Urban Trees for Changing Climates: Insights for Bavarian Cities

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Abstract

Urban trees have the capability to enhance ecological city resilience. By providing vital ecosystem services mitigation of urban heat island effects, management of stormwater, or support of biodiversity can be improved. Climate change, however, poses challenges to urban trees in general, and in particular for Bavarian cities. This study uses the climate envelope approach to assess the future climatic suitability of native and non-native tree species in 21 Bavarian cities (Germany). Using climate projections from the CHELSA dataset under the SSP5-RCP8.5 scenario, we evaluate temperature and precipitation thresholds for 12 tree species over three periods (2011–2040, 2041–2070, and 2071–2100). The results were compared with the land cover share of the respective cities. The results show distinct variations in climatic suitability across cities and time periods. Several species remain climatically suitable over time, especially Black locust, London plane, and European hornbeam. However, tree species, like European beech, Norway maple, and Silver birch, experience a marked decline. These findings underscore the urgent need for a paradigm shift in urban green space management. Although the study employs climate envelope methodologies that have inherent limitations, it provides a proof-of-concept for integrating climate projections with urban data such as tree inventories and land use patterns. Overall, the research contributes to our understanding of urban tree adaptation strategies and highlights the importance of prioritizing heat-tolerant species to preserve urban biodiversity and ecosystem services.

1. Introduction

Urban trees are essential for enhancing the sustainability and liveability of cities, delivering critical ecosystem services such as mitigating urban heat islands, managing stormwater, and supporting urban biodiversity. However, as climate change progresses (Voogt & Oke 2003, IPCC 2022), urban forests as well as solitary trees are increasingly subject to stressors, including rising temperatures, altered precipitation regimes, and the growing frequency of extreme weather events.

This presents a challenge for Bavarian cities, where urban forests or trees are exposed to more challenging conditions compared to natural forests. Specifically, at frequently trafficked and accessed locations, the topsoil is heavily compacted, reducing the water capacity of the soil (Leh, 1991). Furthermore, the activity of symbionts, soil organisms and consequently root growth is reduced. Street trees have a less developed root system than that of trees in natural forests and a noticeably lower proportion of fine roots, which impacts tree's nutrient and water supply (Balder et al., 2007). Due to impervious surfaces, the water and air exchange between the soil and the atmosphere is severely restricted. Furthermore, the groundwater level in cities is often lowered (Wessolek & Renger, 1998) due to channeling, construction activities, and drinking water extraction, which leads to faster drought stress. The increased temperature in urban areas due to the urban heat island effect leads to increased transpiration, resulting in higher water consumption by trees (Roloff, 2013). In addition, light reflections from impervious surfaces and the increased exposure to exhaust gases have a negative impact on urban trees.

In forest science, species distribution modelling frequently applies the concept of climate envelopes to assess the potential future suitability of tree species (Kölling 2007, Wesseley et al. 2024). This approach relies on presence-absence data, analyzing the climatic means of all recorded occurrences of a species to define its climate envelope. These envelopes are typically formed by aggregating climatic averages from known species occurrence areas, creating a framework to predict future distributions of individual species or entire species pools under changing climatic conditions (Mauri et al. 2022, Martes et al. 2024, Wesseley et al. 2024). However, actual species occurrences are often influenced by human-mediated forest composition and silvicultural practices, leading to potential discrepancies between current distributions and their natural ranges. Climatic envelopes can also be derived from tree species fact sheets, which incorporate expert knowledge and define minimum and maximum thresholds for precipitation and air temperature, providing an assessment of climatic suitability regarding the natural occurrence of trees. Beyond the climatic suitability of individual tree species, it is also crucial to consider the long-term development of species pools, particularly native deciduous and coniferous trees, to ensure resilient urban forests. A similar approach is increasingly used in forest science to assess potential shifts in tree species pools under different climate scenarios. The goal is not only to determine where individual species may persist but also to evaluate how forests would or should ideally develop to support both biodiversity conservation and climate resilience (Wesseley et al., 2024). For this purpose, climate envelopes are an appropriate approach for predicting the future development of different forest types.

This study aims to inform adaptive urban strategies by evaluating the potential future suitability of native and non-native tree species in Bavarian cities. Using projected climate data and a climatic tree species suitability matrix, the analysis spans three climate periods: 2011–2040, 2041–2070, and 2071–2100. By identifying trends in climatic suitability, this research

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provides insights into the potential composition of urban forests/trees under changing climatic conditions, with implications for sustainable urban forest planning and long-term ecosystem resilience. Furthermore, the results are compared with city-specific land use data.

2. Methods

The study employed climatic variables from the Max Planck Institute Earth System Model (mpi-esm1-2-hr), downscaled to a 1 km spatial resolution using the CHELSA V2.1 topographic algorithm as the climatic framework (Karger et al., 2017). The analysis covered three time periods: 2011–2040, 2041–2070, and 2071–2100. It focused on two key parameters—mean air temperature (tas) and total annual precipitation (pr)—calculated as 30-year averages for each period (Karger et al., 2021). The climatic projections were based on the SSP5-RCP8.5 scenario, which represents a high-emission pathway characterized by rapid economic growth, heavy reliance on fossil fuels, and high greenhouse gas emissions. This scenario was chosen to assess potential climate impacts under an extreme but plausible trajectory, providing insights into worst-case climate change outcomes.

To define tree species-specific thresholds, a literature review of tree species profiles was conducted. Key sources, including CABI (2018), EuForGen (2024), Forster et al. (2019), Kunz et al. (2020), San-Miguel-Ayanz et al. (2016), and Schütt et al. (2006), provided critical data on the climatic suitability of the 12 most common tree species in European cities according to Rötzer et al. (2024). Based on this, a suitability matrix was developed (Table 1), incorporating threshold values for tas_{min}, tas_{max}, pr_{min}, and pr_{max}. The climatic suitability of the selected tree species was then calculated on a pixel basis for the three climate periods, applying the defined thresholds.

Table 1: Climatic tree species suitability matrix for the 12 most common tree species in European cities according to Rötzer et al. (2024) including thresholds for the mean annual air temperature (tas) and the annual sum of precipitation (pr).

Tree name	Botanic name	pr_{min} [mm]	pr_{max} [mm]	tas_{min} [°C]	tas_{max} [°C]
Norway maple	*Acer platanoides*	675	1275	2.0	12.3
Sycamore maple	*Acer pseudoplatanus*	513	1550	2.8	14.7
Horse chestnut	*Aesculus hippocastanum*	500	1100	10	17.0
Silver birch	*Betula pendula*	417	1767	-15.0	13.3
European hornbeam	*Carpinus betulus*	600	1767	6.3	16.0
European beech	*Fagus sylvatica*	483	1900	3.5	13.3
Common ash	*Fraxinus excelsior*	500	1617	5.0	14.0
London plane	*Platanus x acerifolia*	525	2170	6.5	20.0
Black poplar	*Populus nigra*	350	1250	7.5	16.5
Pedunculate oak	*Quercus robur*	350	2000	1.5	15.5
Black locust	*Robinia pseudoacacia*	533	1700	7.7	16.3
Small-leaved lime	*Tilia cordata*	567	1933	3.8	13.8

In the framework of this study, we focus on the 21 most populated cities in Bavaria (Figure 1). There, we assess potential shifts of climatic tree species suitability under climate change. The percentage of pixels with climatic tree species suitability was calculated for each city using the official administrative boundaries according to the latest Census data (Zensus 2022). Based on these values, the share of unsuitable areas within each city for a specific tree species was calculated for the three time periods (2011–2040, 2041–2070, and 2071–2100), thereby offering a conservative estimate of long-term species suitability. Moreover, cities were ranked in ascending order based on their average unsuitable area across all 12 tree species. By integrating city area data for scaling visual symbols, our approach provides a comprehensive, spatially explicit perspective that simultaneously conveys both, the magnitude of area loss and the urban context. The high-ranking goal is to support informed decisions about tree species selection in urban planning.

Finally, the share of different land-use classes based on the classification of Krüger et al. (2024) for all the investigated cities was calculated. Based on the calculated share of area for each investigated land cover type, we further analyzed the spatial distribution across cities by grouping them according to the projected climatic tree-suitability. Specifically, cities were classified into "High Loss" or "Low Loss" categories based on whether their average unsuitable area was above or below the median value. For this purpose, the lowest value across the three climate periods investigated was extracted, related to the bottleneck approach by Wesseley etal. (2024). Using boxplots, we visualized the distribution of land cover shares for both groups. Moreover, outliers within each land cover and group combination were identified using the 1.5×Interquartile Range rule and annotated with the corresponding city names. This allows to pinpoint extreme cases. Additionally, t-tests were performed to statistically compare the mean land cover shares between the two groups, providing further insight into potential differences in urban morphology.

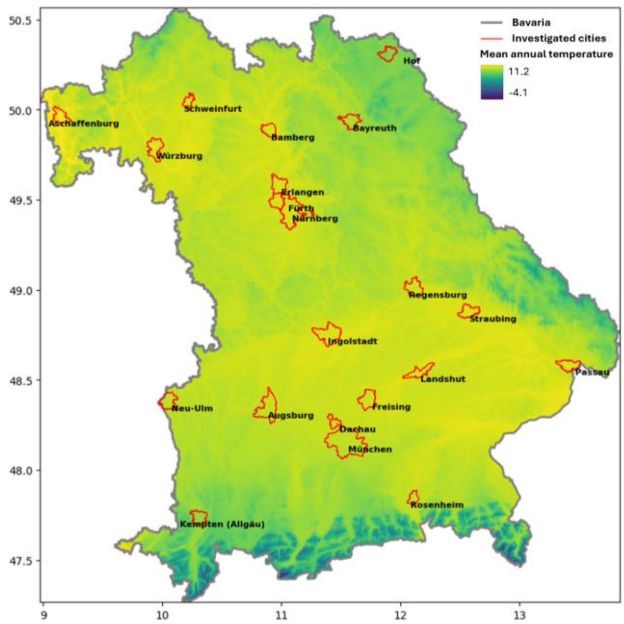

Figure 1: Administrative spatial units of the 21 investigated cities with the mean annual air temperature in degree celsius for the climate period 2011-2040 according to the CHELSA V2.1 dataset (Karger et al., 2021a) in Bavaria.

3. Results

Figures 2a, 2b, and 2c present the climatic suitability of 12 tree species for the 21 biggest Bavarian cities for three time periods: 2011–2040, 2041–2070, and 2071–2100. The red values represent the climatic suitability of each tree species during the corresponding period as a percentage of the total area of the city. A value of 100 indicates a fundamentally suitable climatic situation for the entire city area, while lower values or zero (grey) suggest limited or no suitability.

During the first and second period (2011–2040 and 2041–2070), many tree species exhibit high climatic suitability in almost all cities. This suggests that the current situation in Bavarian cities is still quite resilient in this respect. However, significant changes are observed in the last period (2071–2100).

Notably, the suitability of individual tree species varies considerably across different cities, reflecting local climatic conditions. Except for Rosenheim and Kempten (Allgäu), all other cities show consistently high suitability values of around 100 % for all tree species in the initial periods. In 2071–2100, however, the suitability decreases for certain species, particularly for European beech (*Fagus sylvatica*), Norway maple (*Acer platanoides*), and Silver birch (*Betula pendula*). Kempten (Allgäu) and Rosenheim already show zero values for Horse chestnut (*Aesculus hippocastanum*), Black poplar (*Populus nigra*), and Norway maple in the first period. Northern Bavarian cities tend to experience a decline in the suitability of certain tree species (particularly Norway maple, Silver birch and European beech) until 2100, with Aschaffenburg showing the strongest downward trend.

The development of climatic suitability also reveals species-specific differences. For instance, Horse chestnut and Black poplar remain unsuitable for both Kempten and Rosenheim throughout all time periods due to the high precipitation of these two southernmost cities. In contrast, tree species such as Pedunculate oak (*Quercus robur*), Black locust (*Robinia pseudoacacia*), London plane (*Platanus × acerifolia*), and European hornbeam (*Carpinus betulus*) are classified as climatically suitable for all Bavarian cities until 2100. However, species like European beech and Silver birch, which are initially considered suitable in all cities, show a significant decline in suitability over time.

When considering the absolute area affected per city (indicated by circle size in Figures 2a, 2b, and 2c), the larger cities Ingolstadt, Augsburg, Nürnberg, and München are striking and mainly marked by the climatic unsuitability of Norway maple.

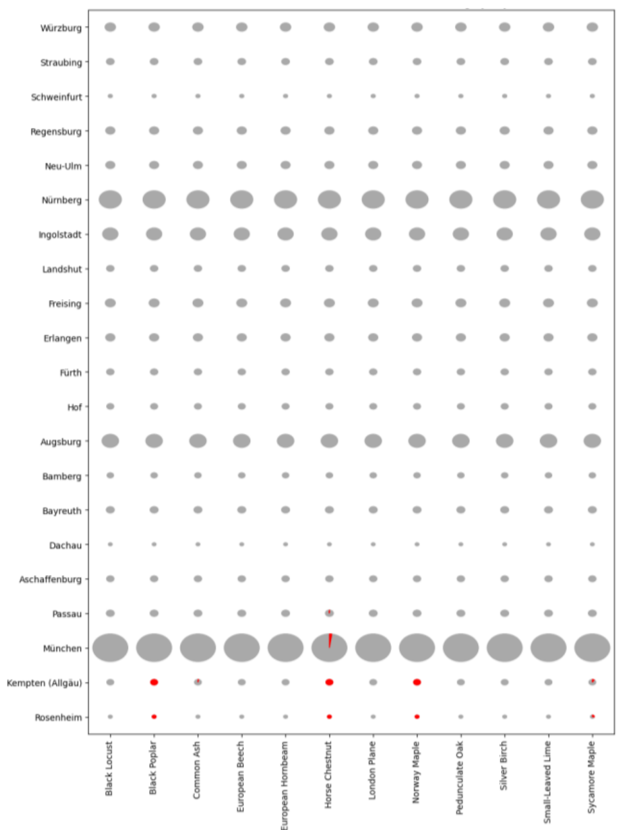

Figure 2a: Proportion of climatically unsuitable tree species (in red) within the total area (indicated by circle size) of the 21 most populated Bavarian cities for the period 2011–2040.

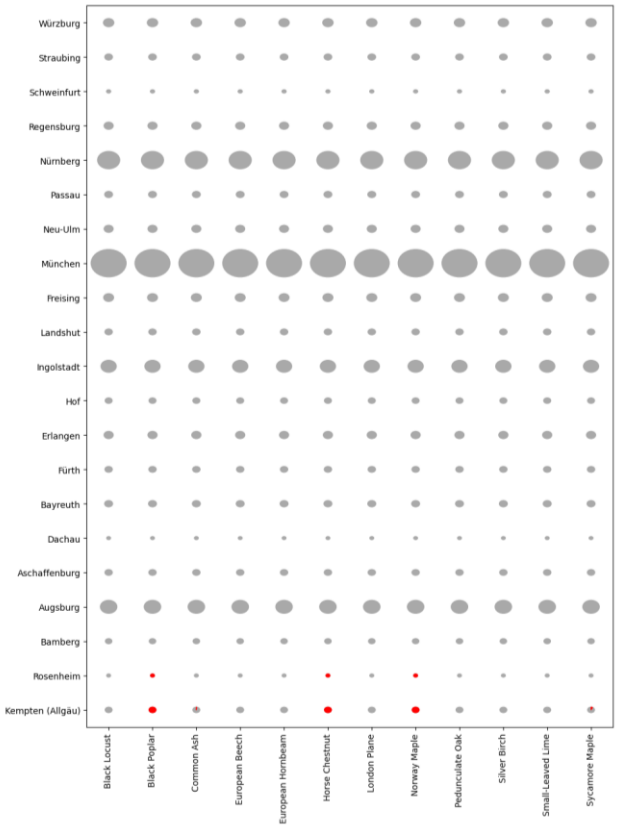

Figure 2b: Proportion of climatically unsuitable tree species (in red) within the total area (indicated by circle size) of the 21 most populated Bavarian cities for the period 2041–2070.

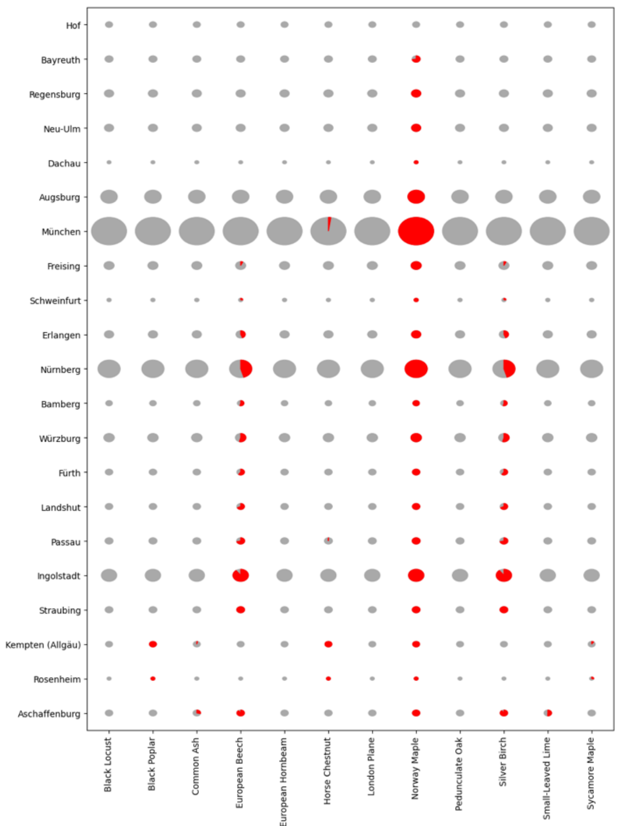

Figure 2c: Proportion of climatically unsuitable tree species (in red) within the total area (indicated by circle size) of the 21 most populated Bavarian cities for the period 2071–2100.

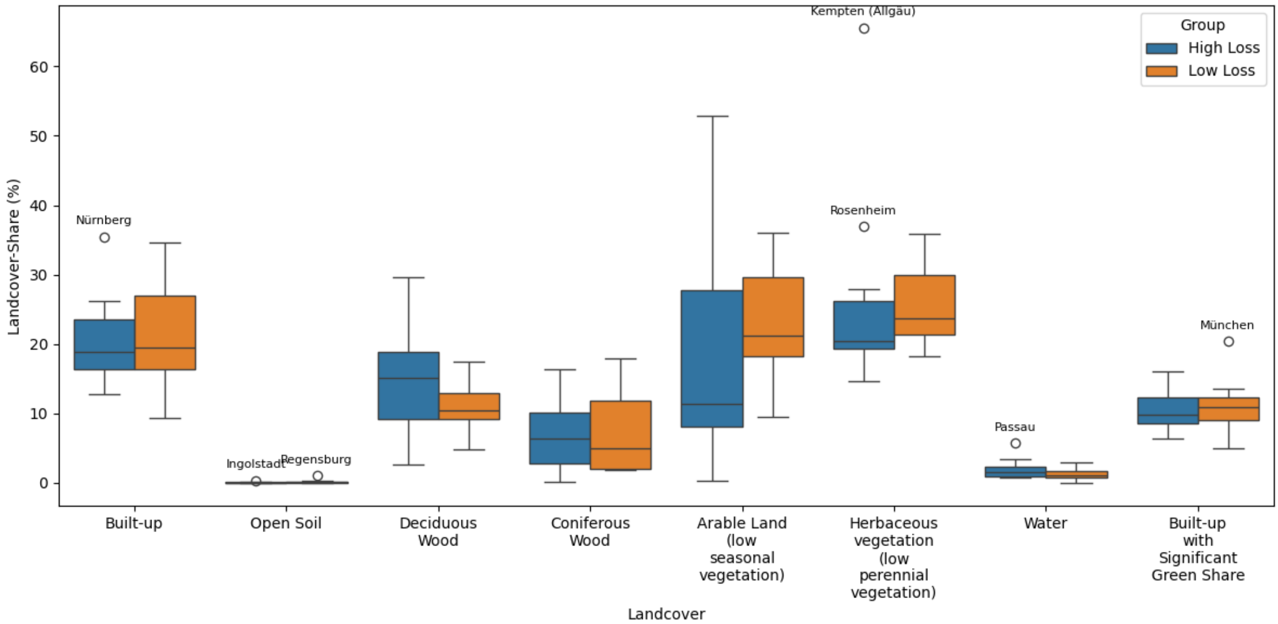

Figure 3: Share of different landcover types in the 21 most populated cities in Bavaria. The cities were classified into two groups: ‘Low Loss’ (orange) represents the group of cities with a low average of climatically unsuited tree species per area and ‘High Loss’ (blue) represents the group of cities with a high average of climatically unsuited tree species per area across the three investigated climate projections.

Furthermore, it is noticeable that in Nürnberg and Ingolstadt the climatically reduced suitability of European beech and Silver birch also has a high impact. In contrast, the cities Schweinfurt, Hof, Bayreuth, and Dachau stand out for their small absolute area, with Hof being the only city where all tree species are area-wide climatically suitable across all three time periods.

In the following, we present results of the additional inclusion of the proportion of different land cover types in the individual cities. In this analysis, the percentage share of each land cover type was computed for every city and the cities were subsequently grouped into "High Loss" and "Low Loss" based on the median of their average unsuitable area out of the climate envelopes for the 12 investigated tree species. The t-test results indicate that none of the investigated land cover types show a statistically significant difference between cities classified as "High Loss" and those classified as "Low Loss”. For example, the built-up category shows a t-statistic of -0.182 with a p-value of 0.858, suggesting negligible differences in the mean share between the two groups. Similarly, other categories such as Deciduous Wood ($t = 1.528$, $p = 0.147$) and Coniferous Wood ($t = 0.012$, $p = 0.991$) fall clearly outside the conventional significance level of 0.05.

4. Discussion

4.1 Interpretation of the results

Our results underscore the climate-induced shifts in the suitability of urban tree species in Bavarian cities. For the largest cities in the north of Bavaria shifts are expected, when considering the proportional amount of the city's area.

The data reveal significant changes in the climatic suitability of tree species especially during the transition to the last period 2071–2100. Tree species, such as European beech, Norway maple, and Silver birch show a considerable decline in suitability, particularly in cities like Aschaffenburg, where a high temperature in the last climate period ist expected. On the other hand, heat-tolerant species such as Black locust, Sycamore maple, London plane, and European hornbeam maintain a high degree of suitability over time, reflecting the need for future urban afforestation strategies to focus on such species.

The findings of this study align with those of previous research on the climatic suitability of forest tree species. For example, studies by Kölling (2007) and Wessely et al. (2024) emphasize the importance of climatic parameters in determining the suitability of tree species but also point to the need to additionally consider local factors and site-specific conditions.

After intersecting the results with the landcover share of all cities (Figure 3), there were no significant differences between cities with a high and low average climatic suitability of the tree species investigated. However, it is interesting to note that Rosenheim and Kempten, the only two cities that have shown an area-wide climatic unsuitability for three tree species (Norway maple, Horse chestnut, and Black poplar) from the first climatic periods on, stand out in Figure 3 as outliers with a very high share of herbaceous vegetation. The increased rainfall in these regions does not only contribute to the climatic unsuitability of Norway maple, Horse chestnut, and Black poplar but also supports the prevalence of extensive agricultural practices, particularly grassland farming.

The methodology applied here enables an overarching estimation of the climatic development of the 12 most common tree species in European cities, as kind of a species pool. In the long term, these insights can help adapt urban trees to changing climate conditions by additionally considering the city-specific landcover share, thus contributing to urban climate adaptation and biodiversity.

Accordingly, the results emphasize that a paradigm shift is needed in urban green space management. This is reflected in the decreasing number of climatically suitable tree species. Therefore, a change in tree species selection and maintenance strategies is necessary to maintain climate-resilient and species-rich urban forests.

4.2 Limitations of the study

Regarding the selection of specific tree species and their future potential there are now more parameters used in forestry, like soil variables, risk of calamities and water balance simulations (Baumbach et al., 2024). In cities, the sequence of soil horizons is disturbed, with the addition of artificial soil substrates, the absence of organic litter layers, covered humus layers in the subsoil as well as interruptions in capillarity due to soil erosion and deposition (Balder et al., 1997). Consequently, the soil is often so heavily altered by human activity that it can only partially fulfil its natural functions – providing plants with water, oxygen, and nutrients, filtering pollutants, or anchoring (Blume, 1998). Inconveniently, such additional soil data doesn't exist for Bavarian cities in a consistent manner, which is why the climate envelope approach is still an issue for urban planning. It is well known that extreme events such as heatwaves, droughts, and heavy rainfall are often the cause of increased tree mortality (Schuldt et al. 2020). Nevertheless, the selection of climatic parameters for this study relied on average climatic values. This idea follows the methodology of Wessely et al. (2024), where mean values are considered good indicators for determining tree growth, vitality, and long-term climatic suitability. This methodology allows for an overarching analysis of urban tree species pools. However, it does not take into account the (epi)genetic adaptability of individual species or further site-specific factors. In addition, anthropogenic interventions, such as regular maintenance activities like pruning, soil improvement, and targeted irrigation, play a significant role in the health of urban trees (Vogt et al., 2015). These actions can influence the interpretation of vitality indicators, as they may mask or alter the trees' natural response to environmental stressors. Our study did not consider additional factors that influence urban tree resilience and health. For instance, extreme weather events, including storms, heatwaves, and heavy rainfall, have a direct impact on the survival and stability of urban trees, stressing their resilience and overall vitality. Soil conditions also pose challenges for city trees, as paving, compaction, and nutrient-poor soils are common in urban environments. The quality of the soil is crucial, as it affects the availability of water and ultimately the trees' resilience to changing climate conditions (Leh, 1991). Additionally, pests and diseases thrive in the altered microclimate of urban areas, which may exacerbate tree decline and mortality. The relatively coarse resolution of the climate data used in this study limits the ability to capture small-scale differences within cities, potentially overlooking significant variations in local conditions, like intra-urban heat islands, that influence urban forest conditions (Frank & Backe, 2023).

In contrast to traditional species distribution models (e.g., Kölling 2007, Mauri 2022, Martes et al. 2024, Wessely et al. 2024), which use presence-absence data, this study used values taken from literature. Species profiles, which include not only climatic threshold values of natural distribution but also expert knowledge, provide an alternative basis for evaluating the climatic suitability of urban tree species. However, this approach cannot solely provide site-specific recommendations for individual tree species, as a pure climatic envelope is insufficient (Bolte et al. 2007). Important factors such as soil, water availability or soil chemistry must be more thoroughly considered in future studies.

Beyond this, our spatial analysis aggregated to entire cities delineated by administrative units. These have proven to be unsuitable for geographic comparisons (e.g. Taubenböck et al., 2021) as the respective units are historic-political based and do not capture geographically homogeneous units.

4.3 Outlook

Overall, the results suggest that the cities differ in terms of the climatic suitability of the tree species studied. However, these differences are not accompanied by significant variations in the share of land cover types. Results from individual cities, such as Kempten and Rosenheim, provide indications of plausible relationships between land use distribution and the climatic suitability of tree species.

Nevertheless, this study provides a first proof-of-concept for predicting the climatic suitability of urban trees and the potential of intersecting them with other urban data. Accordingly, for the derivation of larger trends of differences within and across cities, the application to larger areas of interest (e.g. Germany or Europe) is in demand. Beyond this, further relevant urban tree species, in order to be able to consider both a larger sample size in terms of the cities studied and a larger tree species portfolio are suggested. In addition, future studies should integrate further site-specific parameters, like soil moisture availability, soil chemistry, or microclimatic effects more thoroughly to relieve urban landscape planners in this respect. Regarding the climate projection, just one scenario (SSP5-RCP8.5) was considered in this analysis. Although it seems to be the most realistic scenario, the sensitivity of the results should be assessed by using various climate ensembles.

Another important point that should be pursued in the future is the intersection of the results of climate projections with current city tree inventories (cf. Leichtle et al. 2021). With it, the potential failures of urban green or spatial hotspots could be quantified. Thus, a spatially detailed analysis and location-based increased need for action can be derived. However, it is crucial to note that many current urban tree inventories only cover public trees, which limits their ability to provide a complete overview of urban tree populations. Remote sensing approaches are therefore urgently needed to capture the entire tree stock of cities, like in the study of Pauleit et al. (2022). Furthermore, recent advancements in species classification (García de León et al., 2025) offer promising methods for improving the accuracy of tree species identification from remote sensing data.

Generally, we argue that long-term monitoring with area-wide and spatially and thematically highly resolved remote sensing data in combination with future climate projections is essential to plan climate-resilient urban forests and sustainably manage existing green spaces.

5. Conclusions

This study highlights the importance of considering climate-induced shifts in the suitability of urban tree species as part of climate change adaptation strategies. The results show that cities, particularly in northern Bavaria (e.g., Aschaffenburg), will experience significant changes in the climatic suitability of tree species by the end of the 21st century. Due to locally influenced microclimatic conditions caused e.g. by high shares of impervious surfaces and the related urban heat island effects, this trend is expected to be even more pronounced than shown here. Tree species, such as European beech, Norway maple, and Silver birch, are expected to decline in climatic suitability, while heat-tolerant species like Black locust, Sycamore maple, London plane, and European hornbeam remain suitable over time, emphasizing their importance for future afforestation strategies.

The findings stress the need for a paradigm shift in urban green space management. The decreasing number of climatically suitable species calls for a reassessment of tree species selection and maintenance strategies in urban planning. Despite the limitations of climate envelopes, the methodology provides insights into the city-wise climatic suitability of tree species and serves as a proof-of-concept for intersecting results of climate projections with city-related data, like tree inventories or land use share. Accordingly, this study contributes to understanding how urban green can be adapted to climate change and highlights the need to prioritize heat-tolerant species to preserve biodiversity and ecosystem services in cities.

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Data and Code Availability

The code and output files produced for this contribution are available in a Zenodo repository (Friesen et al., 2025).

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