. The occurrence of compound events will be particularly pronounced in the summer months but may also occur more frequently in the early and late phases of the growing season. Main differences between the cities were a more sever climate (heat spells) for Vienna, particularly in the distant future, differing tree composition and vulnerability, as well as individual exposure patterns within the city.

Different tree species have different mechanisms for avoiding drought damage, with those species applying the avoidance principle being particularly dependent on sufficient water supply (Roloff 2016). As precipitation was not found to increase substantially in the summer month for both cities it may mean that even moderately drought tolerant trees need additional support from irrigation to support drought tolerance. As the majority of trees proved to be moderately or tolerant to heat but less tolerant to drought, the focus of adaptation will be on supporting more drought-tolerant tree species with sufficient water supply so that they can adequately use their drought damage prevention mechanisms. As well as the planned replacement of very sensitive species with less sensitive species.

The city of Berlin states that trees in Berlin live to be about 60 years old on average (Berlin 2021). As the average planting age of the very sensitive trees in Berlin is set in the 1960s, these trees will soon reach their maximum age. It is therefore important to start identifying old and endangered trees now to replace them with new ones very soon. If adaptation preparations are delayed too long, adaptation measures may fall permanently behind. And instead of increasing the GI, maintaining the existing GI may become the main issue. In addition, it turned out that very sensitive trees are often concentrated in certain parks. Replacing these species would therefore have consequences for the overall character of the park. A good balance between the successful surviving of these trees through e.g., irrigation measures and the associated costs and the possible benefit of replacing these trees is therefore essential.

In addition to the analysis of ecological sensitivity and vulnerability, as conducted in this study, social components such as political, institutional, economic and community aspects should also be considered. This is particularly important for the completion of the planning of adaptation measures, as factors like the access to resources (budget), already implemented strategic programs, policies and the overall engagement play a crucial role for the success of possible adaptation measures (Ordóñez and Duinker 2014). The issues of costs and benefits are decisive for decision-making in the western world, in this case Europe. A study conducted by Horváthová et al. 2021 found that the shading benefit of trees exceeds cost from maintenance only if trees are not replanted every 20-30 years, which indicates that trees are more beneficial after a long standing period and that very regular replanting does not yield any cost benefits. This is especially due to high maintenance cost for young trees. However, they also stated that since trees not only support microclimate regulation but also provided several other services, even higher short-term cost could be compensated. The analysis of the age structure of the trees in the different tolerance categories showed that, except for the very sensitive category, Berlin had older trees on average. To ensure that the urban tree populations are at the peak of their performance in the distant future, consideration should be given in the coming years to which trees should be replaced, when and how.

In order to use GI, but also water bodies as efficiently as possible, it has also been shown that the same measures do not have the same effects at every location, but that other surrounding conditions (prevailing climate, urban structure) play a decisive role in successful implementation and have consequently be assessed every time (Žuvela-Aloise et al. 2016). Thus, measures for one city might not be applicable to the other and vice versa, despite the commonality of the risk of increasing extreme events.

5.7 Current adaptation measure in the two cities

Both cities have already taken up the issue of GI in various strategies and projects. Awareness of the value of urban trees in the context of climate change has already been incorporated into several concepts and strategies in the city of Berlin. One of them is a campaign called “Street trees for Berlin” where for every 500 euros donated, a tree is planted in the city. The project has been running since 2012 and a total of 2 million euros in donations have already been collected, with 59,000 Euros for 2021 alone. The campaign was initiated by the Berlin senate due to the increasing cutting down of trees that were weakened by disease, age, or other environmental factors (Berlin 2021). This donation-based Berlin project is a good example of how, as mentioned earlier, the available budget plays a decisive role for implementing adaptation measures. In this case, due to the lack of the city budget, the financial responsibility is carried by the population. The project is currently focussing particularly on renewing previously removed trees in order to keep the tree population level constant. Overall, the focus of the campaign is therefore not primarily on climate adaptation, but also includes urban planning aspects, such as a general upgrading of the living environment through green spaces. The selection of tree species to be planted is fixed and includes both native and exotic species. The selection of species also specifies that new species will also be planted as test trees to find possible trees better adapted to the upcoming climate change (Berlin 2021). Looking to the future, it will be essential for Berlin to provide financial resources to organise the effort of maintaining and adapting the tree population.

The topic of promoting green infrastructure is already widely represented in Vienna. In 2018, the City of Vienna published a detailed strategy, called “Urban Heat Island Strategy”, to counteract the formation of UHI, which, among other measures, focuses on strengthening the green infrastructure. The focus is mainly on the expansion of street trees, but park trees and the greening of facades are also discussed (Brandenburg et al. 2018). Further, the City of Vienna stated to plant at least 4500 new trees every year. The opening of new green areas of 400.000 m^2 until 2025 are planned to support the implementation GI and consequently microclimate regulation and recreational offer. Vienna is part of the program “Lebenswerte Klimamusterstadt” (Livable climate model city), which is dedicating up to 100 million euros to measures to regulate the microclimate (Stadt Wien 2021). Compared to Berlin, the concepts, and projects of the city of Vienna seem much more fundamental and elaborated. Overall, it can be assumed that although Berlin and Vienna will both be affected by climate change and increasing pressure on trees, the budget available to Vienna alone will put the city in a better initial position.

5.8 Uncertainties

5.8.1 Climate data and indicators

For the climate analysis only one ensemble member was analysed from the total EURO-CORDEX dataset. Therefore, no variability in possible model outputs was generated leading to uncertainties in the robustness and likelihood of the predicted changes and results. For future studies, an ensemble analysis could be carried out to make advanced statements about future climate changes (Hennemuth et al. 2013). Furthermore, the results for the analysis of the heat and dry spells are highly dependent on the definition of extreme events and threshold chosen. Therefore, in this study the analysis of dry spells concentrated only on events induced by changes in the amount of precipitation. Thus, no precise information was provided on the effects of combined high temperatures and dry conditions like the standardized precipitation evapotranspiration index (SPEI index) does (Spinoni et al. 2018). This aspect could be of importance for future science to obtain even more precise information about possible dry periods. Another uncertainty arises from the fact that the occurrence of a period was counted in the month in which it ended, not in the month in which it began. This could mean that sometimes most of a period occurred in a different month than it was counted. However, this phenomenon would have occurred to a similar extent if the period had been counted in the month in which it started.

5.8.2 Tree data and tolerance assessment

Possible sources of error and inaccuracies may arise when evaluating tree inventories from different cities. The greatest uncertainty lies in the incompleteness of the tree inventories and their extent. While both Berlin and Vienna state that they record both street trees and trees in public places, the ratio between single trees and trees in larger parks is unknown. Consequently, due to the incomplete representation of the number and distribution of trees, statements made in this study are based on an incomplete assumption of the present and can therefore only be used in a limited way.

Further uncertainties arise from the literature review, which showed quick and easy-to-interpret results as a first overview, but due to the strongly differing definitions of drought and heat tolerance of individual tree species in the different rankings and conducted studies that were reviewed, in some cases partially differing statements regarding the tolerances (e.g., *Betula pendula*) were found. This problem of tolerance rankings has also already been addressed in other studies by Sjöman et al. 2015a and Banks et al. 2019. In addition, the literature analysis showed that the drought tolerance of individual tree species is much more researched than the pure heat tolerance. For this reason, the classification of drought tolerance is based on considerably more literature than heat tolerance and thus provides better information. Moreover, the analyse of heat and drought tolerance provides only part of the information necessary to complete the overall picture, as factors like soil requirements, salt tolerance, and pest vulnerability were not further included in the analysis but are crucial for the successful growth and survival of city trees (Gillner et al. 2014).

6. Conclusion

In summary, it can be stated that both cities studied will be exposed to significant climatic changes in the future, regarding both individual and collective occurrence of more extreme drought and heat spells, especially in the distant future. Since the representation of ground observation data was quite well represented by the climate scenario data in the reference period, the statements about the near and distant future can at least be used as guidelines and orientation for adaptation measures. Furthermore, the study results indicated that the majority of trees analysed in the two cities were categorised as moderately tolerant and moderately sensible, whereby the more extreme categories were less represented.

It became clear that the required adaptation measures will be comparable between cities in the future, but that ultimately city-specific priorities will have to be set. In the end, differences in the timing or duration of extreme events, different compositions of tree populations with different vulnerabilities, and the distribution of trees within the city can be crucial for planning successful adaptation measures and their extent. A frequent exchange between cities on different GI adaptation projects seems to be useful to take successful and efficient measures for the future as soon as possible. Furthermore, a close dialogue between science, politics and economy is necessary, as economic concerns are also crucial for the successful implementation of measures.

Overall, to generate even better adaptation measures in the future, it is crucial to analyse the vulnerability of trees to future extreme events more intensively and more precisely. Furthermore, the analysis of the impact of past extreme events on tree species could contribute to the knowledge of the mortality and vulnerability of trees and thus also be helpful in the selection of species and measures.

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Appendix

Appendix 1: Combined results of the literature review and final categorization (last column) for the drought tolerance of the selected tree species from Berlin and Vienna.

	Forest Commission England (n.A) according to (Niinemets and Valladares 2006)	European Atlas of Forest Tree Species (San-Miguel-Ayanz et al. 2016)	GALK (2021)	Roloff et al. (2009); Roloff (2010)	Citree (2015)	Warda (2001)	Own assessment
Botanical Name	**Drought tolerance**	**Drought tolerance**	**Drought resistance**	**Drought tolerance**	**Drought tolerance**	**Drought tolerance**	**Drought tolerance**
Acer Platanoides	Moderate	moderate	suitable	suitable	moderate	high	Moderately tolerant
Tilia cordata	Moderate	moderate	moderate	suitable	moderate	moderate	Moderately tolerant
Quercus robur	Moderate	Moderate	Moderate	limited suitability	sensitive	high	Moderately sensitive
Platanus acerifolia / Platanus hispanica	Moderate	-	-	-	tolerant	high	Moderately tolerant
Betula pendula	Intolerant	intolerant	Low suitability	Very suitable	moderate	high	Moderately sensitive
Aesculus hippocastanum	moderate	intolerant	Moderate	Very limited suitability	no tolerance	moderate	very sensitive
Tilia platyphyllos	Intolerant	moderate	Low suitability	limited suitability	sensitive	low suitability	Moderately sensitive
Acer pseudoplatanus	Moderate	low suitability	moderate	Very limited suitability	no tolerance	moderate	Moderately sensitive
Robinia pseudoacacia	Tolerant	low suitability	-	Very limited suitability	tolerant	high	Moderately sensitive
Pinus nigra	Tolerant	suitable	-	Very suitable	tolerant	very suitable	very tolerant
Fraxinus excelsior	intolerant	low suitability	Low suitability	Suitable	moderate	moderate	Moderately sensitive
Acer campestre	Moderate	moderate	suitable	Very suitable	tolerant	very suitable	very tolerant
Tilia intermedia / Tilia x europaea/Tilia x vulgaris	Moderate	moderate	suitable	-	sensitive	moderate	Moderately tolerant
Populus nigra	Intolerant	intolerant	Low suitability	-	-	moderate	very sensitive

Rankings								
	5	Very tolerant	Very suitable		very suitable		very suitable	
	4	Tolerant:	suitable	suitable	suitable	tolerant	high	very tolerant
	3	Moderate	moderate	Moderate		moderate	moderate	Moderately tolerant
	2	Intolerant	low suitability	low suitability	limited suitability	sensitive	sensitive	Moderately sensitive
	1	Very intolerant	intolerant		very limited suitability	no tolerance	very limited suitability	very sensitive
		missing	missing	missing	missing	missing	missing	

Appendix 2: Combined results of the literature review and final categorization (last column) for the drought tolerance of the selected tree species from Berlin and Vienna.

	Citree (2015)	Warda (2001)	Own Assessment
Botanical Name	**Heat tolernace**	**Heat tolernace**	**heat tolerance**
Acer Platanoides	medium	good	medium
Tilia cordata	medium	good	medium
Quercus robur	medium	-	medium
Platanus acerifolia / Platanus hispanica	good	good	good
Betula pendula	low	-	low
Aesculus hippocastanum	low	low	low
Tilia platyphyllos	medium	medium	medium
Acer pseudoplatanus	low	low	low
Robinia pseudoacacia	good	good	good
Pinus nigra	good	good	good
Fraxinus excelsior	medium	medium	medium
Acer campestre	good	good	good
Tilia intermedia / Tilia x europaea/Tilia x vulgaris	medium	medium	medium
Populus nigra	-	medium	medium

Ranking

3	good	good	Good (3)
2	medium	medium	Medium (2)
1	low	low	Low (1)

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