INVESTIGATING THE RESILIENCE OF TREES IN RESPONSE TO FUTURE UK CLIMATES: A CASE STUDY WITH *TILIA*

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Investigating the resilience of trees in response to future UK climates: a case study with *Tilia*

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Abstract

Investigating tree resilience in response to the global urban environment is undergoing significant transformation due to climate change, necessitating an integrated approach to urban forestry and ecological management. This study, based on the Royal Botanic Gardens, Kew, synthesizes recent research on the impacts of urban heat islands, climatic variability, and species distribution to inform urban tree management strategies. Urban trees, particularly those from the *Tilia* genus, play a crucial role in mitigating urban heat and improving biodiversity. However, their efficacy is influenced by climate factors, necessitating careful species selection based on local climatic conditions. We explore the use of species distribution models (such as those provided by the WorldClim and TreeGOER databases) to predict suitable tree species for urban environments under future climate scenarios. These models account for factors such as temperature, moisture, and precipitation patterns. Additionally, we examine the environmental factors affecting plant growth, emphasizing the mechanisms of shading and transpiration in mitigating heat stress. The role of local climate zones and urban microclimates in influencing tree growth and health is also discussed. Urban green spaces, as evidenced in studies from cities like London and Paris, significantly affect local microclimates and public health. Effective urban forestry requires not only the selection of appropriate tree species but also consideration of their placement and maintenance to maximize ecological benefits. This review highlights the need for comprehensive, multi-dimensional strategies in urban planning to enhance urban resilience and sustainability in the face of climate change. Future research should continue to refine species selection criteria and develop adaptive management practices that address the complexities of urban ecosystems.

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Author's Declaration

I, **Kevin Martin**, hereby declare that this dissertation is entirely my own work and has not been submitted, in substantially the same form, for the award of a higher degree at any other institution.

All sources of information, published or unpublished, have been fully acknowledged. No part of this dissertation has been published or submitted elsewhere.

Signed:

Date: 01/10/2025

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Chapter 1: Introduction

The United Kingdom’s climate is undergoing significant shifts, with rising temperatures, altered precipitation patterns, and changes in sunshine hours, largely influenced by variations in cloud cover compared to the 20th century (Kendon, 2022). These changes underscore the urgent need to understand their implications for tree populations across diverse environments, including arboreta, botanic gardens, and urban landscapes. Selecting tree species resilient to evolving climatic conditions has become a critical challenge.

The UK government has committed to ambitious tree-planting initiatives, such as the England Tree Action Plan 2021–2024, which aims to establish 30,000 hectares of new tree-based landscapes annually by the end of the last parliamentary term. This represents a significant effort, given that the UK's total forest cover currently stands at approximately 13% of the land area one of the lowest in Europe (Forest Research, 2024). The initiative is supported by £500 million in funding between 2020 and 2025 through the Nature for Climate Fund (Defra, 2021).

Trees, particularly in urban areas, play a pivotal role in mitigating climate impacts, providing cooling, air purification, carbon sequestration, and biodiversity support (Nowak et al., 2014). Effective tree selection tailored to specific environments is vital for achieving sustainability and climate resilience. Research into the traits that confer resilience under future climatic scenarios is crucial for policymakers and institutions like the Royal Botanic Gardens Kew, as well as organizations such as the National Trust and English Heritage. Analytical frameworks are needed to assess the resilience of existing tree populations and identify suitable species for future planting in both urban and rural landscapes.

CLIMATE CHANGE, URBANIZATION, AND TREE RESILIENCE

Tree distribution is strongly influenced by environmental factors such as soil composition and climate (Zhang et al., 2016). Deviations from optimal conditions can impede growth and shift species' distribution patterns (Van der Zanden, E.H., 2008.). Climate change, particularly the global water crisis, has introduced greater unpredictability in water availability, negatively affecting forest productivity and survival (Pita-Barbosa et al., 2023). Urban environments exacerbate these challenges through the urban heat island (UHI) effect, where impervious surfaces retain heat, raising air and soil temperatures and stressing tree physiology (Percival, 2023). During peak temperatures, trees may close their stomata, reducing transpiration and limiting their cooling effect (Meili et al., 2021; Wang et al., 2018). While shading can mitigate surface temperatures, non-transpiring trees may paradoxically elevate air temperatures during the day by up to 2.1°C, compared to the cooling microclimate created under the canopy of a transpiring tree (Meili et al., 2021). As climate change and urbanization intensify, trees face increasing physiological stress, and their ability to provide cooling benefits depends on their capacity to maintain transpiration under extreme conditions.

Urbanization, driven by rapid population growth, adds further complexity. With the global population projected to increase by 2.5 billion by 2050, urban areas face heightened environmental degradation, slum expansion, and ecosystem disruption (Aslam, 2022; Haaland & van den Bosch, 2015). Urban warming exacerbates these issues, increasing energy demands for cooling and pollution levels, such as tropospheric ozone, which compromise public health and air quality (Santamouris, 2015). Elevated O_3 concentrations can also impair tree physiology by reducing stomatal conductance, limiting transpiration rates, and diminishing the cooling effect of urban trees (Fares et al., 2013; Paoletti et al., 2014). Consequently, trees in high-ozone environments may become less effective at mitigating heat and improving air quality, further intensifying urban climate challenges.

URBAN HEAT ISLANDS AND MITIGATION STRATEGIES

Fine-scale raster data from the Royal Botanic Gardens Kew reveals how green infrastructure mitigates UHI effects. Areas with dense canopy cover within Kew exhibit temperatures that are approximately 0.8°C lower than surrounding built environments, which experience temperatures up to 1.4°C higher than the average rural temperatures. This disparity highlights the critical role of urban trees in reducing heat retention and enhancing urban sustainability (Park *et al.*, 2017; Yan *et al.*, 2018). Mitigating UHIs requires strategic urban planning to integrate diverse green infrastructure, such as urban forests, parks, and green roofs. These strategies not only provide cooling through evapotranspiration but also enhance biodiversity, improve air quality, and offer recreational spaces, contributing to sustainable urban environments and human well-being (Gillner et al. 2015). Urban trees are therefore vital for mitigating UHI effects and addressing climate challenges. Urban canopy cover is integral to these efforts, offering shade and cooling benefits, improving thermal comfort, and reducing energy consumption (Meili *et al.*, 2021). However, during extreme heat and drought, these benefits may be constrained by water scarcity. Selecting tree species with high drought tolerance and the ability to cope with high vapor pressure deficits (VPD) is essential for sustaining these cooling effects under future warmer conditions (Meili *et al.*, 2021; Will, 2013). Yet, most tree species will close their stomata at high VPD to conserve water, which reduces transpiration and limits their cooling capacity. Therefore, it is crucial to identify species that can maintain transpiration even under high VPD to effectively support urban cooling during extreme climate events.

TILIA SPECIES IN URBAN FORESTRY

Tilia species are largely distributed across North America, Europe, and Australia (Figure 1.1). Data from the Global Urban Tree Inventory, which catalogues 4,734 tree species across 473 urban areas, shows that *Tilia* species currently account for only 1.18% of urban tree occurrences (Ossola, 2020). Renowned for their resilience to pollution, drought, and heavy pruning, *Tilia* species, including *Tilia cordata*, *Tilia platyphyllos*, and *Tilia tomentosa*, are widely used in European urban landscaping (Sjöman & Busse Nielsen, 2010). Each species exhibits varying degrees of drought and flood tolerance, with *Tilia tomentosa* being particularly well-suited to high vapour pressure deficit (VPD) environments (Ţenche-Constantinescu *et al.*, 2015).

Beyond their resilience, *Tilia* trees contribute significantly to urban biodiversity by providing nectar and pollen resources for pollinators. Despite concerns about nectar toxicity, research indicates that *Tilia* trees are essential for sustaining pollinator populations during critical flowering periods (Daniels *et al.*, 2020). Table 1.1 summarizes the ecological, climatic, and social benefits of *Tilia* species. Table 1.2 presents details of the species that are included in this thesis.

***Table 1.1. Benefits of* Tilia *species in urban environments*[1].**

Benefit	Description
Cooling Effect	Provides shade and reduces UHI effects through evapotranspiration.
Pollinator Support	Supplies nectar and pollen critical for urban pollinators.
Resilience	Tolerant of drought, pollution, and heavy pruning.
Aesthetic Value	Enhances urban landscapes with attractive foliage and flowers.
Carbon Sequestration	Captures and stores carbon, mitigating climate change impacts.
Biodiversity Support	Supports diverse species, including birds and insects.

[1] Rötzer et al. 2019; Daniels et al. 2020; Andrianjara et al. 2021

Table 1.2. Species selected for this study.

Species	Botanical Characteristics	Ecological Preferences	Resilience	Urban Roles
***Tilia americana* L. (American Basswood)**	Large deciduous tree with heart-shaped leaves and fragrant pale-yellow flowers.	Prefers moist, well-drained soils but adapts to various soil types.	Moderate drought tolerance, sensitive to pollution.	Shade tree, pollinator-friendly, enhances urban biodiversity.
***Tilia cordata* Mill. (Small-Leaved Lime)**	Compact tree with small, heart-shaped leaves and fragrant yellow flowers.	Prefers rich, well-drained soils but tolerates urban pollution.	High drought and pollution tolerance.	Excellent street tree, provides shade and supports pollinators.
***Tilia japonica* (Miq.) Simonk. (Japanese Lime)**	Medium-sized tree with glossy green leaves and fragrant flowers.	Adapts to various soils, prefers moderate moisture.	Good resilience to cold and urban stressors.	Used in avenues and ornamental plantings.
***Tilia mandshurica* Rupr. & Maxim. (Manchurian Linden)**	Large tree with deeply serrated leaves and abundant flowers.	Prefers moist, well-drained soils but tolerates some drought.	Cold-hardy, wind-resistant.	Shade tree, wildlife habitat.
***Tilia maximowicziana* Shiras. (Maximowicz's Linden)**	Medium-sized tree with broad, serrated leaves and yellowish-white flowers.	Prefers rich, moist soils but can adapt.	Cold-tolerant, moderate urban stress resistance.	Ornamental planting, shade provider.
***Tilia platyphyllos* Scop. (Large-Leaved Lime)**	Fast-growing tree with broad, soft leaves and fragrant flowers.	Prefers deep, fertile soils but adapts to various conditions.	Tolerates urban stress well.	Popular in streets and parks for shade.
***Tilia tomentosa* Moench (Silver Lime)**	Large tree with silver-backed leaves and dense foliage.	Prefers dry, well-drained soils, resistant to drought.	Highly tolerant of pollution and heat.	Ideal for urban settings, resistant to pests.

Tilia dasystyla **Steven**	Deciduous tree with dark green leaves and dense flowering clusters.	Thrives in moist soils, adaptable.	Moderate resilience to drought and cold.	Provides urban shade, attracts pollinators.
Tilia mongolica **Maxim. (Mongolian Lime)**	Deciduous tree with heart-shaped, serrated leaves and pale-yellow flowers.	Prefers well-drained soils and tolerates a range of soil types.	Tolerant to cold and drought conditions.	Provides shade and ornamental value in urban landscapes.
Tilia endochrysea **Hand.-Mazz.**	Medium-sized tree with leathery, glossy leaves and abundant flowers.	Prefers moist, well-drained soils.	Moderate drought resistance, good pest tolerance.	Attractive ornamental tree.
Tilia oliveri **Szyszył. (Oliver's Lime)**	Medium-sized tree with slightly wavy leaves and fragrant flowers.	Grows best in well-drained soils with moderate moisture.	Cold-tolerant, moderate drought resistance.	Good choice for urban parks and streetscapes.

CONCLUSION AND IMPLICATIONS

Urban trees, particularly *Tilia* species, are indispensable for addressing the dual challenges of climate change and urbanization. By mitigating UHI effects, supporting biodiversity, and enhancing urban liveability, *Tilia* species exemplify the multifunctional benefits of green infrastructure. Selecting resilient species with high drought tolerance and VPD coping mechanisms will be critical to maintaining these benefits under future climatic conditions. To address these challenges, this thesis focuses on evaluating *Tilia* species from the Royal Botanic Gardens Kew's living collection to inform species selection strategies for urban forestry.

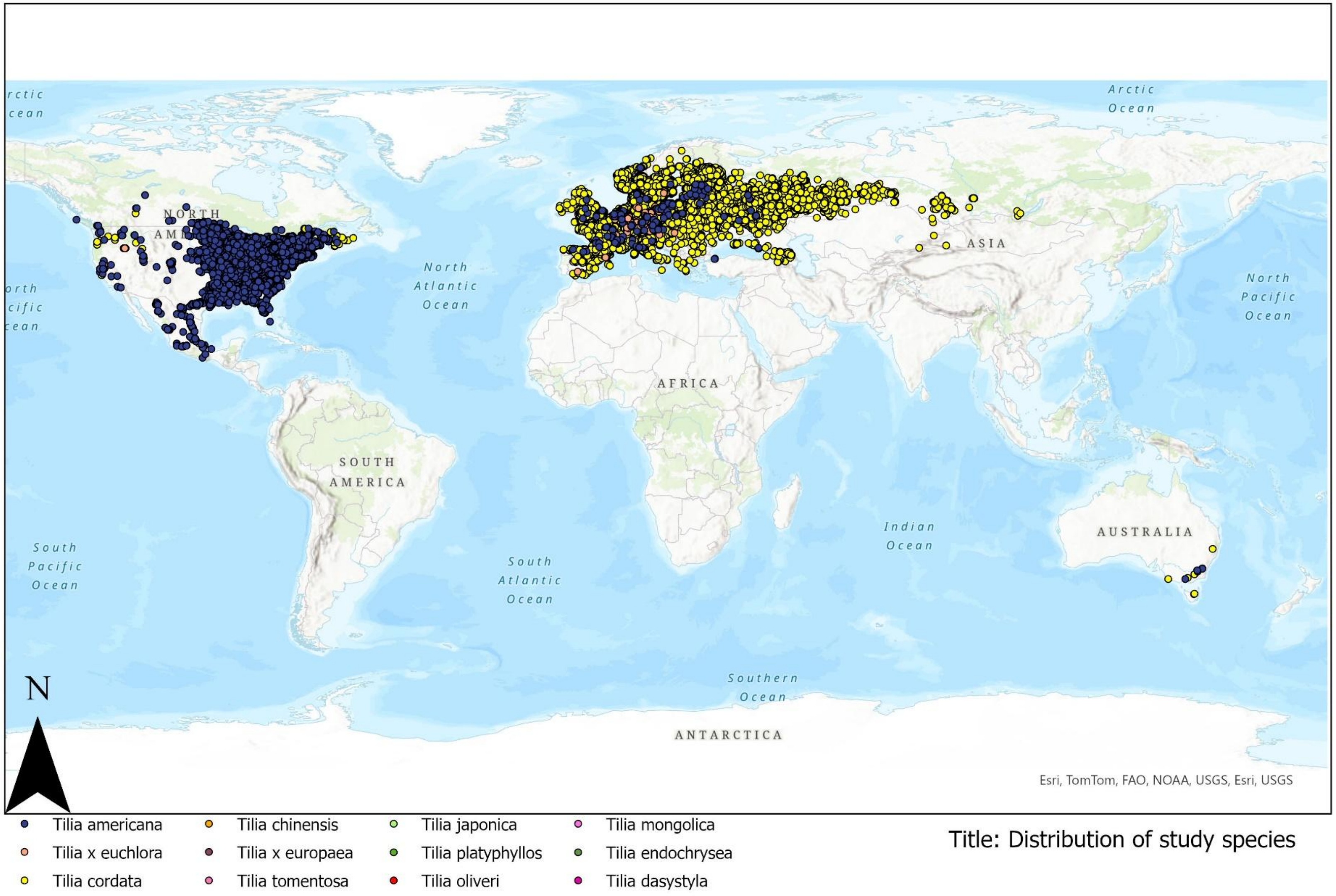


Figure 1.1. Distribution of **Tilia** ***species in this study.***

Chapter 2: Assessing the Future Climate and Urban Heat Island Effects at RBG Kew

INTRODUCTION

Building on the challenges introduced in Chapter 1, this chapter examines future climatic conditions and their implications for urban forestry at RBG Kew, focusing on the role of urban heat islands (UHI) and climate projections. By analysing high-resolution climate data and urban temperature trends, this chapter provides an in-depth look at how climate change and urbanization will affect tree suitability, particularly *Tilia* species, and the role of green infrastructure in mitigating UHI effects.

METHODS

Urban Heat Island (UHI) Analysis

The Urban Heat Island (UHI) effect is a significant consideration for urban environments like the Royal Botanic Gardens (RBG) Kew. To assess this phenomenon, fine-scale temperature data with a 100-meter resolution were analysed. This analysis incorporated various factors, including land-use patterns, soil sealing, anthropogenic heat flux, vegetation indices, and climatic variables such as wind speed and solar radiation. Additionally, to evaluate the influence of canopy cover on temperature variations, we compared areas of high canopy density with open grass areas using the 100-meter resolution data.

Climate Data Sources

To predict the suitability of *Tilia* species at RBG Kew under future climate conditions, this study utilized high-resolution climatic datasets, including **WorldClim2**, **ENVIREM**, and the **Chelsa dataset**. These datasets are integral to Species Distribution Modelling (SDM) and climate suitability predictions due to their high precision and global coverage.

WorldClim2

WorldClim2 provides monthly climatic data for global land areas at a spatial resolution of approximately 1–2 km (Fick & Hijmans, 2017). It includes data from a baseline period (1970–2000), derived from 9,000 to 60,000 weather stations. Key variables include temperature extremes, precipitation, vapor pressure, wind speed, and solar radiation, making it a cornerstone dataset for species distribution modeling (SDM) (Fick & Hijmans, 2017). Using the WorldClim2 dataset, we assessed BIO1 (mean annual temperature) and BIO12 (annual precipitation) to evaluate projected changes under an SSP3 climate change scenario.

Chelsa Dataset

Chelsa offers downscaled global climate data, particularly useful for projections under Shared Socioeconomic Pathways (SSPs). This study focuses on **SSP3**, a high-emission scenario characterized by significant regional disparities (Nazarenko *et al.*, 2022).

Data Extraction and Analysis

Climatic variables were analysed using the **terra** package (Hijmans, 2023, version 4.3.3) in R (*(RCoreTeam,2024)*). The workflow is described below. This methodology was systematically applied across all climatic variables to compare current and projected conditions.

Loading raster data TIFF files containing climate variables (*e.g.,* Bio12 for annual precipitation) were loaded into R using the *rast()* function.

Extracting values for RBG Kew The *extract ()* function was employed to isolate raster values specific to Kew Gardens' location.

Calculating means Average values were calculated for each variable and time period using the *mean()* function, with na.rm = TRUE to handle missing data.

Visualization

Raster data was plotted to illustrate spatial variation in climatic conditions across the UK and Eurasia by isolating data to 35°N to 71°N latitudes and -25°W to 40°E longitudes.

RESULTS

Mean Annual Temperature

Mean annual temperature represents the average temperature over a year, serving as a key indicator of climatic conditions (Figure 2.1 and 2.2). Europe has experienced notable warming, with temperatures increasing at more than twice the global average over recent decades. This rise has led to earlier springs, warmer summers, and milder winters, affecting biodiversity and agricultural cycles. For instance, the 2003 heatwave resulted in approximately 70,000 heat-related deaths across Europe (IPCC, 2021).

Precipitation

Precipitation encompasses all forms of water, liquid or solid, that fall from the atmosphere, including rain, snow, sleet, and hail. It is crucial for replenishing freshwater resources, supporting agriculture, and sustaining natural habitats. In Europe, precipitation patterns are highly variable (Figure 2.1), influenced by factors such as latitude, topography, and proximity to water bodies. Some regions have experienced increased rainfall, leading to a higher frequency of floods, while others face reduced precipitation, resulting in droughts. Between 2012 and 2022, extreme weather events, including those affecting precipitation, cost Europe more than €145 billion in economic damages (European Environment Agency, 2020).

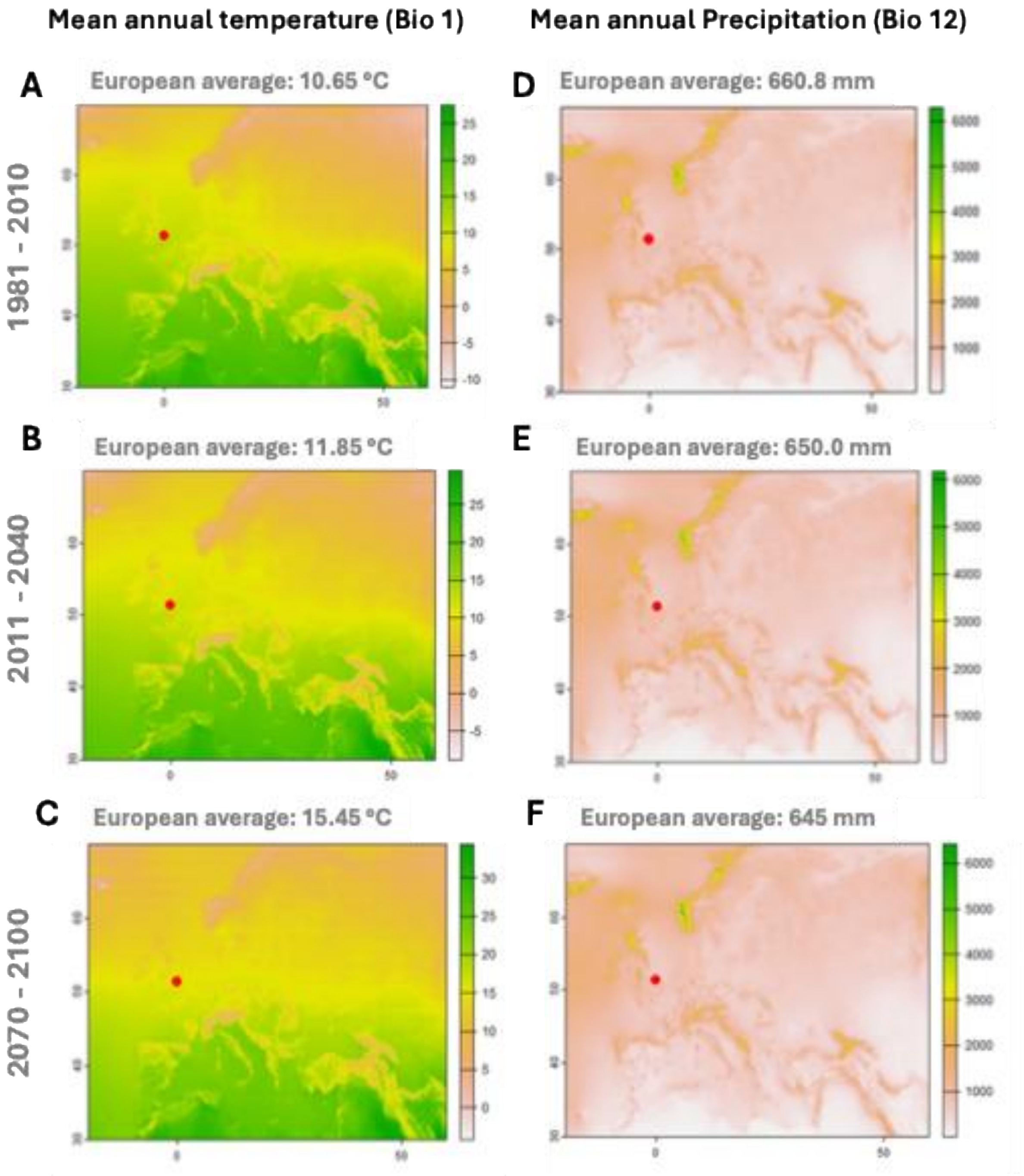
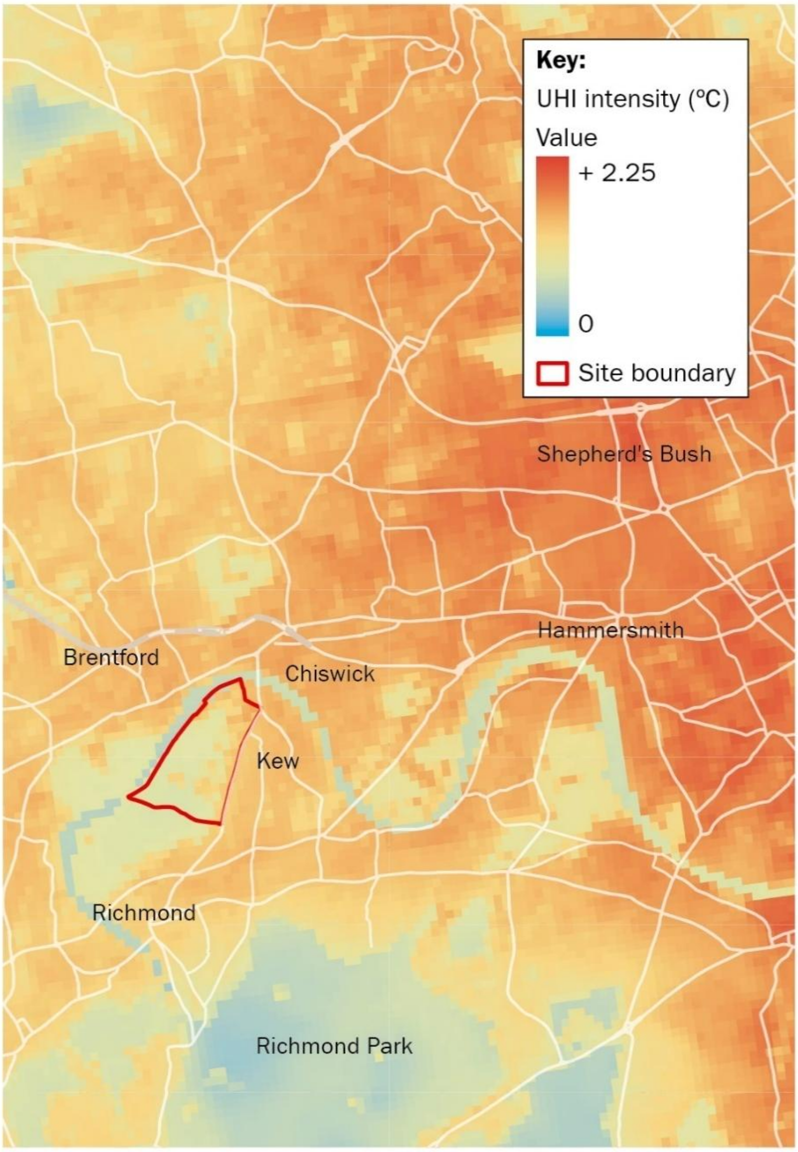


Figure 2.1. Current and predicted mean annual temperature (Bio1) and precipitation (BIO12). Global mean annual temperature (Bio1; left) and annual precipitation (Bio12; right) are shown for the past (1980-2010; top), current (2011-2040; middle) and future (2070-2100; bottom). Average data for each time frame are presented for the European region. RGB Kew is denoted by a red dot on all panels. Climate data are from WorldClim BioClim (Fick & Hijmans, 2017).



European Environment Agency (2020).

Figure 2.2 Urban Heat Island (UHI) heat map of the Greater London area. The heat map illustrates the UHI effect across London, with RBG Kew outlined in red. Background colours represent the UHI Index, with darker shades indicating higher temperatures that are typical of urban areas, and lighter shades corresponding to cooler temperatures, as is typically seen in surrounding rural regions. This visualization aids in understanding the spatial distribution of temperature variations across the Greater London area. Data sourced from European Environment Agency (2020).

DISCUSSION

Temperature analysis at RBG Kew reveals the significant role of urban canopy cover in mitigating the Urban Heat Island (UHI) effect. Areas within the arboretum featuring dense canopy cover were up to 0.8°C cooler than adjacent built environments (Figure 2.1). In contrast, open sections of RBG Kew exhibited temperatures 1.4°C higher than nearby rural areas due to high building density, limited vegetation, and anthropogenic heat sources. The cooling effect of urban trees is attributed to processes like shading and evapotranspiration, which reduce surface and air temperatures. These findings highlight the vital role of green infrastructure in mitigating UHI impacts and maintaining thermal comfort within urban landscapes.

Studies have demonstrated that urban areas with greater canopy cover and green infrastructure exhibit lower surface and air temperatures, thus alleviating some of the adverse effects of UHI, such as increased energy demand and heat-related health risks (*Park et al., 2017; Yan et al., 2018*). Additionally, green roofs have been shown to lower urban temperatures by increasing evapotranspiration and providing insulation, contributing to energy conservation and reduced heat absorption. These findings underscore the importance of integrating green infrastructure into urban planning to enhance ecological resilience and improve human well-being in urban environments.

Strategies for Mitigating Urban Heat Islands

To effectively mitigate UHI effects, strategies like the creation of green spaces, urban forests, and green roofs must be integrated into urban planning. These initiatives not only lower temperatures but also contribute to improving air quality and enhancing urban biodiversity. A diversified approach, combining shaded areas and green spaces, provides significant cooling effects. The effectiveness of these strategies depends on the structure and extent of the green spaces, with studies showing that larger, more diverse green infrastructure provides more substantial cooling benefits (Park *et al.*, 2017; Yan *et al.*, 2018). For example, well-planned urban forests and green roofs are not only effective at cooling but also provide recreational spaces, support wildlife, and contribute to overall urban sustainability.

Chapter 3: Assessment of species suitability using the Climate Risk Assessment Tool

INTRODUCTION

Building upon the insights into future climate projections and their impact on urban environments at RBG Kew discussed in Chapter 2, this chapter delves into the application of the Climate Risk Assessment Tool (Climate Change Alliance of Botanic Gardens, 2023). This tool employs Species Distribution Modelling (SDM) to evaluate the suitability of tree species under the Shared Socioeconomic Pathway (SSP) 3-7.0 scenario. SDM integrates climate data with species occurrence records to assess the potential for tree species to thrive under projected future climate conditions at RBG Kew. The SSP3-7.0 scenario anticipates a global temperature increase of approximately 3.6°C by 2100. Understanding species' responses to such climatic changes is crucial for effective conservation and succession planning of the living collections RBG Kew.

Species Distribution Modelling (SDM) is a versatile tool that facilitates the assessment of future tree species suitability and the evaluation of tree population health. SDM is widely used across various disciplines, including ecology and evolutionary biology (Title & Bemmels, 2018; Kindt, 2023(a). In forestry, SDM helps determine whether a tree species can thrive in its natural habitat or in plantations under projected future climate conditions (Booth, 2018). Current environmental datasets for SDM include WorldClim (Hijmans et al., 2005), PRISM (Daly et al., 2002), ClimateNA (Wang, Hamann, Spittlehouse, and Carroll, 2012; Hamann et al., 2013; Wang, T., Campbell, E.M., O'Neill, G.A. and Aitken, S.N. (2016)), and ENVIREM (Title & Bemmels, 2018). While these datasets are valuable, it should be noted that not all of them are transferable across time periods or geographic regions, and they are not easily integrated with other variables.

In the absence of specific knowledge about the environmental variables most likely to determine species distributions, it may be tempting to construct models using numerous predictor variables. However, focusing on key variables such as Mean Annual Temperature (MAT) precipitation, Evapotranspiration and Climatic moisture index can enhance model accuracy and interpretability.

The initial phase of this study aimed to utilize the Climate Risk Assessment Tool, developed by Botanic Gardens Conservation International (BGCI) in collaboration with the Climate Change Alliance of Botanic Gardens (Climate Change Alliance of Botanic Gardens, 2023). This tool assesses the climate suitability of species based on data from BGCI’s PlantSearch database, which includes over 20,000 tree species cultivated in botanic gardens worldwide.

A key component of the Climate Risk Assessment Tool is its focus on Mean Annual Temperature (MAT) as a primary determinant of climate suitability for tree species. Kendal et al. (2018) have shown that MAT is a reliable predictor of a species' ecological niche, particularly in urban environments. While precipitation can be managed through irrigation and soil amendments, temperature is a more challenging variable to control. Consequently, MAT serves as a practical metric for evaluating the likelihood of tree species adapting to future climate conditions at RBG Kew.

This chapter employs Climate Risk Assessment Tool to assess the potential impacts of projected changes in MAT on the suitability of various tree species at RBG Kew under the SSP3-7.0 scenario. By integrating climate projections with species-specific climate tolerances, we aim to identify species that are likely to thrive or decline under future climate conditions, thereby informing conservation and planting strategies at RBG Kew.

METHODS

For this assessment, the Climate Assessment Tool v1 (Climate Change Alliance of Botanic Gardens, 2023) was utilized to evaluate the suitability of the study species under the SSP3 scenario, which is characterized by regional rivalry and is often referred to as a "business-as-usual" pathway. The tool employs BIO1, representing mean annual temperature, to predict species suitability. Species distribution data within the tool is integrated from multiple datasets, as detailed in Table 3.1.

Table 3.1 Datasets integrated into the Climate Assessment Tool.

Dataset	Description	Last Updated
GardenSearch	Global database of botanic gardens and similar organizations.	27 March 2022
GlobalTreeSearch	Comprehensive database of all known tree species and their country-level distributions.	7 Sept 2022
PlantSearch	Global database of plant taxa in botanic gardens and similar organizations.	Live link
GBIF-BGCI Data	Collaborative dataset between GBIF and BGCI.	13 June 2019
GBIF-Current Data	Live data link to the Global Biodiversity Information Facility (GBIF).	Live link
GlobalUrban Plants	Database focusing on plant species in urban environments.	30 June 2020

The Climate Rating scale, as delineated in Table 3.2, serves as a framework for assessing the climatic suitability of various species within specific environments. This scale ranges from 0 to 11, with each rating corresponding to a particular level of suitability based on the species' position within their respective ranges.

Ratings 0 through 2 are assigned to species that are either not known to occur in the area or are unlikely to thrive under current climatic conditions. Ratings 3 through 5 represent species located near the edge of their Botanic Garden (BG), urban, or natural ranges, suggesting marginal suitability. Ratings 6 through 8 denote species on the shoulder of their BG, urban, or natural ranges, indicating moderate suitability. Ratings 9 through 11 reflect species situated in the middle of their BG, urban, or natural ranges, implying high suitability.

To categorize species based on their climatic suitability, the ratings were grouped into four distinct suitability levels. High Suitability encompasses ratings 9 through 11, identifying species that are well within the optimal climatic conditions of their respective ranges and are highly likely to thrive. Moderate Suitability includes ratings 6 through 8, representing species that can adapt and perform reasonably well under current climatic conditions. Low Suitability comprises ratings 3 through 5, indicating species that may face challenges in thriving due to suboptimal climatic conditions. Not Suitable involves ratings 0 through 2, identifying species that are either not known to occur in the area or are unlikely to survive under the existing climate.

In our assessment, this Climate Rating scale was employed to evaluate and categorize the study species based on their climatic suitability under the SSP3 scenario, characterized by regional rivalry and often referred to as a "business-as-usual" pathway. By assigning each species a rating from 0 to 11, we systematically classified them into the suitability groups. This classification facilitated a clear understanding of which species are most likely to thrive, adapt, or struggle under projected climatic conditions, at the Royal Botanic Gardens.

Table 3.2. Climate rating scoring.

Climate rating	Description
0	Not known and not likely
1	Not known but possible
2	Not known but likely
3	Near edge of Botanic Garden range
4	Near edge of urban range
5	Near edge of natural range
6	Shoulder of Botanic Garden range
7	Shoulder of urban range
8	Shoulder of natural range
9	Middle of Botanic Garden range
10	Middle of urban range
11	Middle of natural range

RESULTS

By prioritizing MAT as the key variable, the study was able to predict which species are most likely to adapt to the warmer conditions expected in the future.

Despite the predictive power of MAT, practical experience at RBG Kew suggests that some species identified as suitable may still struggle to establish and grow. This could be attributed to other climate factors, such as precipitation, which while manageable through irrigation and soil modification, remain important for species establishment and growth. These findings highlight the need to integrate local knowledge with SDM predictions to account for site-specific conditions.

Climate Tool

The findings from the climate assessment tool indicate that *Tilia americana* and *Tilia oliveri* are the most suitable species for the projected future climate at RBG Kew, each receiving the highest climate rating of 11 (Table 3.3). These species are well-adapted to the warmer conditions anticipated by 2090, as demonstrated by their high Mean Annual Temperature (MAT) values. Species with moderate suitability include *Tilia dasystyla* and *Tilia mongolica*, each with a climate rating of 8. Those with average suitability, holding a climate rating of 6, are *Tilia cordata*, *Tilia japonica*, *Tilia platyphyllos* and *Tilia tomentosa*. Species such as *Tilia mandshurica* and *Tilia* maximowicziana have lower suitability, each with a climate rating of 5. These assessments suggest that *Tilia americana* and *Tilia oliveri* are the most resilient to future climate conditions at RBG Kew, while species with lower climate ratings may require more intensive management to thrive under the projected conditions.

Table 3.3. Results from the climate assessment tool. Business as Usual uses the SSP3 or RCP7.0 emission scenario as laid out by the IPCC (IPCC, 2021). It is a 'worst case scenario' and predicts the climate of 2090, which is 65 years into the future.

Taxon	Climate Rating	Mean Annual Temperature (BIO01), °C	Mean Annual Precipitation (BIO12), mm/year
Tilia americana	11	9.5	689.75
Tilia cordata	6	8.4	605.6
Tilia dasystyla	8	9.3	526
Tilia endochrysea	9	16.9	1079.2
Tilia japonica	6	10.9	1003.4
Tilia mandshurica	5	8.5	560.8
Tilia maximowicziana	5	8.7	927
Tilia mongolica	8	10.5	503.9
Tilia oliveri	11	15.1	918.9
Tilia platyphyllos	6	9.8	608.5
Tilia tomentosa	6	10.7	667.7

DISCUSSION

The species distribution model (SDM) results from the climate assessment tool indicate that species such as *T. oliveri* and *Tilia* americana are the most resilient to the future climate conditions predicted for the Royal Botanic Gardens, Kew. Conversely, species like *T. mandshurica* and *T. maximowicziana,* which have lower climate ratings, may require more intensive management to thrive under future conditions. The absence of data on hybrid species underscores the need for further research to fully assess the potential species range for the botanic garden.

A significant limitation of the current climate assessment tool is its reliance solely on mean annual temperature (MAT) (Bio1) for evaluations. While precipitation is listed among the results, it does not influence the climate rating. This is a considerable shortcoming, as factors such as humidity, evapotranspiration, and precipitation are not considered in the climate variables assessed by the species distribution model in this case.

These findings align with existing literature that highlights the constraints of SDMs based exclusively on climatic variables. For instance, studies have shown that models incorporating both climatic and topographic variables provide more reliable projections than those based solely on climate data. Relying exclusively on climatic variables can limit the accuracy of SDMs, particularly in predicting the distribution of forest species under climate change scenarios (Elith and Leathwick, 2009).

Furthermore, research on European mammals has demonstrated that closely related species often occupy distinct climate niches, suggesting rapid adaptation to changing climatic conditions (Pearson and Dawson, 2003). This rapid adaptability implies that Species Distribution Models (SDMs) based solely on current climatic variables may not reliably predict future species distributions. However, this comparison may be less directly applicable to sessile trees, which typically exhibit slower rates of adaptation due to their longer life cycles and limited dispersal capabilities (Barton et al., 2017). While mammals can shift their ranges or adapt more rapidly to climatic changes, trees especially sessile species are more constrained by their immobility and longer generational times, making their response to climate change slower and potentially less predictable (Jump et al., 2009(a).Additionally, studies have shown that soil properties, such as soil pH, texture, and nutrient availability, can play a more crucial role than climate in determining tree species distribution in temperate forests (Kearney et al., 2008). For example, certain species may be better adapted to specific soil types, such as those with high acidity or high fertility, while others may prefer well-drained or moisture-retentive soils. This finding underscores the importance of integrating edaphic factors into Species Distribution Models (SDMs) to enhance their predictive accuracy, as soil conditions can limit or facilitate the establishment and survival of tree species, independent of climate conditions.

In summary, while the current SDM provides valuable insights into the potential resilience of various *Tilia* species at RBG Kew, its limitations particularly the exclusive focus on MAT—must be acknowledged. Incorporating a broader range of climatic and edaphic variables into the assessment tool would likely yield more comprehensive and accurate projections, facilitating more effective conservation and management strategies.

CONCLUSION

Analysis of the Climate Risk Assessment tool

While the Climate Risk Assessment Tool provides a useful initial assessment, its reliance on MAT as the sole predictor of species suitability is a significant limitation. The tool overlooks other critical climate factors, such as seasonal temperature fluctuations and extreme weather events, which can have substantial impacts on species distribution (Gutiérrez-Hernández & García, 2021; Harsch & HilleRisLambers, 2016(a). Additionally, the tool does not incorporate water availability, a key factor influencing plant growth and health, particularly under changing precipitation patterns. A more comprehensive approach that includes seasonal precipitation data and other ecological variables, such as soil moisture and frost-free periods, would significantly improve the tool's predictive accuracy (Leuschner & Lendzion, 2009). This underscores the need for a refined SDM approach that incorporates a broader range of climate and ecological factors. Another notable limitation of the tool is the absence of hybrid species data, which is essential for a comprehensive analysis, as hybrid species may constitute a significant portion of species suited to future climates.

Chapter 4: Determining the suitability of *Tilia* trees to future climate projections at RBG Kew using a broad range of environmental variable

INTRODUCTION

To better understand the relationship between climate variables and the suitability of *Tilia* species under future conditions, Principal Component Analysis (PCA) was employed using several environmental variables from the WorldClim2(Fick & Hijmans, 2017) and ENVIREM datasets (Title and Bemmels 2018). These variables offer deeper insights into the environmental conditions affecting plant species' habitats, particularly those related to moisture availability and temperature extremes.

METHODS

WorldClim2 Dataset

WorldClim2 is a high-resolution climate dataset providing global coverage at a spatial resolution of approximately 1-2 km. It integrates climate data from an extensive network of weather stations (ranging from 9,000 to 60,000) and covers the baseline period from 1970 to 2000 (Fick & Hijmans, 2017). The dataset includes a comprehensive set of 19 climate variables essential for modeling both past and future climate scenarios (Table 4.1).

ENVIREM Dataset

The ENVIREM dataset further enriches the analysis by providing additional biologically relevant climatic and topographic variables (Table 4.2).

Table 4.1 WorldClim2 variables and descriptions.

Code	Variable Name	Description
BIO1	Annual Mean Temperature	Mean of the monthly average temperatures over the year.
BIO2	Mean Diurnal Range	Mean of the monthly differences between maximum and minimum temperatures.
BIO3	Isothermality (BIO2/BIO7 × 100)	Measures the degree to which mean diurnal temperature variation is related to annual temperature variation.
BIO4	Temperature Seasonality (Standard Deviation × 100)	Reflects the variation in temperature throughout the year.
BIO5	Max Temperature of Warmest Month	Highest mean monthly temperature during the warmest month.
BIO6	Min Temperature of Coldest Month	Lowest mean monthly temperature during the coldest month.
BIO7	Temperature Annual Range (BIO5 - BIO6)	Difference between the maximum temperature of the warmest month and the minimum temperature of the coldest month.
BIO8	Mean Temperature of Wettest Quarter	Average temperature during the three consecutive months with the highest total precipitation.
BIO9	Mean Temperature of Driest Quarter	Average temperature during the three consecutive months with the lowest total precipitation.
BIO10	Mean Temperature of Warmest Quarter	Average temperature during the warmest three consecutive months.
BIO11	Mean Temperature of Coldest Quarter	Average temperature during the coldest three consecutive months.
BIO12	Annual Precipitation	Total precipitation accumulated over the year.
BIO13	Precipitation of Wettest Month	Highest mean monthly precipitation.
BIO14	Precipitation of Driest Month	Lowest mean monthly precipitation.
BIO15	Precipitation Seasonality (Coefficient of Variation)	Variation in precipitation throughout the year.
BIO16	Precipitation of Wettest Quarter	Total precipitation during the three consecutive months with the highest total precipitation.
BIO17	Precipitation of Driest Quarter	Total precipitation during the three consecutive months with the lowest total precipitation.
BIO18	Precipitation of Warmest Quarter	Total precipitation during the warmest three consecutive months.
BIO19	Precipitation of Coldest Quarter	Total precipitation during the coldest three consecutive months.

Table 4.2 ENVIREM variables and descriptions.

Variable Name	Abbreviation	Description
Climatic Moisture Index	CMI	A measure of the balance between precipitation and potential evapotranspiration, indicating the moisture availability in a region.
Thornthwaite Aridity Index	Aridity Index	An index quantifying the dryness of a climate based on temperature and precipitation data.
Growing Degree Days (base 5°C)	GDD5	The sum of daily mean temperatures above 5°C, used to estimate plant growth and development.
Growing Degree Days (base 0°C)	GDD0	The sum of daily mean temperatures above 0°C, another measure for assessing plant growth.
Annual Potential Evapotranspiration	Annual PET	The total amount of water that could evaporate and transpire from a surface if sufficient water were available.
Continentality	Continentality	An index reflecting the degree of continental influence on the climate, based on temperature differences between coastal and inland areas.
Terrain Roughness Index	TRI	A measure of the variation in elevation over a landscape, indicating the ruggedness of terrain.

Principal Component Analysis (PCA) and Biplot Construction

Data preparation

Principal Component Analysis (PCA) was performed on a standardized environmental dataset to explore the relationships between variables and identify key gradients. Prior to conducting PCA, all variables were standardized by subtracting the mean and dividing by the standard deviation to ensure comparability. The analysis was carried out using the *prcomp()* function in R, with centering and scaling applied.

Species assessed

The following tree species were included in the analysis: *Tilia americana, Tilia cordata, Tilia japonica, Tilia mandshurica, Tilia maximowicziana, Tilia platyphyllos, Tilia tomentosa, Tilia dasystyla, Tilia mongolica, Tilia endochrysea,* and *Tilia oliveri* (Table 1.2).

Extraction of principal component loadings

The PCA loadings, representing the contribution of each variable to the principal components, were extracted from the output of the analysis. Each variable was assigned a unique identifying number to reduce visual clutter in the final plot.

PCA biplot construction

A PCA biplot was generated using the ggplot2 package in R to allow precise customization of plot elements. The arrows representing variable loadings were scaled and labelled with their corresponding numbers to minimize overlap. The thickness of the arrows was adjusted for clarity, and their endpoints were aligned with the numbered labels. To further enhance readability, a grid was included, and the variance explained by each principal component was displayed along the axes.

The entire analysis and visualization were conducted in R using the ggplot2 package for visualization, with additional support from grid for arrow customization. This approach ensured a clear and interpretable representation of the relationships among environmental variables.

RESULTS

A Principal Component Analysis (PCA) was conducted on a set of climatic and edaphic variables to identify the primary gradients influencing the distribution of *Tilia* species. The first principal component (PC1) explained 42.0% of the total variance, with PC2 accounting for an additional 29.9% (Figure 4.1). Together, these two components captured over 70% of the variation in the dataset.

PC1 was strongly associated with temperature-driven variables, including growing degree days (GDD5, GDD0), mean temperature of the warmest month (bio10), potential evapotranspiration (PET), and thermicity index (Figure 4.1; Table 4.2). These variables had the highest loadings on PC1 (>0.21), indicating that the principal climatic gradient in the dataset is driven by thermal conditions, particularly heat accumulation and seasonal temperature extremes.

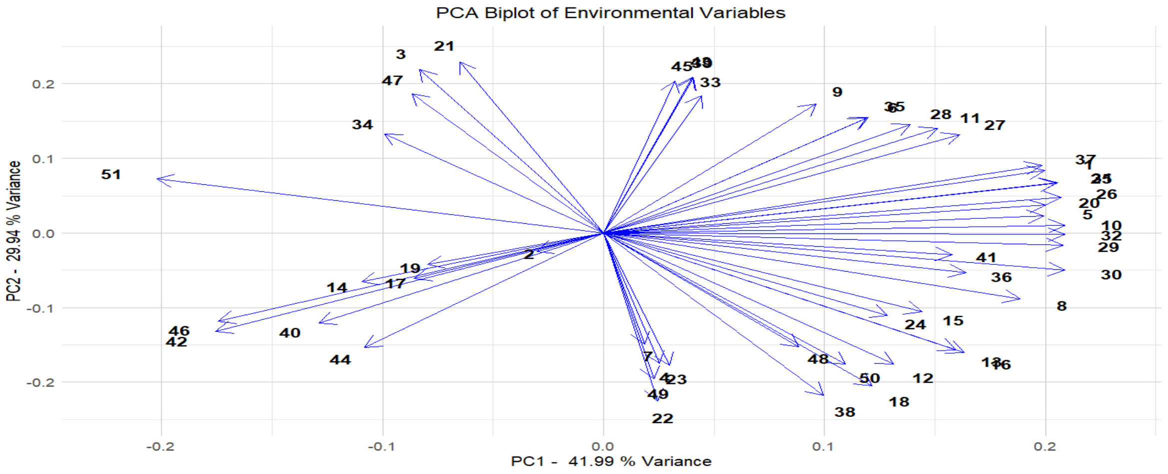


Figure 4.1 Principal Component Analysis (PCA) Results. PCA loadings plot showing the distribution of climate variables influencing the growing conditions of Tilia species. See Table 4.2 for variable names.

Table 4.3 Principal Component Analysis Variables as shown in Figure 4.1.

Number on PCA plot	Variable name	Number on PCA plot	Variable name
1	Bio 01	27	maxTempColdest
2	Bio 02	28	meanTempColdest
3	Bio 03	29	meanTempWarmest
4	Bio 04	30	minTempWarmest
5	Bio 05	31	monthCountByTemp10
6	Bio 06	32	PETColdestQuarter
7	Bio 07	33	PETDriestQuarter
8	Bio 08	34	PETseasonality
9	Bio 09	35	PETWarmestQuarter
10	Bio 10	36	PETWettestQuarter
11	Bio 11	37	thermicityIndex
12	Bio 12	38	MCWD
13	Bio 13	39	bdod
14	Bio 14	40	cec
15	Bio 15	41	clay
16	Bio 16	42	nitrogen
17	Bio 17	43	phh2o
18	Bio 18	44	sand
19	Bio 19	45	silt
20	annualPET	46	soc
21	aridityIndexThornthwaite	47	topoWet
22	climaticMoistureIndex	48	tri
23	continentality	49	elev
24	embergerQ	50	LON
25	growingDegDays0	51	LAT
26	growingDegDays5		

DISCUSSION

A Principal Component Analysis (PCA) explored the climatic and edaphic variables influencing the distribution of *Tilia* species. The first principal component (PC1) explained 41.5% of the total variance, while the second principal component (PC2) accounted for an additional 29.9%. Together, these two components captured approximately 71.4% of the variation in the dataset, highlighting the importance of these primary gradients in shaping species distributions.

Key Drivers of PC1: Temperature-Related Variables

PC1 was predominantly influenced by temperature-related variables, such as growing degree days (GDD5, GDD0), the mean temperature of the warmest month (bio10), potential evapotranspiration (PET), and the thermicity index. These variables showed the highest loadings on PC1 (>0.21), indicating that the principal climatic gradient in the dataset is strongly driven by thermal conditions, particularly heat accumulation and seasonal temperature extremes (Hijmans et al., 2005; Wang et al., 2017). This gradient reflects the role of temperature in shaping the environmental suitability for *Tilia* species, particularly with respect to heat and drought tolerance.

Climatic Moisture Index (CMI) and Its Negative Association with PC1

Interestingly, the Climatic Moisture Index (CMI) exhibited a negative loading on PC1 (-0.2), suggesting that as PC1 increases, indicating warmer and drier conditions, the CMI decreases. This relationship aligns with the ecological interpretation of CMI as a measure of water balance, reflecting the differences between precipitation and evaporative demand. As PET rises in warmer environments, moisture loss increases, thus lowering CMI (Zomer et al., 2007). Conversely, cooler and wetter conditions are associated with higher CMI values (Stephenson, 1990). Therefore, species with high PC1 scores are associated with warmer, drier climates, while those with lower PC1 scores tend to thrive in cooler, moister environments.

Relevance of CMI for Species Distribution Modeling (SDM)

CMI's integration of both temperature and precipitation into a single measure of water availability makes it a biologically significant variable for predicting species distributions. Unlike precipitation alone, CMI accounts for the actual water availability experienced by plants, offering a more comprehensive metric for species distribution models (SDMs). This is particularly relevant in regions where temperature-driven evaporation is a significant constraint on plant growth (Hogg, 1997; Allen et al., 2010). Given its ability to capture both thermal conditions and moisture availability, CMI is a superior predictor for SDMs, especially in arid and semi-arid regions where drought stress is a major ecological factor.

CONCLUSION

The PCA results underscore the dominant role of temperature-related factors in shaping the distribution of *Tilia* species, with CMI emerging as a key variable for distinguishing between moist and arid habitats. Its integrative nature, combining both temperature and precipitation effects, makes CMI a crucial metric for species distribution modeling. As such, it should be prioritized in future SDM frameworks, particularly for species that are sensitive to drought stress. This approach will enhance our ability to predict species responses to climate change, with important implications for conservation and land management strategies (Franklin, 2010).

Chapter 5: Building an Improved Species Distribution Model for RBG Kew

INTRODUCTION

Chapter 4 identifies a broad set of climate variables that are most influential in shaping the growing conditions at RBG Kew. There is a clear need to integrate these new climate variables into a more robust Species Distribution Model (SDM) to build upon SDM work initiated in Chapter 3. This chapter outlines the steps and considerations necessary for building an enhanced SDM that more accurately predicts the suitability of *Tilia* species under future climate scenarios.

Incorporating Water Availability Variables

A key element of the improved SDM presented in this chapter is the incorporation of variables related to water availability. By adding the variables Mean annual temperature (BIO1) and Thornthwaite's Climatic Moisture Index (CMI), the SDM will now be able to simulate water balance scenarios. These are crucial for understanding the potential for water stress and its impact on species survival, particularly considering changing climatic conditions. Water stress can significantly affect tree health and growth (Zanden, 2008; Pita-Barbosa *et al.*, 2023; Gutiérrez-Hernández & García, 2021; Harsch & Hille, RisLambers, 2016(b), making these variables vital for the model's accuracy and application.

The Role of Thornthwaite's Climatic Moisture Index (CMI)

The Climatic Moisture Index (CMI), available from the ENVIREM dataset (Title and Bemmels 2018), is a critical tool for assessing moisture availability. Developed by Thornthwaite (de Oliveira Aparecido et al., 2023), CMI accounts for both temperature and precipitation, helping to understand how well growing conditions match the moisture needs of plant species. CMI is especially useful in refining SDMs, as it helps evaluate the balance between water inputs and outputs over time, which is key to plant health (Gutiérrez-Hernández & García, 2021; Harsch & Hille, RisLambers, 2016). This chapter adopts the revised CMI methodology proposed by Feddema (2005), which integrates both moisture and thermal factors, aiming to provide a comprehensive assessment of climate changes at RBG Kew over the study period.

Several studies highlight the effectiveness of CMI for evaluating climate impacts. For example, Grundstein (2009) demonstrate how CMI captures the balance between water inputs and outputs, offering a more comprehensive understanding of land-surface wetness than relying solely on precipitation. Cao *et al.* (1995) used CMI alongside temperature data to characterize the climate ranges of species, such as *Fagus* in southern China. Furthermore, Sjöman *et al.* (2019) emphasize that CMI serves as a simpler, more practical alternative to other complex models, especially in urban environments like RBG Kew. Together, these studies underline the importance of CMI for managing ecosystems, particularly in urban environments where moisture availability is crucial to species distribution and growth.

METHODS

Climate Variables

This study focuses on two key climate variables: Thornthwaite's Climatic Moisture Index (CMI) and mean annual temperature (BIO1). CMI is valuable for assessing the moisture balance of an area, indicating relative moisture and aridity. In contrast, mean annual temperature informs the growing season length and temperature suitability for the species.

We adopted the revised CMI methodology proposed by Feddema (2005), which integrates both moisture and thermal factors, to comprehensively assess climate changes at RBG Kew over the study period. This updated approach enhances our understanding of how moisture and temperature interact to shape plant growing conditions.

The calculation of CMI involves evaluating the water balance across a year, comparing precipitation against evapotranspiration losses. The potential evapotranspiration (ET_M) is calculated using Thornthwaite's regression formula, which incorporates temperature and other climatic factors. The formula for monthly potential evapotranspiration is:

$$ET_M = 16\left(10\frac{T}{I}\right)^a ,0^oC \leq T \ \leq 20^oC$$

where I is a thermal index imposed by the local normal climate temperature regime (Tn, oC) and the exponent a is a function of I, both computed by:

$$I = \sum_{n=1}^{12}(0.2T_n)^{1.514} ,T_n \ > \ 0^oC$$

$$a = 6.75\,x\,10^{-7}I^3 - 7.71\,x\,10^{-5}I^2 + 1.7912\,x\,10^{-2}I + 0.49239$$

For temperatures above 26 oC, the equation of Willmott *et al.* (1985) was used, in which ETM is represented as:

$$ET_M = \ -415.85 + 32.24T - 0.43T^2 ,T \ > \ 26^oC$$

To convert the estimates from a standard monthly (ETM, mm per month) to a daily time scale (ETD, mm per day), the following correction factor (C) was used:

$$C = \frac{N}{360}$$

N represents the photoperiod (hours) for a given day. Estimates of water runoff for the study site (RBG Kew) were based on data from P90 (2004), assuming a 10% runoff.

The Climatic Moisture Index (CMI) zones for the years 1981, 2020, and 2090 were classified based on the following criteria. CMI between -0.35 and 0: Areas falling within this range were categorized as having slightly lower moisture levels, indicating a transition from moist to drier conditions. For the 2090 scenario, regions with CMI values between -0.35 and 0 were also classified into this same category, reflecting a projected trend toward drier conditions. This classification approach was used to assess the changes in moisture availability and to model the potential impacts of future climate scenarios on the suitability of *Tilia* species.

Integrating Future Climate Scenarios for RBG Kew

To predict future climate scenarios at RBG Kew, data were extracted using the Terra Package in R (Hijmans, 2021) which allows spatial data analysis and integration of satellite remote sensing data. Projections for the year 2090 focus particularly on changes in CMI and their implications for plant suitability at RBG Kew. We applied the revised CMI methodology proposed by Feddema (2005), which integrates both moisture and thermal factors. This approach enhances the accuracy of future climate predictions by considering both temperature and precipitation effects on water availability**.**

Methodology for the Species Distribution Model (SDM)

Species Distribution Modeling (SDM) is widely used in ecological and conservation studies to predict the suitability of species under different climate scenarios (Title & Bemmels, 2018; Kindt, 2023(b). In this study, we focus specifically on two key climate variables: Climatic Moisture Index (CMI) and mean annual temperature (BIO1). These variables were selected for their direct relevance to plant health and growth under future climate projections.

The TreeGOER database (Kindt, R. (2023) 'TreeGOER)) provided essential environmental data, including bioclimatic, soil, and topographic variables necessary for the SDM analysis. The TreeGOER database also aided in classifying climatic zones and visualizing global CMI distribution patterns. Both databases allowed for detailed spatial analysis of climatic trends and species distribution under future climate scenarios.

Data Sources and Tools

The CitiesGOER database (Kindt, R. (2023) *CitiesGOER)*) provided key environmental data, including bioclimatic, soil, and topographic variables, necessary for the SDM analysis. The TreeGOER database was also used to classify climatic zones and visualize the global distribution patterns of CMI. Both databases allowed for detailed spatial analyses of climatic trends and the distribution of species under projected climate scenarios.

RESULTS

Climatic Zone Classification

Climatic Moisture Index (CMI) values and mean annual temperature were analysed for RBG Kew across five time points: 1981, 2010, 2020, 2050, and 2090, to assess long-term trends in moisture availability and climatic classification. Figure 5.1 presents the changes in the Climate Moisture Index and Mean Annual Temperature at RGB Kew over time. The figure illustrates a clear trajectory toward warmer and drier conditions over time, with a substantial decline in CMI and a concurrent rise in MAT. These trends suggest a progressive reduction in moisture availability at RBG Kew under projected future climate scenarios. In 1981, a mean annual temperature of 10.6°C and a CMI of 0.73 indicated a humid or wet climate ($CMI \geq 0.5$). By 2010, while temperature remained relatively stable at 10.75°C, the CMI declined to 0.25, classifying the region as moderately moist ($0 \leq CMI < 0.5$). This trend persisted in 2020, with a temperature of 10.85°C and a further CMI decrease to −0.15, signifying slightly dry conditions ($-0.35 \leq CMI < 0$).Projected values for 2050 suggest a mean annual temperature of 13.2°C and a CMI of −0.28, while by 2090, temperatures are expected to reach 15.45°C, with the CMI decreasing slightly to −0.3. These values maintain the classification within the slightly dry range but reflect a continued trajectory of declining moisture availability.

The consistent reduction in CMI, despite substantial increases in temperature, points to a progressive drying trend at RBG Kew. For *Tilia* species, which exhibit sensitivity to changes in moisture availability, such shifts are likely to impact growth performance, distribution, and persistence. Incorporating these temporal changes into species distribution models (SDMs) enhances the ability to forecast habitat suitability under future climate scenarios by accounting for both thermal and hydric constraints.

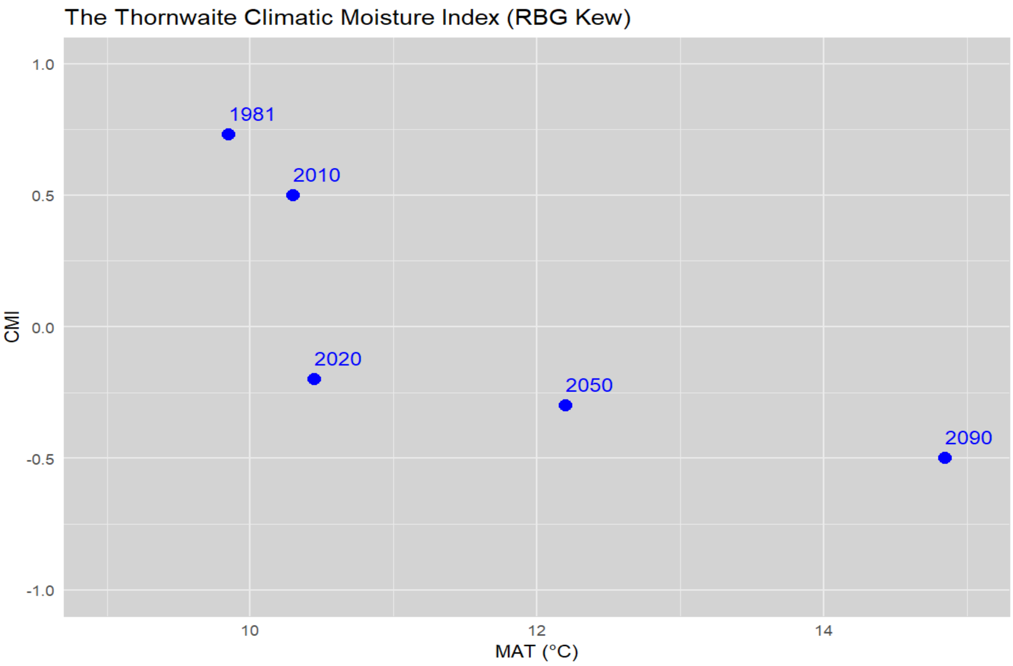


Figure 5.1 Changes in Climatic Moisture Index (CMI) and Mean Annual Temperature (MAT) over time at RBG Kew. Temperature (MAT) for the years 1981, 2020, and 2090 at RBG Kew. CMI represents the balance between precipitation and potential evapotranspiration, with lower values indicating increasingly dry conditions. MAT reflects the long-term average temperature.

DISCUSSION

The transition to drier conditions over time has significant implications for species distribution. As moisture levels decrease, drought-tolerant species are likely to become more suitable for the area, while species like *Tilia*, which require higher moisture levels, may struggle to thrive (Jump et al., 2009(b)). In a study of *Tilia cordata*, drought stress has been shown to reduce growth rates and negatively impact reproductive success under water-limited conditions (Bennett et al., 2012). Reduced moisture availability will not only impact plant health but also affect the broader ecosystem, which depends on adequate water resources. Additionally, changes in temperature and moisture could disrupt phenological events such as flowering and fruiting, potentially affecting biodiversity and overall ecosystem health. For example, *Tilia* species are sensitive to shifts in growing season timing and can exhibit altered flowering patterns in response to changes in temperature and moisture (Alonso et al., 2021).

Actionable Insights

To help mitigate the impacts of climate trends on the arboretum’s plant collections, we propose several strategies. Firstly, assess tree health and suitability by monitoring existing collections to identify species most vulnerable to climate change, allowing targeted conservation efforts. Additionally, future-proofing collections by using current and projected Climatic Moisture Index (CMI) data will aid in selecting species from ecosystems with similar future climate conditions. Sustainable practices, such as adapting water management techniques to increase soil moisture retention and employing drought-resistant species, will help ensure the long-term viability of the collections. Finally, increasing biodiversity resilience by diversifying plant collections with species that have varying moisture and temperature tolerances will further safeguard against changing climatic conditions.

CONCLUSION

This chapter has outlined a comprehensive approach to improving the Species Distribution Model (SDM) for *Tilia* species at RBG Kew by integrating key climate variables, particularly those related to water availability and temperature. By incorporating Thornthwaite’s Climatic Moisture Index (CMI) and mean annual temperature into the SDM, we enhance the model’s accuracy and improve its ability to predict future growing conditions for these species. The refined SDM will support RBG Kew’s efforts to manage its plant collections under changing climate scenarios, fostering sustainability and resilience in the face of environmental changes.

Chapter 6: Implementing the Species Distribution Model with CMI & BIO1

INTRODUCTION

In this chapter, we describe the implementation of the Species Distribution Model (SDM) for *Tilia* species at the Royal Botanic Gardens (RBG) Kew. This SDM aims to assess the potential distribution of *Tilia* species under current and projected climate scenarios. By leveraging climate data, specifically the Climatic Moisture Index (CMI) and mean annual temperature (BIO1), the model assesses the suitability of different regions for *Tilia* species' growth. This chapter details the use of the R programming language for data manipulation, statistical analysis, and model construction, employing packages such as dplyr for efficient data handling and other statistical tools for modeling.

METHODS

Data Input

As mentioned in the previous chapter, the CitiesGOER database (**Kindt, R. (2023) *CitiesGOER)***) provides essential environmental data, including bioclimatic, soil, and topographic variables, which are necessary for the SDM analysis. Alongside this, the TreeGOER database (Kindt, R. (2023) TreeGOER) was used to classify climatic zones and visualize global distribution patterns based on the Climatic Moisture Index (CMI). These two datasets, combined, offer a robust foundation for analysing species distribution and the potential impact of future climatic changes on *Tilia* species.

Data Filtering

Data filtering was performed to narrow down the scope of analysis to regions of interest, particularly those within the United Kingdom. The filtering criteria were based on latitude, longitude, and climatic zones relevant to the species of interest. This ensured that only data from locations suitable for *Tilia* species under the study's geographical scope was included. The dataset was further refined based on predefined climatic thresholds to isolate relevant data for our analysis.

Data Transformation and Mutation

Various data transformation and mutation steps were applied to derive additional insights from the dataset. The Climatic Moisture Index (CMI) zones were assigned based on predefined thresholds that categorize regions according to their moisture availability. For example, zones with CMI values between -0.35 and 0 represent areas where moisture availability is slightly lower, transitioning from moist to drier conditions. These transformations ensure that both water availability and temperature are accounted for in modeling species suitability, which is crucial for understanding the environmental requirements of *Tilia* species.

Summary Statistics and Merging

Summary statistics were calculated for each *Tilia* species to assess their climate suitability in different regions. The statistics include the count of occurrences (Zone_Status) and summary metrics (mean, minimum, and maximum) for the Q05 and Q95 values of CMI. Specifically:

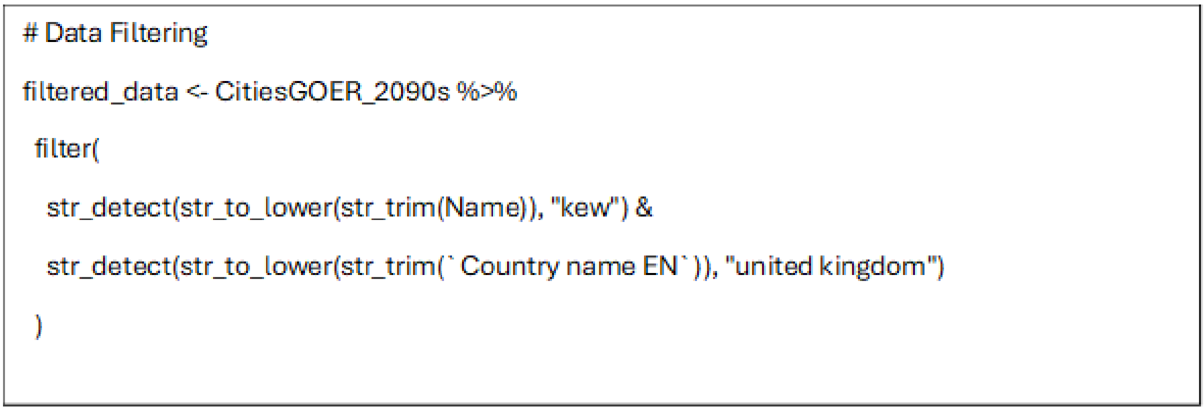
Zone Status Summary: Counts occurrences for each Zone Status, classifying species into categories such as 'Within Wider Range,' 'Lower Limits,' or 'Outside of Range.'

Quantile Summary: Calculates the mean, minimum, and maximum values for both the Q05 and Q95 CMI metrics for each species, reflecting the variability and potential climatic thresholds that influence species distribution.

Merging Summaries: The summary statistics for Q05 and Q95 are then merged with the Zone Status summary to create a comprehensive dataset that provides a detailed overview of species suitability across climatic zones.

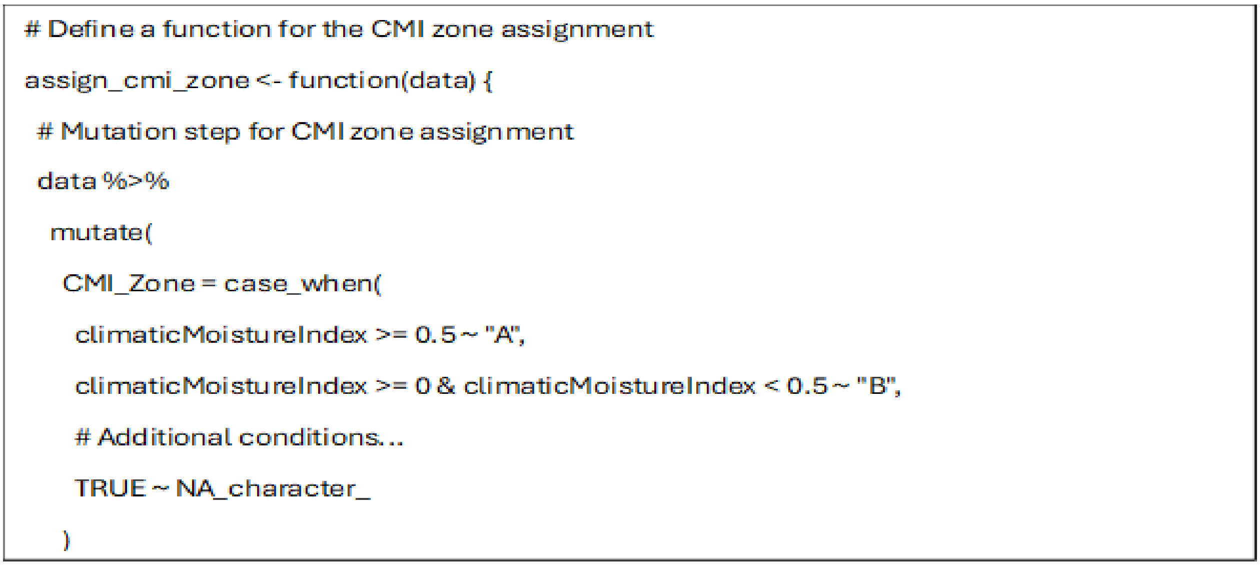
```
# Data Input

CitiesGOER_baseline <- read_csv("D:/database/CityGOER/CitiesGOER_baseline.csv")

CitiesGOER_2090s <- read_csv("D:/database/CityGOER/CitiesGOER_2090s.csv")
```

Figure 6.1. Data input to the model



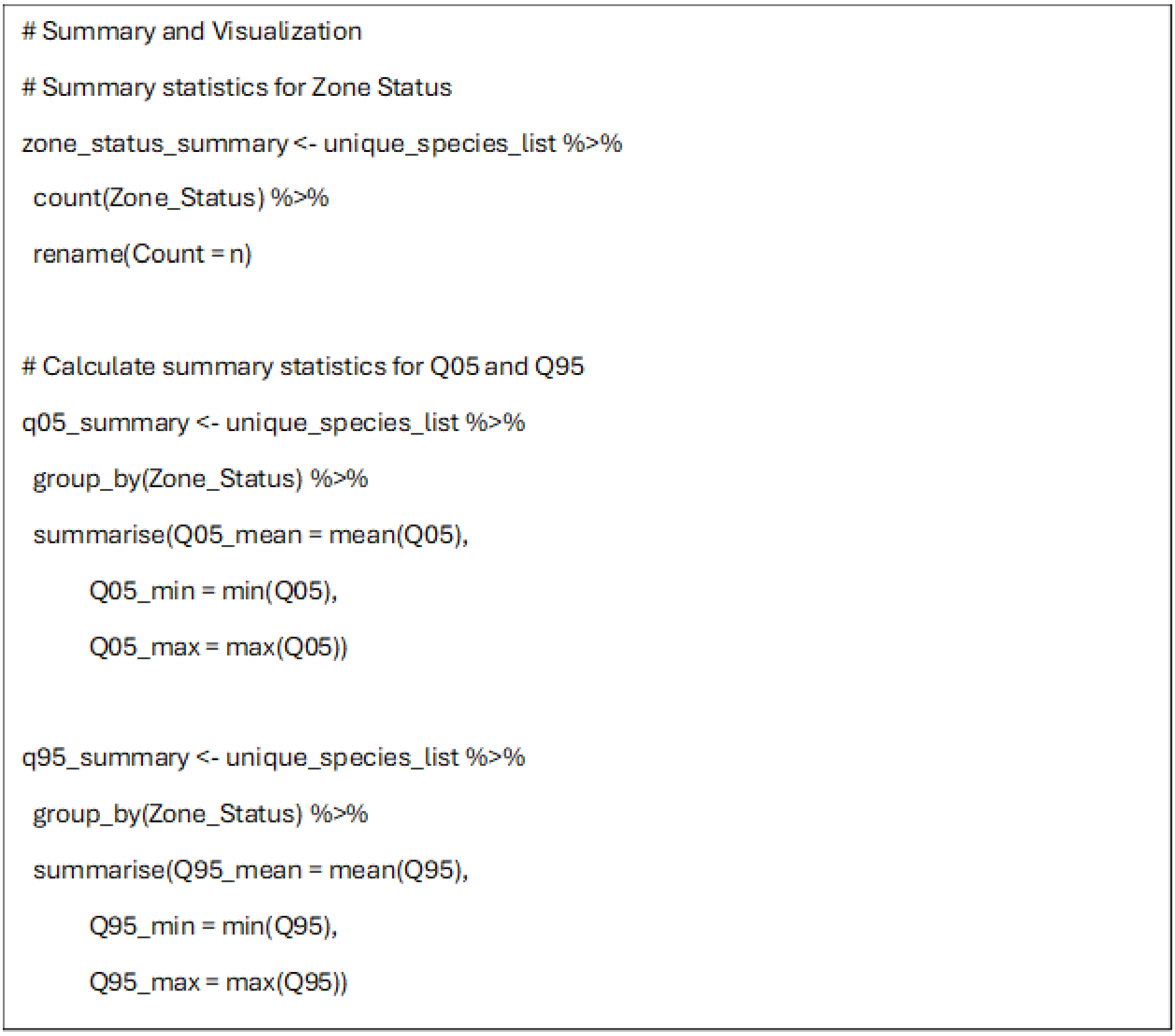
```
# Data Filtering

filtered_data <- CitiesGOER_2090s %>%

 filter(

  str_detect(str_to_lower(str_trim(Name)), "kew") &

  str_detect(str_to_lower(str_trim(` Country name EN` )), "united kingdom")

 )
```

Figure 6.2. data filtering



```
# Define a function for the CMI zone assignment
assign_cmi_zone <- function(data) {
 # Mutation step for CMI zone assignment
 data %>%
  mutate(
   CMI_Zone = case_when(
    climaticMoistureIndex >= 0.5 ~ "A",
    climaticMoistureIndex >= 0 & climaticMoistureIndex < 0.5 ~ "B",
    # Additional conditions...
    TRUE ~ NA_character_
   )
```

Figure 6.3. calculation of CMI zone for model output



```
# Summary and Visualization
# Summary statistics for Zone Status
zone_status_summary <- unique_species_list %>%
 count(Zone_Status) %>%
 rename(Count = n)

# Calculate summary statistics for Q05 and Q95
q05_summary <- unique_species_list %>%
 group_by(Zone_Status) %>%
 summarise(Q05_mean = mean(Q05),
      Q05_min = min(Q05),
      Q05_max = max(Q05))

q95_summary <- unique_species_list %>%
 group_by(Zone_Status) %>%
 summarise(Q95_mean = mean(Q95),
      Q95_min = min(Q95),
      Q95_max = max(Q95))
```

Figure 6.4. final summary of species results from the model

RESULTS

CMI & BIO1 Model Results

The model results present the climatic suitability of various *Tilia* species based on their Q05 and Q95 values in relation to the Climatic Moisture Index (CMI) and mean annual temperature (BIO1), specifically under Kew's future climate projections. Species are classified into three categories based on their projected climatic conditions: "Within Wider Range," which includes species with Q05 and Q95 values spanning a broad climate range, indicating adaptability to diverse environmental conditions; "Lower Limits," which includes species with suitability only at the lower end of their climatic range, suggesting vulnerability to warming or drier conditions; and "Outside of Range," which includes species with Q05 and Q95 values that do not align with the projected climate, indicating unsuitability under Kew's future climatic scenarios.

The Q05 value represents the lower climatic threshold at which a species can persist, while the Q95 value marks the upper limit of its climatic suitability. A lower Q05 suggests greater tolerance to drier conditions, whereas a higher Q95 indicates the species' ability to survive in more humid or temperate environments. In this analysis, *T. dasystyla*, *T. × europaea*, and *T. × euchlora* exhibit the widest climatic tolerance, with Q05 values extending into negative CMI ranges, indicating resilience in drier future climates. Conversely, species such as *T. japonica* and *T. kiusiana* have relatively high Q05 and Q95 values, positioning them "Outside of Range" and suggesting a requirement for more humid conditions that are not expected under Kew's future climate projections.

A total of fifteen species falls within the "Within Wider Range" category, demonstrating broad climatic adaptability under future conditions. This includes commonly cultivated species such as *T. americana* and *T. cordata*, which are well-suited to a range of projected climatic conditions and are ideal candidates for conservation and urban planting. Two species, *T. chingiana* and *T. membranacea*, are classified as "Lower Limits," indicating that they are only suitable for the most humid or temperate portions of their projected range, making them more susceptible to future climatic shifts. Nine species are categorized as "Outside of Range," meaning their climatic suitability is limited under Kew's future climate projections. These include *T. japonica*, *T. kiusiana*, and *T.maximowicziana*, which may struggle to persist without targeted conservation efforts. Their restricted climate range suggests they may face habitat loss due to the changing environmental conditions predicted for the future.

These results highlight which species are most likely to thrive under Kew's projected climate scenarios, aiding conservation planning and species selection for seed sourcing. Species within the "Within Wider Range" category should be prioritized for conservation in diverse habitats, while species classified as

"Lower Limits" or "Outside of Range" may require targeted interventions, such as assisted migration or habitat management, to ensure their survival in the face of changing climatic conditions.

Table 6.1. CMI & BIO1 Model Results.

	Species	Q05	Q95	Zone-Status
1	*Tilia americana*	-0.2500	0.2400	Within Wider Range
2	*Tilia amurensis*	-0.2800	0.4500	Within Wider Range
3	*Tilia chinensis*	0.1900	0.2400	Outside of Range
4	*Tilia chingiana*	0.2100	0.3300	Lower Limits
5	*Tilia cordata*	-0.2000	0.4400	Within Wider Range
6	*Tilia dasystyla*	-0.6100	0.4600	Within Wider Range
7	*Tilia endochrysea*	0.1800	0.4000	Outside of Range
8	*Tilia henryana*	-0.0300	0.4600	Within Wider Range
9	*Tilia japonica*	0.2600	0.6300	Outside of Range
10	*Tilia kiusiana*	0.2600	0.6600	Outside of Range
11	*Tilia kueichouensis*	0.0600	0.3100	Outside of Range
12	*Tilia likiangensis*	0.0000	0.0000	Outside of Range
13	*Tilia mandshurica*	-0.4400	0.3800	Within Wider Range
14	*Tilia maximowicziana*	0.2500	0.6100	Outside of Range
15	*Tilia membranacea*	0.2400	0.2800	Lower Limits
16	*Tilia miqueliana*	-0.0100	0.5200	Within Wider Range
17	*Tilia mongolica*	-0.5800	0.1375	Within Wider Range
18	*Tilia nobilis*	-0.3000	0.3100	Within Wider Range
19	*Tilia oliveri*	0.1710	0.3000	Outside of Range
20	*Tilia paucicostata*	0.1900	0.2200	Outside of Range
21	*Tilia platyphyllos*	-0.2500	0.4300	Within Wider Range
22	*Tilia tomentosa*	-0.2600	0.2300	Within Wider Range
23	*Tilia tuan*	0.1805	0.3200	Outside of Range
24	*Tilia × euchlora*	-0.6150	0.2150	Within Wider Range
25	*Tilia × europaea*	-0.6665	0.2530	Within Wider Range
26	*Tilia × flavescens*	-0.3145	0.1445	Within Wider Range

DISCUSSION

The results of the Climatic Moisture Index (CMI) and mean annual temperature (BIO1) model provide valuable insights into the future climatic suitability of various *Tilia* species, which can inform conservation strategies and planting decisions under Kew's projected climate scenarios. The classification of species into three categories"Within Wider Range," "Lower Limits," and "Outside of Range"—highlights the differential vulnerability and adaptability of *Tilia* species to future climate changes, particularly with regard to moisture availability.

Species classified within the "Within Wider Range" category, such as *T. americana*, *T. cordata*, and *T. dasystyla*, demonstrate broad climatic adaptability, making them well-suited for future planting and conservation efforts. These species, with Q05 values that extend into drier conditions and relatively high Q95 values, appear resilient to anticipated changes in climate, including increased drought stress. Their ability to tolerate a wider range of climatic conditions, including warmer temperatures and reduced moisture availability, suggests that they could play a crucial role in enhancing urban green infrastructure, particularly as cities face increasing challenges from the urban heat island (UHI) effect and climate change (Meili et al., 2021).

In contrast, species such as *T. japonica* and *T. kiusiana*, which are categorized as "Outside of Range," face a more uncertain future. These species are projected to struggle in Kew's future climate projections due to their high moisture requirements, with both Q05 and Q95 values indicating limited climatic suitability. Their sensitivity to temperature and moisture shifts suggests that without targeted conservation efforts, such as assisted migration or habitat management, they may be at risk of local extinction or significant habitat loss. This finding aligns with research on species that are more restricted to specific climatic conditions, which face heightened vulnerability as global warming accelerates (Pearson and Dawson, 2003).

The classification of *T. chingiana* and *T. membranacea* as "Lower Limits" underscores their sensitivity to drier and warmer conditions, with these species showing suitability only in the more temperate or humid portions of their projected range. These species will require careful monitoring and possibly more intensive conservation measures, such as ensuring that suitable habitats are maintained or restored to prevent their displacement due to changing environmental conditions.

The results further highlight the importance of considering a species' ability to adapt to shifts in both temperature and moisture levels when selecting trees for future conservation or urban planting. *Tilia* species with broad climatic tolerance are particularly valuable in this context, as they can provide critical ecosystem services, such as air quality improvement, carbon sequestration, and urban cooling, in the face of rapidly changing climate conditions (Nowak et al., 2014).

However, it is important to acknowledge that the model's reliance on current climate variables and projected future conditions may not fully account for the long-term physiological responses of these species, especially under extreme climatic shifts (Jump et al., 2009(b). Thus, while *T. americana* and *T. cordata* are currently well-suited for a range of climates, ongoing monitoring and research into their physiological responses to changing climatic factors will be crucial to ensure that they remain resilient over time.

In conclusion, the findings emphasize the need for adaptive management strategies in urban forestry and conservation planning. Species with broad climatic adaptability should be prioritized for planting in diverse habitats, while those with narrower climatic ranges require more targeted conservation efforts to help mitigate the impacts of climate change. Future studies should continue to refine these models, incorporating additional factors such as soil properties and phenological changes, to further enhance the predictive accuracy and effectiveness of conservation and planting strategies.

Chapter 7: Comparative Analysis and Model Performance for Climate Suitability of *Tilia* Species at RBG Kew

INTRODUCTION

This chapter builds upon the integration of climate variables into Species Distribution Models (SDMs), as discussed in the previous chapters. It presents a comparative analysis of two models assessing the climate suitability of *Tilia* species at the Royal Botanic Gardens (RBG) Kew. By evaluating model performance under SSP3 climate scenario, we aim to explore insights into potential future species distributions, which are critical for informed conservation and management strategies.

METHODS

Comparative Model Analysis

To evaluate species suitability under future climate scenarios, two distinct models were applied.

Model 1: BIO1-Based Model This model is based solely on Mean Annual Temperature (BIO1), which rates climate suitability across different environments, such as botanical gardens (BG), urban, and natural areas. Suitability is assessed based on whether a species' temperature range aligns with these zones.

Model 2: BIO1 & CMI-Based Model This model integrates the Climatic Moisture Index (CMI) with BIO1, offering a more nuanced climate suitability assessment. It categorizes species as within, outside, or at the edge of their climatic range by considering both temperature and moisture availability.

Species Comparisons

The following table compares the results for various *Tilia* species across both models.

Table 1.1 Result out puts from model 1 and model 2

Species	Model 1: Climate Rating	Model 2: Range Status
Tilia americana	11 (Middle of natural range)	Within Wider Range
Tilia cordata	6 (Shoulder of BG range)	Within Wider Range
Tilia oliveri	11 (Middle of natural range)	Outside of Range
Tilia × europaea	No results	Within Wider Range
Tilia × euchlora	No results	Within Wider Range
Tilia platyphyllos	6 (Shoulder of BG range)	Within Wider Range
Tilia tomentosa	6 (Shoulder of BG range)	Within Wider Range
Tilia dasystyla	8 (Shoulder of natural range)	Within Wider Range
Tilia mongolica	8 (Shoulder of natural range)	Within Wider Range
Tilia henryana	11 (Middle of natural range)	Within Wider Range

Model Insights

Mode1(BIO1Focus)

This model provides a broad, temperature-focused climate suitability rating, which is useful for high-level assessments of climate suitability across various environments. However, it omits moisture-related factors, which may limit its accuracy, particularly in future scenarios where water availability could be a critical factor in species survival**.**

Model2(BIO1&CMIFocus)

The inclusion of CMI alongside BIO1 results in a more comprehensive climate suitability model. This model considers both temperature and moisture availability, leading to more precise range classifications, particularly in areas where water availability is crucial for species survival.

Verification of Model Results through Data Analysis

To further understand the implications of model outputs for predicting future species distributions at RBG Kew, a detailed data extraction and analysis process was conducted using R. The terra package was used to handle spatial data and extract environmental variables from climate datasets. Future Climate Projections were based on Shared Socioeconomic Pathways (SSPs), particularly SSP3, a high-emission scenario characterized by significant regional disparities (Nazarenko *et al.*, 2022). The primary climate data source used was the Chelsa dataset (Karger *et al.*, 2017), which provides high-resolution, globally downscaled climate projections at a 30 arc-second (~1 km) resolution.

Modelling Data Source: Chelsa Dataset

The Chelsa dataset is essential for evaluating species' adaptability to future climate conditions. It provides detailed climate projections, including both temperature and moisture changes, making it an invaluable resource for modeling future species distributions. Hosted by the Swiss Federal Institute for Forest, Snow, and Landscape Research (WSL), the dataset supports robust, high-resolution modeling efforts.

Data Collection and Processing

This study examines the climatic preferences of nine *Tilia* species: *Tilia americana, Tilia cordata, Tilia platyphyllos, Tilia japonica, Tilia mandshurica, Tilia maximowicziana, Tilia tomentosa, Tilia dasystyla, and Tilia mongolica*. The following steps outline the data collection and analysis process:

Species Occurrence Data Collection

Occurrence data were obtained from the Global Biodiversity Information Facility (GBIF) using the rgbif package in R. These records provided geospatial coordinates representing known occurrences of each species.

Data Cleaning

To ensure data accuracy and reliability, the occurrence records underwent cleaning steps, including the removal of duplicate records, handlings of missing or erroneous values, and verification of coordinates to exclude implausible or mislocated data points.

Environmental Data Extraction

For each occurrence point, Mean Annual Temperature (MAT, °C) and Climatic Moisture Index (CMI, unitless) values were extracted from raster datasets. These environmental variables were linked to species occurrence data to facilitate suitability analysis.

Data Aggregation

The extracted MAT and CMI values were aggregated to create a unified dataset, allowing for cross-species comparisons of climatic preferences and adaptability to future climate conditions.

Visualization

The aggregated data were visualized using ggplot2 in R to highlight climatic distributions across *Tilia* species. The violin plots illustrate the distribution of CMI values, showing the range and density of climatic conditions, each species occupies.

The aggregated data were visualized using ggplot2 in R to illustrate climatic distributions across *Tilia* species. The scatter plots show individual occurrences of each species, highlighting the range of Mean Annual Temperature (MAT) and Climatic Moisture Index (CMI) values. Projected climatic conditions for RBG Kew in 2090 are indicated by red triangles, marking the specific MAT (14.9°C) and CMI (-0.3) values. Labels for these projections are positioned near the triangles for clarity. This visualization allows comparison between current species distributions and future climate projections, helping assess which *Tilia* species may be most suitable under anticipated conditions.

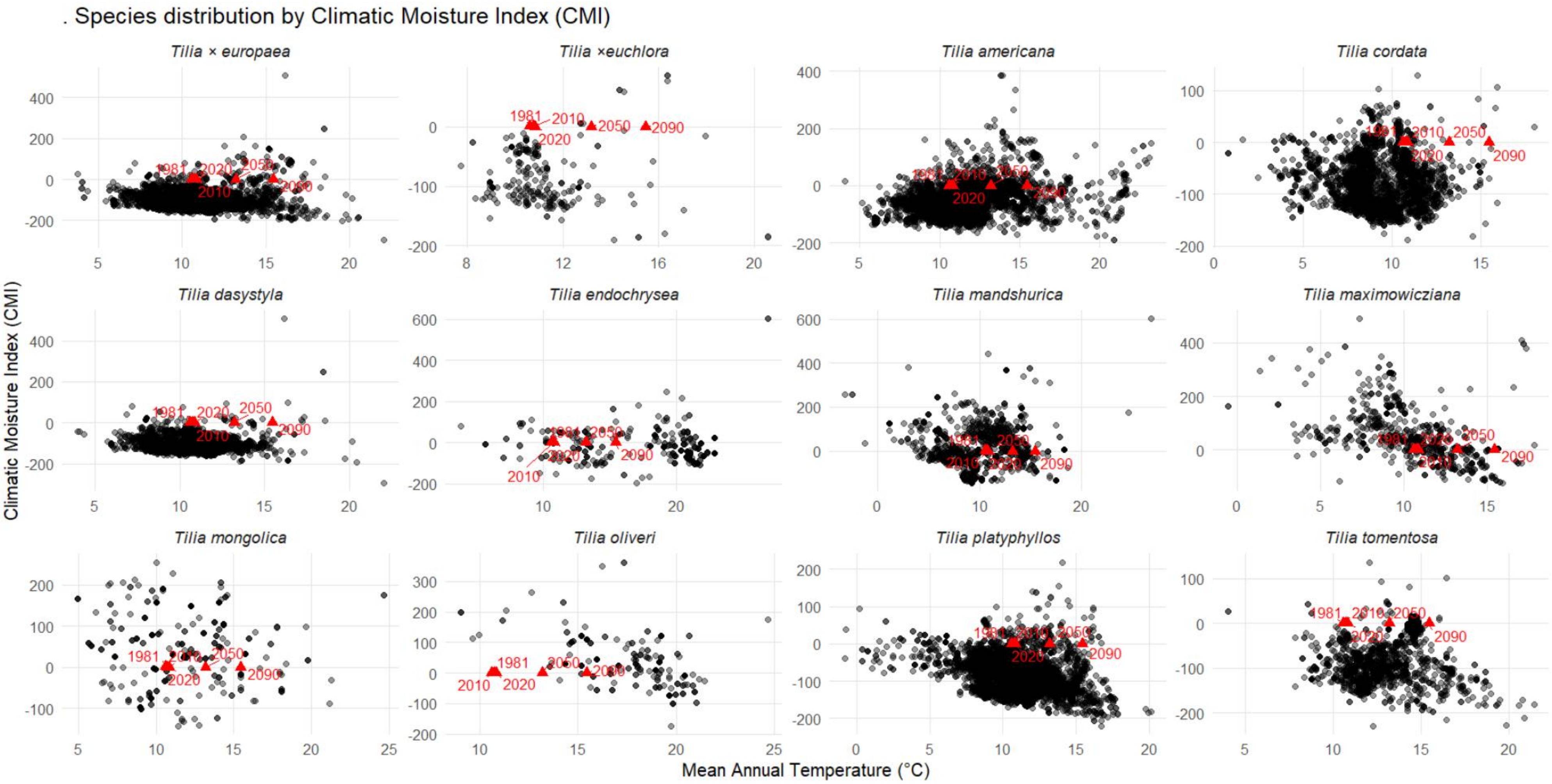


Figure 7.1 Scatter plot of Tilia species occurrences showing their climatic distribution in terms of MAT and CMI. Red triangles mark projected 2090 climate conditions at RBG Kew (MAT = 14.9°C, CMI = -0.3), highlighting potential matches between species' niches and future climate.

RESULTS

The scatter plots illustrate the climatic distribution of *Tilia* species based on Mean Annual Temperature (MAT) and Climatic Moisture Index (CMI). Each point represents an observed occurrence, showing the range of climatic conditions, each species occupies. Red triangles indicate projected 2090 climate conditions at RBG Kew (MAT = 14.9°C, CMI = -0.3), highlighting potential future matches between species' niches and expected climate. This visualization provides insight into species' adaptability and potential shifts in habitat suitability under future climate scenarios.

T. americana, T. mongolica, T. platyphyllos, and *T. tomentosa* show a broad distribution in both MAT and CMI, indicating a higher adaptability to varying climatic conditions. However, projected warming and increased aridity at Kew may push these species outside their optimal climatic range, particularly in terms of moisture availability*. T. tomentosa* has a small violin plot due to the limited range of climatic conditions in which it has been recorded. This suggests that its occurrences are concentrated within a narrow band of Mean Annual Temperature (MAT) and Climatic Moisture Index (CMI) values, indicating a more specialized climatic preference compared to other *Tilia* species. The narrow distribution could be due to ecological constraints, habitat specificity, or limited sampling across its native range.

T. cordata and *T. maximowicziana* exhibit more constrained distributions, with mean MAT values lower than the projected 2090 conditions at Kew. This suggests that these species may struggle to persist at Kew as temperatures increase beyond their observed climatic limits*. T. dasystyla, T. mandshurica, and T. endochrysea* show higher MAT tolerances, particularly *T. endochrysea*, which has a mean MAT above (17°C). These species might be better suited to future conditions at Kew, although their CMI distributions suggest that moisture availability could become a limiting factor. *T. oliveri* has a relatively high MAT tolerance, like *T. endochrysea*, but with a lower range of observed moisture conditions, making it moderately adaptable to projected climate scenarios at Kew. Hybrid species *T. × euchlora* and *T. × europaea* display intermediate climatic distributions, suggesting potential resilience to changing conditions, although their reliance on higher moisture availability could limit their future viability at Kew.

DISCUSSION

While some *Tilia* species may remain viable at Kew under projected 2090 climate conditions, others are likely to experience climatic stress due to increased temperatures and reduced moisture availability. Species with broad MAT and CMI distributions, such as *T. americana*, *T. mongolica*, and *T. tomentosa*, may have a greater chance of persisting, whereas species like *T. cordata* and *T. maximowicziana* could be at risk. The projected MAT of (14.9°C) exceeds the mean values observed for many species, indicating that Kew's future climate may become less suitable for some traditionally cultivated *Tilia* species. Future conservation strategies should consider assisted migration or *ex situ* conservation efforts for species at risk, particularly those with restricted climatic distributions. Additionally, introducing drought-resistant cultivars or hybrids may help maintain *Tilia* diversity at Kew under changing environmental conditions.

CONCLUSION

This analysis underscores the importance of incorporating climate projections into plant conservation and landscape management. While some *Tilia* species show resilience to changing conditions, others may require proactive conservation measures to ensure their survival at RBG Kew. Future research should explore physiological adaptations, soil moisture interactions, and potential hybridization strategies to enhance species resilience in urban and managed landscapes.

Chapter 8: Incorporating Euclidean Distance for Identifying Suitable Ecosystems

INTRODUCTION

To further refine the identification of suitable ecosystems for the future distribution of *T. × europaea*, we employ Euclidean distance as a key analytical tool. Euclidean distance, a fundamental concept in geometry, measures the straight-line distance between two points in a multidimensional space. In this study, it enables us to assess the similarity between climate conditions at different locations, facilitating the identification of regions with climates analogous to future projections for RBG Kew (Nabout *et al.*, 2010; Tessarolo *et al.*, 2014; Wu *et al.*, 2019; Obunga *et al.*, 2022).

Application in Climate Suitability Assessment

In this study, we apply the Euclidean distance formula to compute the distance between each observed climate data point and a designated target point, representing future climate scenarios. For example, we calculate the distance between MAT and CMI values from seed source regions and the projected MAT and CMI values for RBG Kew in 2090. The data point with the smallest Euclidean distance to the target point is considered the most climatically similar.

By calculating these distances, we identified regions with climates most compatible with RBG Kew's future environment. For instance, *T. × europaea* seed sources can be strategically selected from areas with climates closely resembling RBG Kew's 2090 projections, ensuring better adaptation and resilience

Conservation and Seed Sourcing Implications

Integrating Euclidean distance calculations into our analysis provides several critical conservation outcomes. First, regions with climates most similar to RBG Kew's 2090 projections are prioritized for seed collection. This approach helps identify areas where genetic material should be sourced to ensure that plant populations are well-suited to future conditions. By introducing genetic material from populations pre-adapted to projected conditions, we enhance the fitness and adaptability of *T. × europaea*. Furthermore, this method supports the development of proactive conservation strategies tailored to future climate scenarios. Overall, this approach bridges the gap between theoretical modeling and practical conservation, enabling informed decision-making to future-proof botanical collections.

METHODS

Mathematical Framework

Euclidean distance measures the proximity between climate data points in a multidimensional space, allowing for a straightforward comparison of observed and projected climate conditions. This approach is particularly powerful when identifying areas with environmental conditions that closely resemble RBG Kew's projected future climate.

The Euclidean distance formula for two points (x1,y1)(x_1, y_1)(x1,y1) and (x2,y2)(x_2, y_2)(x2,y2) in a two-dimensional space is expressed as:

Distance = √ [(x2 – x1)2 + (y2 – y1)2].

Here, the xxx and yyy variables represent Mean Annual Temperature (MAT) and Climatic Moisture Index (CMI), respectively, for various geographic locations.

Identifying Suitable Ecosystems Using Euclidean Distance Calculations

To identify suitable ecosystems for seed sourcing, we employ Euclidean distance calculations within a Decision Support Model (DSM). This method minimizes the risk of plant selection errors and ensures that species are appropriately matched to specific areas (Utama, 2020). By calculating the proximity between current and future climatic conditions, we pinpoint regions with environments compatible with projected scenarios. This proactive approach enhances the fitness and resilience of tree populations, contributing to the sustainability of diverse species in a changing climate.

Methodology for Identifying Closest Climate Match

Data Preparation

The dataset for *Tilia cordata* occurrences, containing geographical coordinates (decimal Latitude and decimal Longitude), as well as climate data (Mean Annual Temperature (MAT) and Climatic Moisture Index (CMI)), was prepared. This dataset was filtered to retain only occurrences with MAT values greater than or equal to 15°C and a CMI of -0.3, which were set as the criteria for the "Kew 2090" climate values.

Euclidean Distance Calculation

The Euclidean distance was computed between each occurrence's geographical coordinates and a reference point located in central Europe (50.0°N, 13.0°E).

Identification of the Closest Match

The closest match was identified by finding the occurrence with the minimum Euclidean distance to the reference point. This was considered the climate match that most closely approximates the specified MAT and CMI conditions.

Visualization

A scatter plot was created to display the distribution of Mean Annual Temperature (MAT) and Climatic Moisture Index (CMI) values for *Tilia cordata* occurrences. This plot was generated using the ggplot2 package, which provides flexible and visually appealing plotting tools. Each black point represents an observed occurrence of the species. The closest match to the reference climate conditions, calculated using Euclidean distance, is highlighted with a red point. The label "Closest Match: Motovun, Croatia" marks the location of this best climate match, showing where the species aligns most closely with the projected climate conditions.

Labelling the Closest Match

A label was added to the plot to indicate the location of the closest climate match. The label, "Closest Match: Motovun, Croatia," is positioned near the red triangle representing this point. Its placement was adjusted for clarity to ensure it is easily visible within the scatter plot.

R Packages Used

ggplot2 (Wickham, 2016): Used to create scatter plots for visualizing the climatic distribution of *Tilia* species. This package provides high-quality and flexible plotting capabilities. Red triangles mark projected climate points (MAT = 14.9°C, CMI = -0.3) to indicate RBG Kew's 2090 scenario.

dplyr (Wickham et al., 2023): Used for data manipulation, including filtering datasets based on MAT and CMI conditions and calculating Euclidean distances between occurrences and reference points.

RESULTS

The results highlight the practical utility of Euclidean distance in identifying suitable ecosystems. For example, Motovun, Croatia, emerged as a region with a climate similar to RBG Kew's projected conditions for 2090. This finding facilitates the strategic sourcing of seeds from regions with similar climatic profiles, thereby enhancing the resilience of tree populations in urban and botanical environments. By identifying climatically compatible regions, we ensure that tree species selected for planting in gardens, arboreta, and urban spaces are better equipped to thrive under future conditions.

The visual representation (Fig. 5) underscores the importance of detailed climate models in guiding conservation efforts.

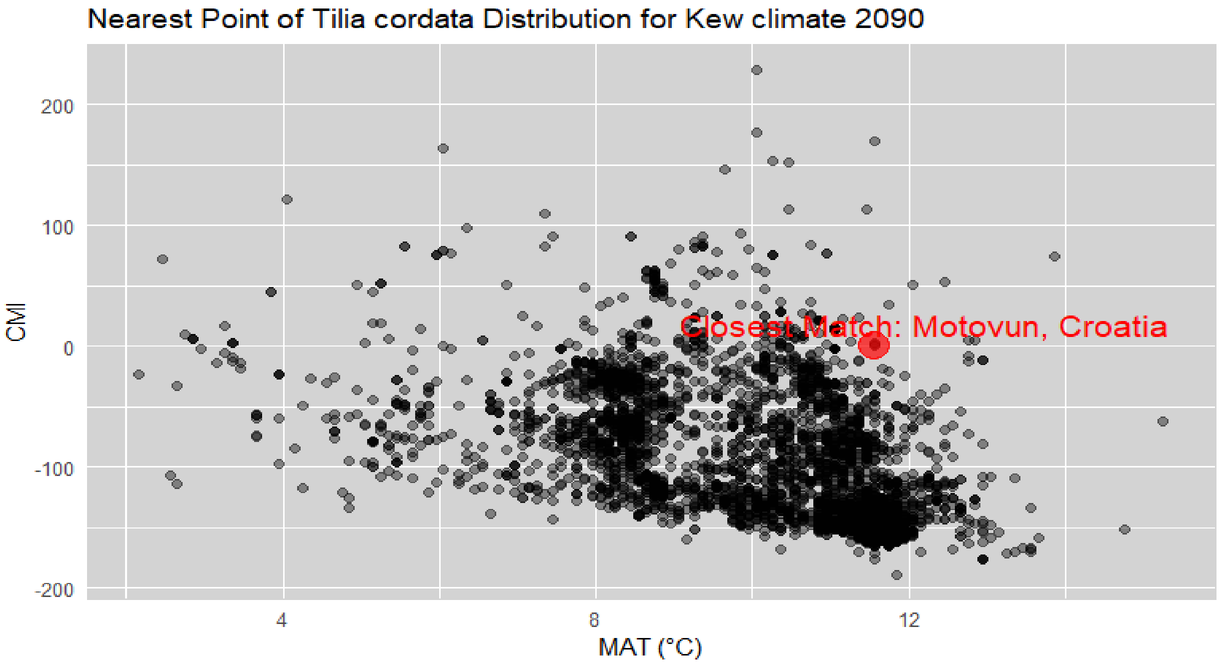


Figure 8.1 Distribution of Mean Annual Temperature (MAT) and Climatic Moisture Index (CMI) for Tilia cordata occurrences. Each black point represents an observed occurrence of the species. The red point indicates the closest occurrence to the reference climate conditions, calculated using Euclidean distance. The label "Closest Match: Motovun, Croatia" marks the location of the best climate match, showing where in the world the species best aligns with the projected climate conditions.

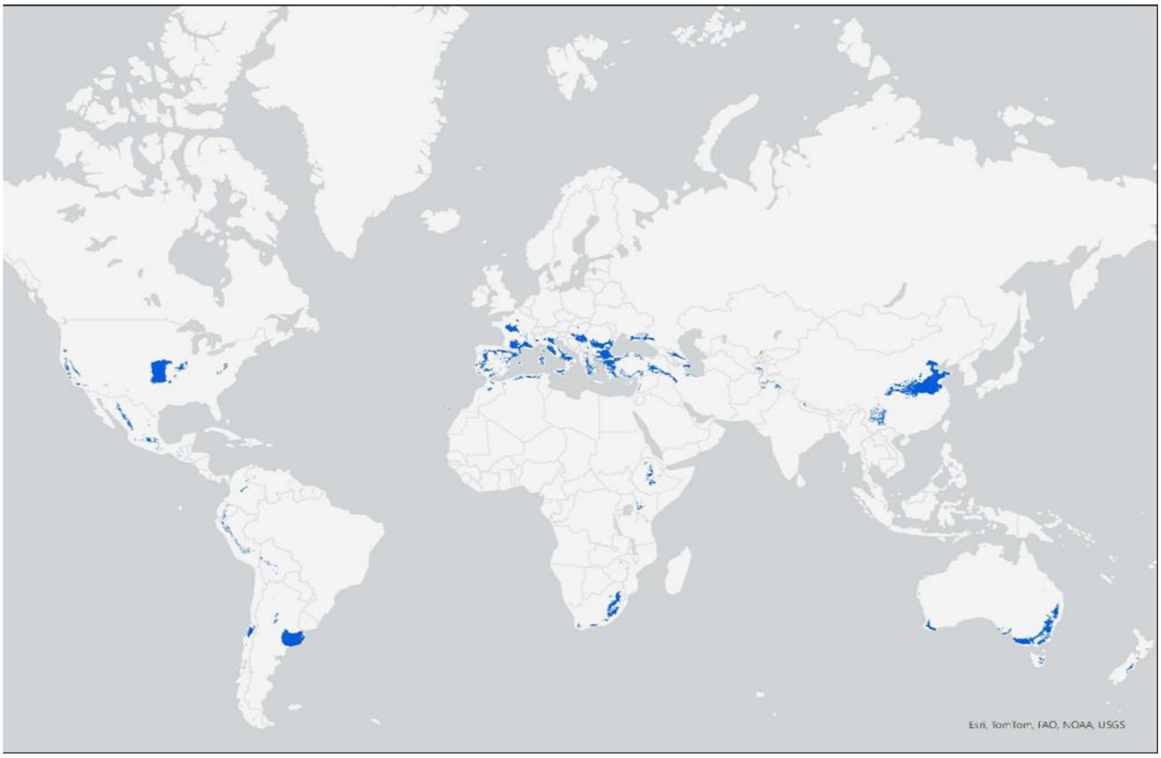


Figure 8.2 Global map displaying the suitable ecosystem for Kew future climate as possible source for seed for future trees represented using ArcGIS software, with the climate variables of mean annual temperature and climatic moisture index.

Projected Climatic Suitability for CMI -0.3 and MAT 14.9 Under Kew's 2090 Scenario

The map illustrates the global distribution of areas where the Climatic Moisture Index (CMI) is projected to be -0.3 and the Mean Annual Temperature (MAT) is 14.9°C under Kew's 2090 climate projections. These regions represent potential future climatic analogues for specific *Tilia* species, highlighting zones where conservation efforts, seed sourcing, and assisted migration strategies could be targeted.

Key findings indicate that suitable conditions are expected to be concentrated in temperate regions across the Northern Hemisphere, particularly in parts of Europe, East Asia, and the eastern United States. Large portions of central and southern Europe, including areas spanning France, Germany, and Turkey, align with these climatic conditions, suggesting that these regions may serve as refugia for *Tilia* species currently found in similar climates. In East Asia, parts of China exhibit strong matches, reinforcing the importance of these regions for future conservation planning.

In the Southern Hemisphere, notable pockets of climatic suitability emerge in parts of South America, particularly in Chile and Argentina, as well as in southeastern Australia and New Zealand. These regions, although geographically distant from the native ranges of many *Tilia* species, could provide insights into alternative conservation strategies, such as *ex situ* conservation or assisted migration trials.

This spatial distribution highlights the importance of proactive conservation strategies in anticipation of future climate shifts. Areas where suitable climatic conditions persist or expand could be prioritized for *in situ* conservation, while regions where *Tilia* species are projected to move outside their current climatic niche may require adaptive management, including translocation or assisted gene flow. These findings contribute to the broader understanding of how climate change will reshape tree species distributions and emphasize the need for future-proof conservation planning.

DISCUSSION

This analysis combines occurrence data with predicted climate data to provide deeper insights into how species like *Tilia × europaea* will interact with future landscapes. However, challenges persist, including variability in data collection methods (e.g., GPS coordinates versus grid-based atlas records) and the absence of metadata in many records. These factors can introduce inconsistencies in model outputs (Meyer *et al.*, 2016; Zizka *et al.*, 2019). To address these challenges and improve accuracy, future research should incorporate plant trait data. Traits such as leaf morphology, water-use efficiency, and phenology provide valuable indicators of how species interact with their environment and respond to climate change. Integrating trait-based data into climate modeling will significantly enhance predictive accuracy, enabling more precise conservation strategies. Future studies should combine trait-based data with climate modeling to refine predictions of species responses to environmental shifts. This approach will improve species selection for conservation and ensure adaptability to future climate conditions.

CONCLUSIONS

By leveraging environmental datasets such as WorldClim2, we mapped suitable ecosystems for future climate scenarios at RBG Kew. The integration of Euclidean distance calculations, Species Distribution Models (SDMs), and trait-based research offers a robust framework for adapting to future climate dynamics. This study provides actionable insights for selecting tree species and sourcing seeds that are pre-adapted to anticipated climatic conditions. By applying these methodologies, conservationists and urban foresters can ensure the long-term resilience and sustainability of urban green spaces. These approaches can be applied to other species and landscapes, broadening the scope of climate-resilient conservation programs and fostering ecological stability in the face of environmental change.

Chapter 9: Summary and Conclusions

OVERVIEW OF THE STUDY

This thesis addresses the critical challenge of adapting tree species to future climatic conditions, with a focus on *Tilia* species. Using a combination of Species Distribution Models (SDMs), Euclidean distance calculations, and climate data, this research identifies suitable ecosystems for seed sourcing. By aligning seed collection strategies with projected climate scenarios, it aims to enhance the resilience of *Tilia* populations in urban and botanical settings, exemplified by the Royal Botanic Gardens, Kew (RBG Kew).

Key Findings

Climate Suitability Modeling SDMs revealed significant insights into the relationships between *Tilia* species distributions and key climate variables, including Mean Annual Temperature (MAT) and Climatic Moisture Index (CMI). By comparing current conditions with projections for 2090, regions such as Motovun, Croatia, were identified as climatically analogous to RBG Kew's future environment, making them ideal for seed sourcing.

Euclidean Distance Analysis The integration of Euclidean distance calculations allowed precise identification of regions with climates most like future scenarios. This straightforward yet powerful approach highlighted the potential for climate-informed seed sourcing to mitigate the impacts of climate change on *Tilia* species.

Trait-Based Insights While the focus was on climate variables, the study underscored the need to incorporate plant traits—such as drought tolerance, water-use efficiency, and phenological adaptations—into future models. These traits are crucial for refining predictions and ensuring adaptability to future environmental conditions.

Conservation and Urban Forestry Implications The findings emphasize the importance of integrating climate data into conservation and urban forestry strategies. Proactive seed sourcing from climatically suitable regions can bolster the genetic diversity and resilience of urban tree populations, fostering more sustainable and biodiverse landscapes.

BROADER IMPLICATIONS

This research demonstrates the practical application of climate models in biodiversity conservation and urban forestry. While centred on *Tilia* species, the methods and findings offer a scalable framework for other plant species. By integrating SDMs, climate variables, and trait-based insights, this thesis contributes to the global effort to mitigate the effects of climate change on ecosystems and ensure the long-term viability of urban greenery.

LIMITATIONS AND FUTURE DIRECTIONS

Despite its strengths, this study acknowledges several limitations. Data gaps, including sparse occurrence records and variability in climate projections, affect the precision of species distribution models. Additionally, the limited integration of plant traits constrains the predictive power of these models. Future research should focus on expanding the spatial and temporal scales of climate and occurrence data while incorporating microclimatic and urban-specific conditions into modeling. Further integration of plant trait data, leveraging genetic studies and controlled experiments, will improve model accuracy. These advancements will enhance the robustness of species distribution predictions and provide actionable insights for conservation.

CONCLUDING REMARKS

This thesis offers a scientifically robust approach to addressing the challenges of climate change in tree conservation and urban forestry. By leveraging SDMs, Euclidean distance calculations, and climate data, it presents a framework for identifying suitable ecosystems for seed sourcing, ensuring that *Tilia* species and other trees are better equipped to thrive under future conditions.

The study's findings not only support the proactive management of urban green spaces but also contribute to the broader discourse on climate resilience and biodiversity conservation. By aligning conservation practices with scientific modeling, this research paves the way for sustainable and adaptive strategies that protect our botanical heritage and promote ecological stability in an era of rapid environmental change.

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