



Evaluating urban tree population fitness for a changing climate: Using climatic moisture index

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ABSTRACT

Species Distribution Models (SDMs) are essential tools for understanding how species respond to climatic and environmental changes. In this study, we examine the relationship between Climatic Moisture Index (CMI) and leaf water potential (Ψ_{p0}) across a variety of tree species to explore how climatic moisture conditions influence tree physiology, particularly in terms of drought tolerance. Using linear regression analysis, we found a statistically significant relationship between CMI and Ψ_{p0} , with the direction of the slope indicating how species respond to changes in moisture availability. Species with a positive relationship between CMI and Ψ_{p0} exhibited greater tolerance to fluctuating moisture conditions, while those with a negative relationship showed a higher susceptibility to drought stress. The findings underscore the importance of incorporating climatic factors into conservation and management strategies, particularly for species at risk of water stress under changing climate conditions. This research contributes to a broader understanding of tree physiology, with implications for conservation, restoration, and urban tree selection efforts in the face of global climate change.

Introduction

The distribution of plants is shaped by a complex interplay of environmental factors, including soil composition and climatic conditions. Together, these factors define the growing environment for plants, and any deviation from optimal conditions can impair growth and alter distribution patterns (Archibold, 2012). The escalating global water crisis, driven by climate change, has led to unpredictable water availability, significantly impacting the productivity of planted forests (Payn et al., 2015). There is mounting evidence that forests are becoming increasingly susceptible to climate-induced tree dieback due to more frequent and intense droughts, a phenomenon particularly prevalent in Europe (e.g., Knutzen et al., 2025; Senf et al., 2018). In urban areas, this challenge is further intensified by unique microclimatic conditions, such as the urban heat island effect. This occurs when urban environments experience higher temperatures than surrounding non-urban areas (Deilami et al., 2018), exacerbating water loss through evapotranspiration. As a result, trees' cooling mechanisms are compromised due to stomatal closure during peak temperatures, driven by high vapor pressure deficits, which limits transpiration (Meili et al., 2025). Although

tree shade can mitigate surface temperatures, non-transpiring trees paradoxically elevate air temperatures by 1.6–2.1 °C during peak daytime hours, counteracting the cooling effect of evapotranspiration (Meili et al., 2025).

Understanding the intricate interactions between urban environments, climate change, and their impact on tree populations is crucial for the development of effective management strategies. In the United Kingdom, evidence indicates a significant climate shift, with warmer, wetter, and sunnier conditions in recent decades compared to the 20th century (Kendon et al., 2024). This climate transition underscores the need to comprehend the long-term effects on tree populations in urban settings, including both street and park environments. The anticipated climate change presents a heightened challenge in selecting tree species capable of thriving in evolving landscapes. This challenge is further compounded by the prevailing growing conditions for urban trees, which are often confined to planting pits with limited water, nutrients, and aeration, while being exposed to elevated temperatures, radiation, pollution, and soil compaction (Moser et al., 2017). The urban heat island effect exacerbates the detrimental impacts of urban microclimates on tree growth and health. This is likely to lead to the introduction of

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new pests and diseases, and a decline in the vitality and growth of commonly used urban tree species that are adapted to historical climates (Sjöman et al., 2012). As a result, it is paramount to adapt urban forestry practices to these changing conditions to ensure the resilience and sustainability of tree populations in the face of evolving climates and urban landscapes.

Species distribution modelling (SDM) is a versatile tool that can facilitate 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). 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 data sets for SDM include WorldClim (Hijmans et al., 2005), PRISM (Daly et al., 2002), ClimateNA (Wang et al., 2012; Hamann et al., 2013; Wang et al., 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, such models risk poor performance (Dormann et al., 2012). For example, models constructed with many highly collinear variables are more likely to suffer from overfitting and overparameterization. Furthermore, such models may exhibit unexpected behavior when projected to different time periods or geographic regions. Instead, the focus should be on reducing the number of variables, either through statistical methods or by selecting those that are ecologically relevant based on the species' physiology. It is evident that water stress represents a significant factor capable of impeding urban tree growth (Meineke and Frank, 2018). When temperatures exceed the species-specific thermal limits and extreme events, such as heatwaves and prolonged droughts, become more frequent and intense, adverse effects on tree growth can be observed (e.g. Nitschke et al., 2017; Bialecki et al., 2018). This emphasises the importance of drought tolerance when selecting urban trees for ecosystem services in a future climate. In the context of climate modelling, an essential element pertains to the availability of water, given its essential role in determining tree resilience within urban environments. The climate moisture index (CMI) emerges as a key metric for predicting this, offering a discernible indication of water availability during the growing season, in conjunction with mean annual temperature. The employment of CMI in a diverse array of climate-related studies facilitates the integration of the effects of temperature and precipitation (e.g., Suzuki et al. 2006; Feddema 2005). The index is typically calculated as a ratio of the climatic water demand to the water supply within a specific area. It can be derived from commonly available data, such as annual mean temperature and annual total precipitation, and thus is suitable for long-term studies, since the moisture index accounts for the balance between inputs and outputs of water, and better accounts for the wetness of the land-surface than precipitation alone (Mather and Feddema 1986). The Thornthwaite moisture index (Thornthwaite and Mather 1955), in particular, has been widely used in studies of climate change and water resources (e.g. Karim et al. 2024; Leao 2014). A significant number of these studies have employed global circulation models to investigate moisture changes in response to anthropogenic greenhouse forcing, as well as to study possible shifts in vegetation types in response to a changing climate (Mather and Feddema 1986; Hodny and Mather 1995). Given that CMI integrates both precipitation and temperature effects, it serves as a superior predictor for Species Distribution Models (SDMs), particularly in regions where temperature-driven evaporation significantly influences plant survival (Hogg & Bernier 2005; Allen et al., 2010).

This study explores the use of the Climate Moisture Index (CMI) methodology proposed by Pereira and Pruitt (2004) which integrates both moisture and thermal factors, to predict the future fitness of an

urban tree population in response to climate change, with the overarching goal of identifying research directions necessary to develop sustainable urban tree populations that can deliver crucial ecosystem services under future climate scenarios. The Royal Botanic Gardens, Kew (RGB Kew) in London, UK, were selected as a case study site due to its representation of a large public park in a major city affected by the urban heat island effect. To further assess CMI as an indicator for evaluating the resilience of existing tree populations to future climates, its applicability is tested in evaluating the physiological drought tolerance of 27 tree species.

Methodology

Climate evaluation

This study employs the use of species distribution modelling (SDM) to evaluate the fitness of the tree collection in the arboretum at the Royal Botanic Gardens Kew (51° 28' 41.8728' N and 0° 17' 52.6344' W) under future projected climate scenarios. The chosen variables used for this study is Thornthwaite's Climatic Moisture Index (CMI) and mean annual temperature (MAT). CMI is the index of the degree of water deficit below water need, a metric of relative wetness and aridity while MAT determines the length of the growing season. The utilization of Thornthwaite's Climatic Moisture Index (CMI) offers valuable insights into assessing climate change impacts on ecosystems, where Grundstein (2009) highlights the importance of the moisture index in capturing the balance between water inputs and outputs. This approach provides a more comprehensive understanding of land-surface wetness compared to solely relying on precipitation data.

Through calculation of CMI it is possible to view the water balance over the year where loss of water through evapotranspiration is compared with precipitation. In calculating potential evapotranspiration, the regression presented by Thornthwaite (1948) was used, with monthly potential evapotranspiration based on the values of temperature, number of sunshine hours per day, water runoff, and cloudiness. The potential evapotranspiration (or reference evapotranspiration, mm per month) for a typical month of 30 days with a 12-h photoperiod/day was modeled with an average temperature (T , °C) using the scheme proposed by Thornthwaite (1948) and modified by Pereira and Pruitt (2004) as:

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

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

$$I = \sum_{n=1}^{12} (0.2T_n)^{1.514}, \quad T_n > 0^\circ\text{C}$$

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

For temperatures above 26 °C, the equation of Willmott et al. (1985) was used, in which ET_M is represented as:

$$ET_M = -415.85 + 32.24T - 0.43T^2, \quad T > 26^\circ\text{C}$$

In order to convert the estimates from a standard monthly (ET_M , mm per month) to a daily time scale (ET_D , mm per day), the following correction factor (C) was used:

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

where N is the photoperiod (h) for a given day.

Estimates of water run-off for the study site (RBG) were based on P90 (2004) with an assumed 10 % run-off.

To further communicate and understand RBG Kew future climate scenarios we extracted the data using the Terra Package – R Spatial (Hijmans, 2021), used for spatial data analysis with vector (points, lines, polygons) and raster (grid) data which includes models for spatial prediction, including satellite remote sensing data.

The above methodology was used to form a data set for the current and projected conditions. The projection of the future climate is complex with the uncertainty which are dependent on different possible scenarios caused by human activity and how this relates to the interaction with global emissions (Nazarenko et al. 2022). The Shared Socioeconomic Pathways (SSPs) are scenarios used in climate change research to explore future societal and economic conditions, which in turn influence greenhouse gas emissions and other drivers of climate change (Fig. 1).

A seminal report issued by the Copernicus Climate Change Service (C3S), managed by the European Centre for Medium-Range Weather Forecasts on behalf of the European Commission and funded by the EU, meticulously monitored critical climate indicators over the course of the year. The report, published in (C3S, 2023), unequivocally asserts that 2023 emerged as the hottest year on record, with global temperatures nearing the critical 1.5-degree Celsius threshold stipulated in the Paris Agreement of 2015 (C3S, 2023). This alarming revelation underscores the pressing need for comprehensive climate action to mitigate the adverse effects of global warming and uphold the objectives outlined in international climate accords. In response to the profound implications of the C3S findings, this research study harnesses future climate projection datasets based on the Shared Socioeconomic Pathway 3 (SSP3). By leveraging these datasets, the study endeavours to analyse potential future climate scenarios and their implications for the tree collection at RBG Kew.

The climate modelling data was downloaded from the Chelsa dataset using a very high resolution (30', ~1 km) global downscaled climate data set currently hosted by the Swiss Federal Institute for Forest, Snow and Landscape Research WSL (Karger et al. 2017).

Mean annual temperature is calculated from Chelsa data base by using mean annual temperature climate data which is then projected to the SSP3 scenario. This is thereafter download from tif file in the R Terra

Package (Hijmans, 2021), where the longitude and latitude is used to find the projected mean annual temperature of 1980, 2020 and 2090

Tree drought evaluation

To test CMI as a strong indicator for evaluating the capacity of an existing tree population to cope with a future climate, we have chosen to evaluate the drought tolerance of 27 tree species and see how this matches with the CMI models. For drought tolerance evaluation we used water potential at turgor loss point (Ψ_{p0}) as a key trait for evaluating drought tolerance in different species of trees. Ψ_{p0} is a highly instructive trait, as it represents a quantifiable measure of physiological drought tolerance. More negative Ψ_{p0} values represent greater drought tolerance by allowing the leaf to maintain physiological function over a greater range of leaf water potentials (Sack and Holbrook, 2006; Lenz et al., 2006). Ψ_{p0} has also been demonstrated to differentiate a wide range of species and cultivars with respect to drought tolerance and has helped to inform plant species selection guidance for green infrastructure (Sjöman & Anderson, 2023). The current technique for determining Ψ_{p0} uses vapor pressure osmometry to predict osmotic potential at full turgor ($\Psi_{\pi100}$) and is sensitive enough to resolve differences in drought tolerance between closely related genotypes and provenances (Hannus et al., 2021; Hiron et al. 2021).

Plant material was taken from Royal Botanic Gardens, Kew, London, UK (51° 28' 41.8728" N and 0° 17' 52.6344" W). The trees used in the study were all trees established for over 10 years in unconstrained rooting space, growing in full sun or only subjected to short periods of partial shade, with no visual symptoms of stress indicating that the tree was fit for purpose within the climate being evaluated. Kew are considered to have a fully humid, oceanic temperate climate with a warm summer (Cfb of the Köppen–Geiger climate classification system; Kottek et al., 2006). A total of 27 different species were evaluated (Fig. 5). The number of replicates (number of individuals in the collection at Kew) varied among the species by 5–7 trees. The selection of species for the study was based on dendrological sources that described variations in tolerance (Bean 1980; Krüssman 1986; Dirr 2009). This

SSP1 (Sustainability)

Emphasizes the reduction of anthropogenic emissions. Focuses on transitioning to renewable energy sources. Prioritizes investments in education and healthcare. Aims for sustainable development and environmental stewardship. Represents a future where sustainability and environmental protection are key priorities.

SSP2 (Middle of the Road)

Reflects a continuation of historical trends in terms of emissions and environmental developments. Represents a scenario where there are no significant shifts towards sustainability or rapid development. Represents a "business-as-usual" trajectory where no major policy changes or global transformations occur.

SSP3 (Regional Rivalry)

Characterized by high radiative forcing, indicating high levels of greenhouse gas emissions and air pollutants. Features an expansion of cropland and a rapidly growing population. Investments in education and healthcare are limited. Reflects a future with regional disparities and conflicts over resources. Includes two variants: SSP3-7.0 and SSP3-7.0LOW, which represent different trajectories for near-term climate forcers.

Fig. 1. Shared socioeconomic pathways (SSP) are climate change scenarios of projected socioeconomic global changes up to 2100 as defined in the IPCC sixth assessment report on climate change on 2021.

was done in order to obtain a broad representation of both sensitive and tolerant tree species.

The methodology follows the protocol developed by Bartlett et al. (2012a). One sun-exposed branch with no symptoms of abiotic or biotic damage was collected from 5–7 individual trees of each selected species during early evening, when transpiration was low. Excised branches were immediately recut under water at least two nodes distal of the original cut and placed in a tube of water without exposing the cut surface to the air. Shoot material was then rehydrated overnight in a dark chamber with > 95 % relative humidity. After overnight rehydration, one leaf disc per leaf was taken from fully expanded leaves using an 8-mm cork borer. All discs were tightly wrapped in aluminum foil to limit condensation or frost after freezing. The foil-wrapped leaf discs were then submerged in liquid nitrogen for 2 min to fracture the cell membranes and walls. Next, the leaf discs were punctured 10–15 times with sharp-tipped forceps to allow evaporation through the cuticle and decrease equilibration time (Kikuta & Richter, 1992). Finally, each leaf disc was sealed in a vapor pressure osmometer (Vapro 5600, Westcor, Logan, UT, USA), using a standard 10 µL chamber. Initial readings of solute concentration (cs, mmol kg⁻¹) were taken after 10 min of equilibration time and then cs was recorded in repeated readings at ~2 min intervals while the value remained <5 mmol kg⁻¹. Solute concentration values were converted to osmotic potential (Ψ_{p0}) using the Van't Hoff's equation:

$$\Psi_{p0} = -RTc_s$$

where R is the gas constant, T is temperature in Kelvin, and cs is solute concentration in the leaf disc.

An equation developed by Bartlett et al. (2012b) allowing prediction of Ψ_{p0} from osmotic potential at full turgor ($\Psi_{\pi100}$) is based on a global dataset that includes data from tropical biomes. Since the present study was limited to the temperate biome, an equation developed by Sjöman et al. (2015) for deriving Ψ_{p0} from $\Psi_{\pi100}$ in temperate species, based on a subset (woody temperate, Mediterranean/temperate-dry and temperate conifer species) of the supplementary data provided by Bartlett et al. (2012a), was used here:

$$\Psi_{p0} = -0.2554 + 1.1243 \times \Psi_{\pi100}$$

This equation provided a higher coefficient of determination ($R^2 = 0.91$) than the Bartlett et al. equation ($R^2 = 0.86$), and therefore provided a more reliable means of predicting Ψ_{p0} .

Species distribution mapping

To further evaluate studied species matching with future climate scenarios we evaluate the conditions that these species are naturally distributed in where climate distribution models (CDMs) were used rather than species range maps on the grounds that CDMs allow for comparative studies to be carried out between species that are widely distributed. Presence records for each species were sourced from GBIF online database (www.gbif.org). The latitude and longitude points for the species is used to plot occurrences in CMI and MAT. Species distribution maps were created from the sampled populations, and scatter plots of the climate envelope for each species were created using the methodology of Watkins et al. (2020). The sampling and climate analysis were carried out in R v3.6.2 (R core team, 2019) using the dismo, ggplot2, raster and rgdal packages (Wickham, 2016).

Statistical analyses

To explore the relationship between the Climatic Moisture Index (CMI) and leaf water potential (Ψ_{p0}), a linear regression model was constructed using the lm() function in R. The dependent variable, Ψ_{p0} (MPa), was modelled as a function of the independent variable, CMI.cmi, to assess the impact of climatic moisture conditions on leaf water

potential across various tree species. The linear regression model was defined as:

$$\begin{aligned} \Psi_{p0}(\text{MPa}) &= 0 + 1\text{CMI} + \Psi_{p0}(\text{MPa}) \\ &= \beta_0 + \beta_1 \cdot \text{CMI.cmi} + \epsilon \end{aligned}$$

Where Ψ_{p0} (MPa) is the leaf water potential (dependent variable), CMI.cmi represents the Climatic Moisture Index (independent variable), β_0 is the intercept term, β_1 is the coefficient for the independent variable (CMI), and ϵ is the error term, assumed to follow a normal distribution with mean zero.

The model was fitted using the lm() function in R, which performs least squares estimation to minimize the sum of squared residuals. The output of the lm() function was summarized using the summary() function in R, which provides key information about the model's fit, including the coefficients, their standard errors, t-values, and p-values for hypothesis testing. To further assess the relationship between CMI and Ψ_{p0} , a scatter plot was generated, with CMI.cmi plotted on the x-axis and Ψ_{p0} (MPa) on the y-axis. The regression line was superimposed to illustrate the linear trend. The coefficients and p-value were annotated on the plot to provide a clear understanding of the model's results. To ensure the validity of the linear regression model, diagnostic checks were performed to assess assumptions such as linearity, homoscedasticity, and normality of residuals.

Results

Species distribution mapping

The data presented herein demonstrates a marked increase in both CMI and MAT from 1981 to contemporary values, with projections extending to the year 2090. For RBG Kew, the CMI has been calculated to be -50 in 1981, which, by 2090, is projected to reach -95, thus indicating a substantial increase. Similarly, MAT has been projected to rise by almost +5 °C, a phenomenon that will significantly impact total evaporation (Fig. 2). It is important to note that this calculation does not

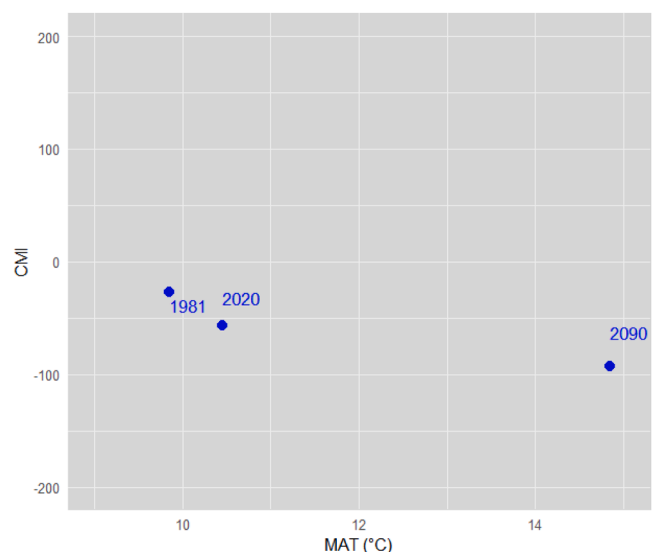


Fig. 2. Changes in Climatic Moisture Index (CMI) and Mean Annual Temperature (MAT) over time at RBG Kew. CMI represents the balance between precipitation and potential evapotranspiration, with lower values indicating increasingly dry conditions. MAT reflects the long-term average temperature. The plot 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.

include the UHI effect, which may further exacerbate conditions with a more negative CMI and an increased MAT.

In order to further evaluate the species studied and ascertain their correlation with the climate scenarios of RGB Kew, it is necessary to consider the conditions in which these species are naturally distributed. This will clearly show differences concerning its distribution of CMI and MAT. The species distribution maps presented in Fig. 3 were created from the sampled populations, presented through scatter plots of the climate envelope for each species. Studied species were found to be distributed across a range of environmental gradients, both between and within species. The species distribution maps presented illustrate species that are sensitive to drought and those that are more tolerant to drought - for a complete summary of the drought tolerance of studied species, see Fig. 5. The species distribution maps in correlation to changing climate conditions for RGB Kew demonstrate how more sensitive species have a more limited match with future climate scenarios, such as 2090. For *Acer platanoides*, *Carpinus betulus* and *Tilia x europaea*, there is a distribution concentration that includes a less negative CMI and a cooler MAT, thus demonstrating a poorer match with RGB Kew 2090. Conversely, *Carpinus orientalis* and *Koelreuteria paniculata* exhibited a considerably higher distribution concentration under the conditions of RGB Kew 2090, with a marginal match under the conditions of 1981 and 2020. These species require, or benefit from, significantly warmer growing conditions. It was demonstrated that each species exhibited multiple outlier populations, characterized by elevated levels of CMI or MAT. The identification of these outlier populations is of vital importance for species exhibiting extreme distribution patterns that closely align with the 2090 scenarios. In contrast, species with more concentrated distribution under these conditions are less accurate yet possess a greater margin of safety during the onset of extreme events, such as heat waves or prolonged droughts.

When evaluating the different species based on CMI only, it is evident that the suitability of different species for a future climate varies significantly (Fig. 4). For example, *Cercidiphyllum japonica*, shows a poorly adaptation to the present climatic conditions at RGB Kew. Projections indicate that its compatibility will be even more problematic by

the year 2090, as the climate become warmer and drier. On the contrary, *Platanus orientalis*, *Fraxinus angustifolia* and *Zelkova carpinifolia* shows greater capacity to adapt to a future climate scenario (Fig. 4).

Drought tolerance

The evaluation of drought tolerance based on the species Ψ_{p0} revealed a considerable range, from -4.56 MPa for *Koelreuteria paniculata* to -1.8 MPa for *Tilia x europaea* (Fig. 3). However, the data set from the study demonstrates a significant discrepancy between the various species of *Tilia*. *Tilia dasystyla* exhibit notable drought tolerance, with Ψ_{p0} values of -3.52 MPa, while *Tilia x europaea* and *Tilia cordata* exhibited the weakest drought tolerance, with Ψ_{p0} values of -1.80 MPa and -1.90 MPa, respectively indicating a significantly lower tolerance to drought.

Relationship between climatic moisture index (CMI) predicted leaf water potential (Ψ_{p0})

The linear regression analysis revealed a statistically significant relationship between the Climatic Moisture Index (CMI) and predicted leaf water potential (Ψ_{p0} , in MPa) across studied tree species. The model equation, $\Psi_{p0} = -2.643 - 0.00148 \times \text{CMI}$, indicates a negative slope ($\beta = -0.00148$), suggesting that as CMI decreases (i.e., conditions become drier), Ψ_{p0} becomes more negative, reflecting greater drought tolerance. This relationship is statistically significant ($p < 2.2 \times 10^{-16}$), although the explanatory power of the model is limited ($R^2 = 0.021$), indicating high variability among species. To explore this variation, we fitted species-specific regressions using mixed-effects models, allowing slope and intercept to vary by species (Fig. 6).

The results highlight substantial interspecific differences. Species such as *Fraxinus excelsior* and *Celtis occidentalis* exhibited strongly negative slopes, suggesting these species increase their drought tolerance (i.e., more negative Ψ_{p0}) as conditions become drier. In contrast, species like *Tilia cordata* and *Magnolia acuminata* showed flatter or

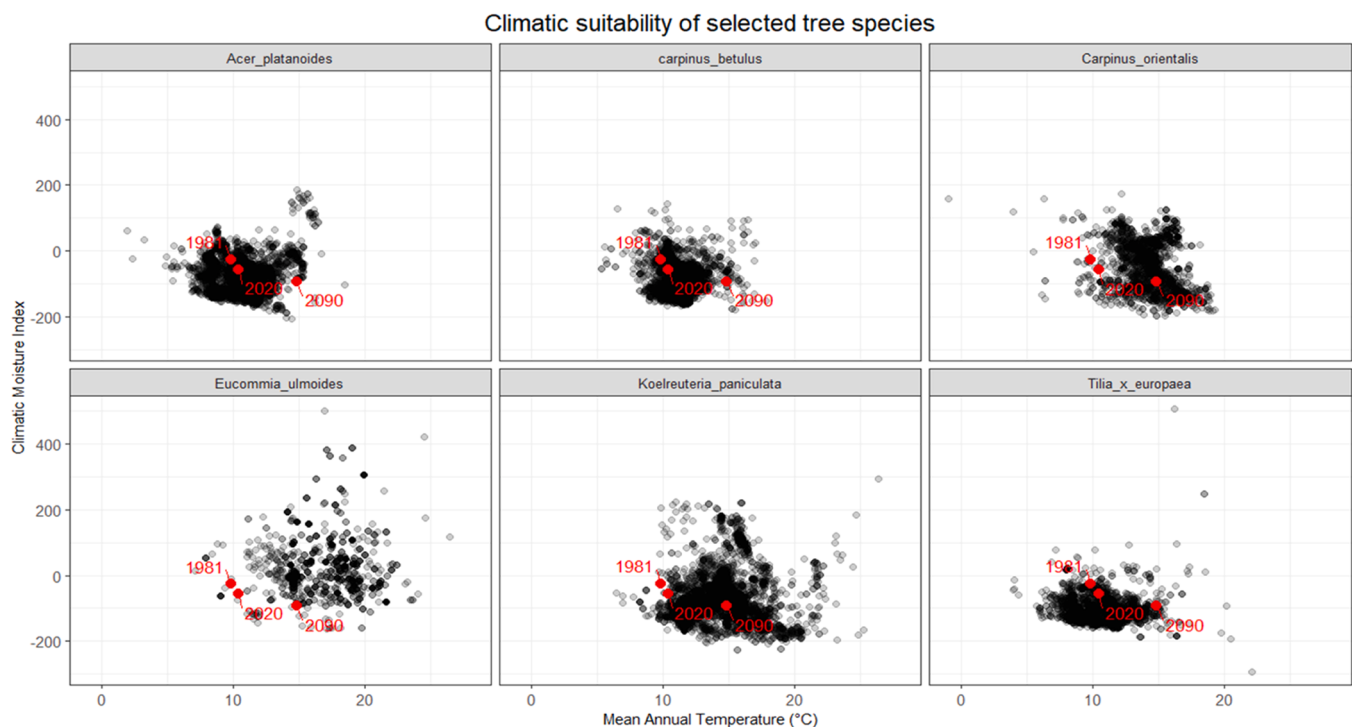


Fig. 3. Distribution of the Climatic Moisture Index (CMI) values for each species, providing further insight into the climatic suitability of selected species in the study. The CMI is a measure of the climatic moisture conditions at the species' locations, where positive values indicate higher moisture and negative values indicate drier conditions. The analysis excludes outliers to enhance clarity and focuses on the central distribution of CMI values for each species.

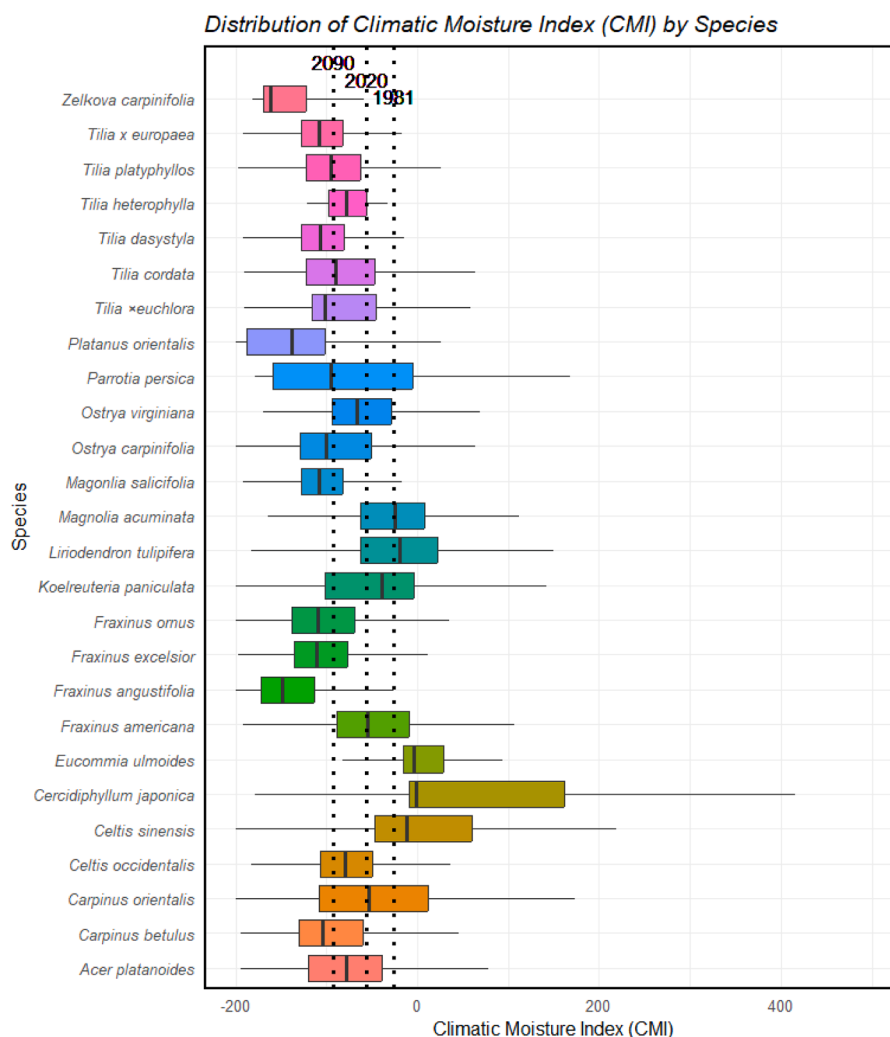


Fig. 4. Distribution of Climatic Moisture Index (CMI) values across 27 tree species. Each boxplot represents the range, interquartile range (IQR), and median CMI of occurrence records for each species, illustrating their climatic moisture tolerance. Vertical dashed lines mark the CMI values at a reference location for three time points: 1981, 2020, and projected 2090 (in black text). The shift of these reference points across time highlights changes in climatic moisture conditions relevant to species suitability under future climate scenarios.

even slightly positive slopes, indicating limited physiological adjustment to declining CMI and potentially greater vulnerability under drought stress.

These species-specific trends are especially relevant in the context of projected climate change. At the Royal Botanic Gardens, Kew, the climate is predicted to become warmer and drier, with Mean Annual Temperature (MAT) rising from 10.0 °C in 1981 to 14.6 °C by 2090, and CMI declining from −0.10 to as low as −0.80. Under these conditions, species with the capacity to maintain or increase drought tolerance as CMI declines such as *Fraxinus excelsior* may have a physiological advantage, while species like *Tilia cordata* may experience increased stress or reduced performance.

This analysis demonstrates the value of linking species-level hydraulic traits with climate indices. By incorporating both mean and species-specific slope responses into projections, it becomes possible to assess relative vulnerability or resilience under future climate scenarios and guide more informed tree selection and management in urban landscapes.

Discussion

The potential benefits of trees for human well-being and the urban environment are manifold. These include the regulation of temperature

through shading and transpiration (Rötzer et al., 2019; Zölch et al., 2018), the storage and sequestration of carbon (Davies et al., 2011), the regulation of the water balance in urban areas and the reduction of the risk of flooding (Medina Camarena et al. 2022), act as a filter for air pollutants (Klingberg et al., 2022), provide a noise and wind buffer (Roy et al., 2012), and serve as habitats for biodiversity and areas of human recreation (Kowarik et al., 2025). The extensive range of functions and services that urban tree plantations are capable of providing is of paramount importance for the development of resilience to future challenges. Consequently, the implementation of high-quality tree planting is a crucial factor. However, for the successful delivery of these ecosystem services, size and well-being remain fundamental factors. This underscores the significance of site tolerance, particularly in terms of drought tolerance, which enables trees to flourish under challenging conditions and attain their full potential in delivering these services and functions (Rötzer et al. 2019). In an extensive review by Xing et al., several examples emerged of assessments of urban tree populations and their capacity for a future climate. For instance, Esperón-Rodríguez et al. discovered that 53 % of the 1342 tree species in Australia experienced intolerable heat or moisture stress in their urban habitats, rendering them highly vulnerable to local climate conditions. Furthermore, Burley et al. (2019) identified a potential for a significant decline in more than 70 % of 176 native species in Australia under the projected climate

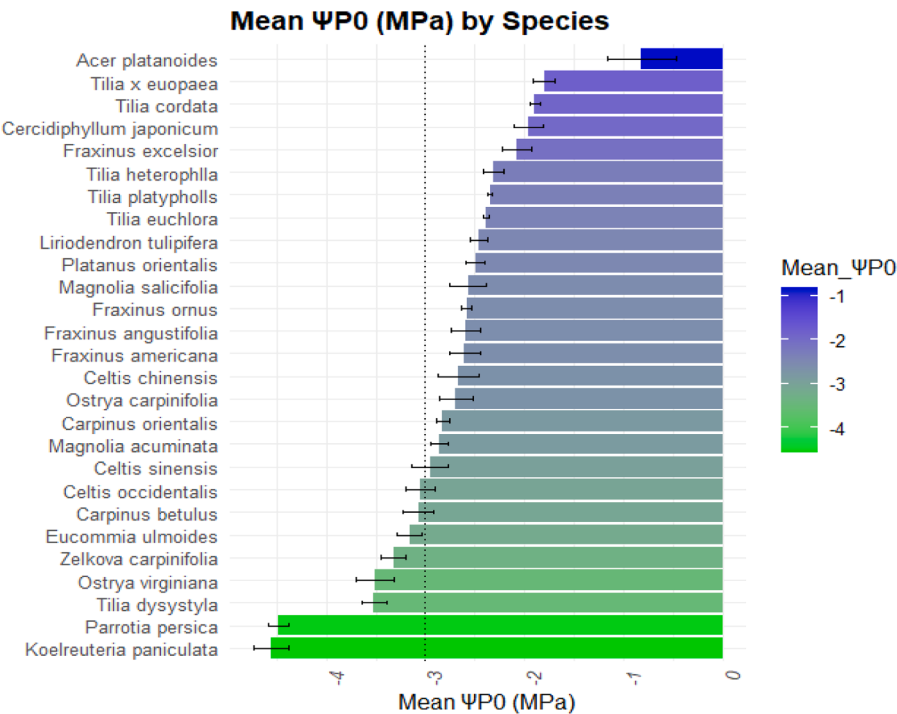


Fig. 5. Mean leaf turgor loss point of 27 tree species at Royal Botanic Garden Kew ranked by summer leaf turgor loss values (Ψ_{P0}) where an increasing negative value (MPa) indicate an increasing drought tolerance. The error bars represent the standard error of collected TLP data.

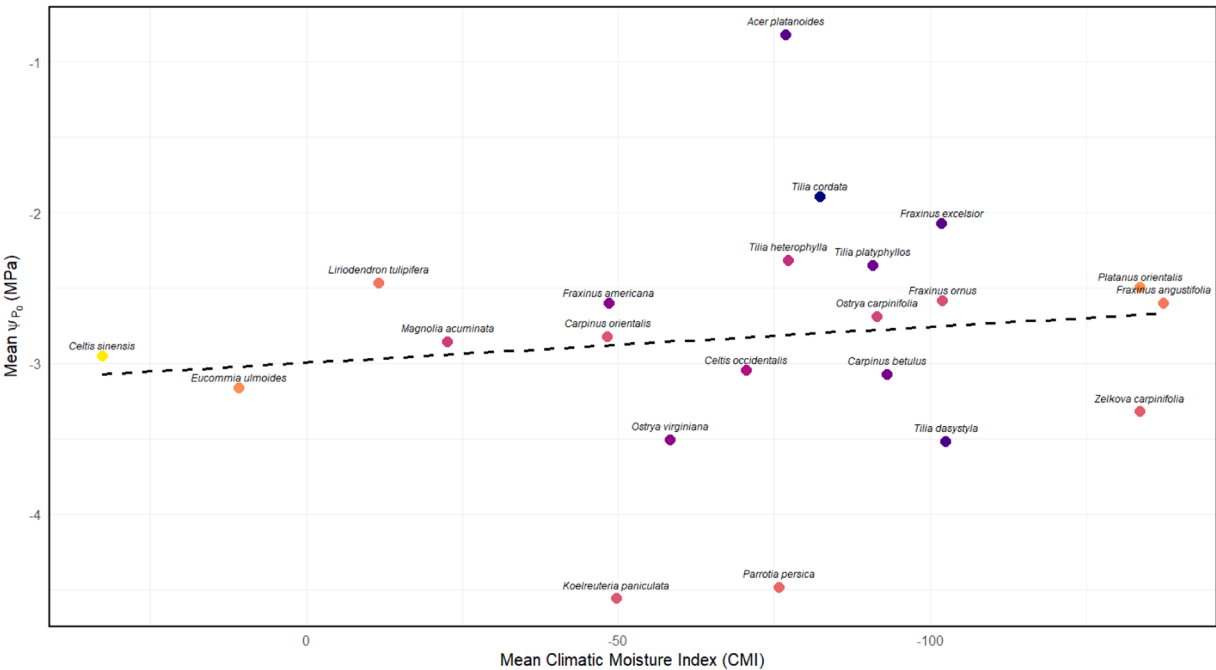


Fig. 6. Relationship between Climatic Moisture Index (CMI) and predicted leaf water potential at the turgor loss point (Ψ_{P0} , MPa) across temperate tree species. The linear regression line (dashed black) illustrates the overall negative trend indicating increased drought tolerance (more negative Ψ_{P0}) with decreasing CMI (drier conditions). Points represent species-specific mean values, labelled in italics. The model equation is $\Psi_{P0} = -2.643 - 0.00148 \times \text{CMI}$ ($p < 2.2 \times 10^{-16}$, $R^2 = 0.021$), highlighting significant but variable physiological responses to moisture availability among species.

period (2070) compared to the historical period (1960–90). Esperón-Rodríguez et al. conducted a comprehensive evaluation of the habitat suitability of over 16,000 plant species in global urban forests. Their findings revealed that over half of the species were residing in an urban climate that was not conducive to tolerating the prevailing temperature and precipitation conditions, and that these species would face an

increased risk in the future. These examples demonstrate the necessity to enhance our anticipation of the capacity of different species to adapt to challenging urban environments in conjunction with a changing climate. This is imperative, as a substantial proportion of existing urban trees may lack the capacity to persist in their current state and continue to provide essential ecosystem services.

The challenge of identifying which species possess the capacity to thrive in urban environments despite challenging growing conditions and a changing climate has been a subject of considerable interest (Kibria et al. 2024). This identification is of critical importance, as it is essential to plant the trees today in order to ensure the provision of functions and services in e.g. 2090, when they will have reached a size at which they can make a significant impact in a particular location. In this study, we have chosen to investigate the capacity and function of species distribution models (SDMs) as a screening tool for site matching between species distribution and drought tolerance. This is done through compare modelling with CMI as the primary factor with physiological drought tolerance of a wide range of tree species, with a representation between proven sensitivity and tolerance to drought. SDMs have become an essential tool in ecological and environmental research, particularly as climate change and environmental degradation continue to impact species distributions. These models offer valuable insights into the potential invasiveness of species (Thuiller et al., 2005), the influence of climate change on species' range shifts (Thuiller, 2004; Hijmans & Graham, 2006; Morin & Thuiller, 2009), and the relative importance of environmental predictors in determining range boundaries (Glor & Warren, 2011). Additionally, SDMs have proven crucial in historical reconstructions of species distributions (Svenning et al., 2011), conservation applications for identifying suitable habitats for reintroductions and understanding broad-scale patterns of species richness. A key strength of SDMs lies in their ability to predict how species distributions may shift in response to climatic changes. By simulating past species ranges, researchers can gain a deeper understanding of the ecological history and factors that have shaped species' current distributions.

A significant aspect of the development and utilisation of SDMs relates to the factors that ought to or are required to be incorporated, as these factors are instrumental in determining the strength, validity and accuracy of the models. In this study, CMI was employed as the primary factor to facilitate a more comprehensive evaluation of water budgets, thereby enabling precise determination of the ecological niches of trees and their responses to climate warming. This approach is particularly salient in the context of climate change, which has the potential to exert a substantial influence on the water cycle (Holsten et al., 2009). Furthermore, Guisan et al. (2017) and Mod et al. (2016) demonstrated that the selection of variables based on expert knowledge, as opposed to an automated selection from a multitude of predictors, can result in enhanced predictive capabilities and a more profound reflection of biological and ecological understanding. This is particularly evident in fine-scale studies, such as the selection of specific tree species for urban environments. As Araújo and Guisan (2006) further emphasise, greater emphasis should be placed on the relative weight (explanatory power) of each predictor or factor, including SDM models. Favorable growth of trees is very much connected to site tolerance, whereby stressors exert a detrimental impact on trees when they are engaged in the acquisition of essential resources. This is particularly evident in instances where photosynthetic capacity is significantly compromised under conditions of elevated temperatures and low humidity which is showed in two studies in Japan and China demonstrating a reduction in photosynthetic activity during periods of elevated temperatures and low humidity (Wang et al., 2020). Furthermore, the presence of impervious ground covers in urban environments intensifies these challenges by elevating surface and air temperatures while reducing humidity, thereby impeding photosynthetic activity in urban trees (Wang et al., 2020). In a related study, Martínez-Sancho et al. (2022) sought to enhance our comprehension of the intricate physiological processes and structural adaptations associated with tree water use and photosynthetic capacity. The study employed a tree-centered approach to accurately identify the onset and severity of physiological drought. The study revealed that a reduction in wood-forming capacity, as indicated by alterations in wood structure, led to a considerable decline in stored carbon by 67 % during drought periods in comparison to typical years. This finding emphasises the substantial influence that drought-induced constraints exert on

photosynthetic capacity and indirect growth rate in trees, while also underscoring the intricate dynamics of urban forest ecosystems under stress (Martínez-Sancho et al., 2022). It is therefore evident that water stress represents a significant factor capable of impeding urban tree growth (Meineke and Frank, 2018). When temperatures exceed the species-specific thermal limits and extreme events, such as droughts, become more frequent and intense, adverse effects on tree growth can be observed (e.g. Nitschke et al., 2017; Bialecki et al., 2018) which makes drought tolerance one of the most important factors to include when selecting urban trees for ecosystem services in a future climate. By clarifying the input and output of water into the trees growing environments and distribution a clear insight into the water budget and the species' capacity to manage this can be visualized making CMI a strong factor. In order to calculate CMI, the Thornthwaite formula was selected to compute the water balance for the periods 1980, 2020 and 2090. This is due to the fact that they are among the most commonly used methods and require a limited number of parameters for the studied area (Lutz et al., 2010). The formulae allow estimation of monthly fluctuations in water content driven by precipitation (P) and potential evaporation (PET). The study indicates an augmentation in the negative water budget for RBG Kew from the present situation to 2090, signifying that PET exceeds P in conditions of significant aridity. This suggests that the utilisation of more drought-sensitive species may become increasingly challenging for effective development.

A frequently described limitation of SDM models is the use of the natural range of a species to evaluate its capacity to cope with a future climate, which does not provide a comprehensive overview of the other climates in which the species could successfully evolve in (Booth 2024). Using only the current distribution creates only recent visualisation and may miss the capacity of species beyond these conditions (Pecchi et al., 2019). In this study, we have utilised distribution data from the Global Biodiversity Information Facility (GBIF), which not only records species' natural distribution, but also data connect to their existence outside their natural distribution. This additional information can provide significant indications of their occurrence in climates beyond their natural distribution (Booth 2024; Pecchi et al. 2019). However, it should be recognised that records of more unusual species in GBIF may provide a very limited image of the capacity of different species under different climates, which may provide a weakened picture for those species with a low occurrence of records in GBIF. This limitation becomes particularly problematic when analysing less common or unconventional species, such as those in the screening of its capacity for a future climate. In Fig. 3 it is evident that a more reliable representation of the respective species' capacity to withstand hot and dry conditions is provided by *Carpinus betulus*, as evidenced by the greater number of documented records. In contrast, *Eucommia ulmoides*, due to its rarity, may potentially compromise the reliability of the data, resulting in a less robust and more ambiguous assessment of its heat and drought tolerance. In this scenario, these species risk being de-prioritised in continued selection work for trees for a future climate due to the limitation of registrations, and we may miss strong candidates. In order to create a more comprehensive picture of the capacity of different species to develop successfully outside their natural range, including more unconventional species, it is very important to evaluate different botanical plant collections. Botanical gardens and arboreta typically possess comprehensive databases that meticulously document the long-term development and provenance of various plant species. This is of paramount importance when assessing the capacity of different species. Another salient nuance in evaluations of this nature is the necessity of an understanding of intraspecific variation, for example in relation to drought, where considerable variation exists within a single species (see Hannus et al. 2021; Hirons et al. 2021). Today, there are numerous examples of attempts to categorize or scoring the capacity of different species for challenging urban growing environments and future climate situations using various scoring systems (e.g., Roloff et al. 2009; Royer-Tardif et al. 2021). In these compilations, species are treated as a collective mass, rather than acknowledging the

intraspecific variation that is evident within the different species. In order to select trees for specific cities with greater accuracy, it is necessary to be much more detailed in order to identify the unique genetic material that has the best possible capacity for the site and the area. An illustration of this phenomenon can be found in [Martin and Sjöman \(2025\)](#), wherein CMI was utilised to assess the capacity of five distinct tree species for RGB Kew under prospective climate scenarios. The climate in Altamira, Spain, exhibits greater similarity to Kew 2090 ([Fig. 7](#)), signifying that plant material from this region ought to be evaluated presently. This evaluation should be extended to several other cities, encompassing the assessment of contemporary genetic material in cultivation and the necessity for its update ([Sjöman & Watkins 2020](#)).

In this study we wanted to assess the applicability of CMI models in predicting the capacity of different tree species to thrive in a changing climate at a specific location. For this we wanted to test the relationship between CMI models and the physiological drought tolerance of 27 tree species through evaluation of the water potential at turgor loss point (Ψ_{p0}) as a key trait for evaluating drought tolerance. The observed relationship between CMI and Ψ_{p0} in this study has significant implications for understanding tree physiology under varying climate scenarios. Leaf water potential is crucial for assessing a tree's water status, which directly influences its ability to maintain essential physiological functions like photosynthesis and transpiration even under drought stress ([Laughlin 2023](#)). It is known that species with low (more negative) Ψ_{p0} values tend to maintain leaf gas exchange, hydraulic conductance, and growth at lower soil water potential (Ψ_{soil}); therefore, they are at an advantage when soil water deficits occur during the growing season. The Ψ_{p0} value also acts as a surrogate for the critical Ψ_{soil} value below which the plant cannot recover from wilting ([Bartlett et al. 2012a](#)). It is also related to leaf and stem conductivity, which are hydraulic traits reflecting drought impacts on the water supply for transpiration and photosynthesis ([Bartlett et al. 2012a](#)). Therefore, Ψ_{p0} is a trait that

provides information about the capacity of a species for growth in dry environments and is particularly relevant for urban environments characterized by restricted soil volumes and impermeable surfaces ([Sjöman et al. 2015](#)). It is of significant interest as a quantifiable measure of drought tolerance, and species with lower values (i.e., with a greater tolerance to drought) are more likely to survive in challenging sites and have a greater ability to deliver the ecosystem services sought by urban forest professionals. Understanding which species are more vulnerable to water stress can also guide the selection of species for reforestation projects, particularly in areas that are projected to become drier or experience more variable rainfall. This research likewise provides valuable insights into which species may be at greater risk due to climate change, informing conservation strategies aimed at protecting vulnerable species.

While this study provides valuable insights, several limitations should be considered. The linear model assumes a constant relationship between CMI and Ψ_{p0} , which may not fully capture more complex, non-linear interactions between climatic moisture conditions and tree physiology. Future research could explore non-linear models or include additional environmental variables, such as temperature or soil moisture, to better reflect the complex nature of tree responses to climate. Expanding the study to include a wider range of species and geographic areas would also help to improve the generalizability of the findings. Longitudinal studies would be particularly useful for examining how the relationship between CMI and Ψ_{p0} evolves over time, especially in the context of ongoing climatic shifts.

Conclusion

As climate change accelerates, urban tree selection must be guided by evidence-based approaches that ensure resilience to future conditions. This study demonstrates the value of integrating Species

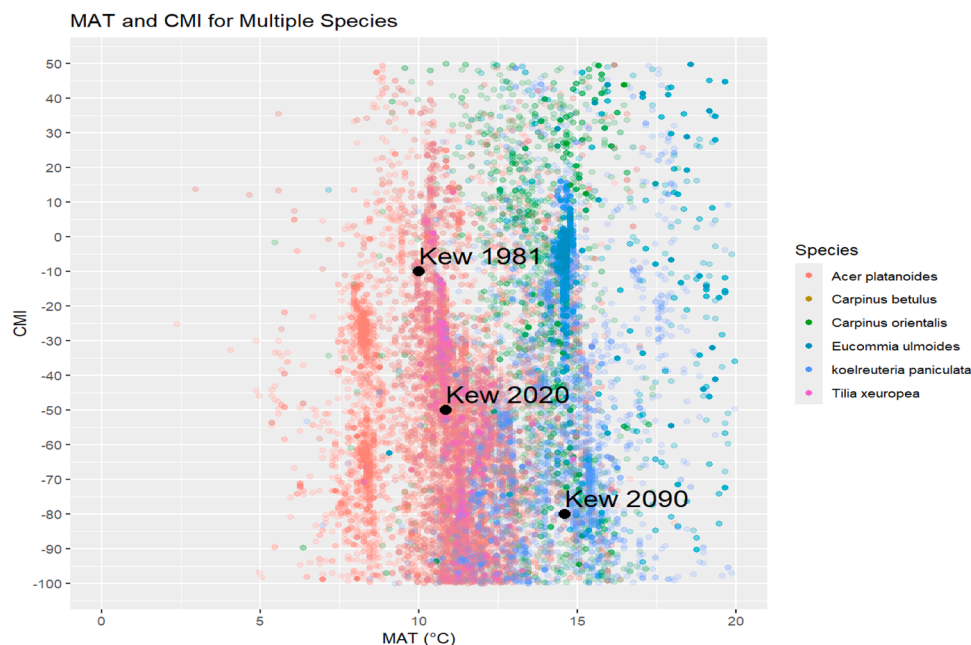


Fig. 7. Mean Annual Temperature (MAT) and Climatic Moisture Index (CMI) for six urban tree species presented in [Martin and Sjöman \(2025\)](#). This scatter plot illustrates the relationship between mean annual temperature (MAT, °C) and climatic moisture index (CMI) for six tree species currently cultivated at the Royal Botanic Gardens, Kew: *Acer platanoides* (red), *Carpinus betulus* (brown), *Carpinus orientalis* (green), *Eucommia ulmoides* (turquoise), *Koelreuteria paniculata* (blue), and *Tilia × europaea* (pink). Each point represents a species occurrence location, overlaid with its corresponding MAT and CMI values based on high-resolution (30 arc-second) CHELSA v2.1 climate data ([Karger et al., 2017, 2021](#)). Climate data points for Kew are marked for three time periods—historical (1981), present-day (2020), and future (2090)—to illustrate projected climate trajectories under the SSP3–7.0 scenario using ensemble means from six CMIP6 global climate models (GCMs). SSP3–7.0 represents a high-emissions, regional rivalry pathway characterized by limited climate mitigation and adaptation efforts. This visualisation provides insight into the climatic niches of these species relative to past, present, and projected future conditions at Kew, supporting climate-informed tree selection and urban forestry planning.

Distribution Models (SDMs) with physiological drought tolerance traits to predict species suitability in urban environments. By using CMI as a key predictor, we identified species with high drought resilience, providing a framework for selecting trees that can sustain ecosystem services under increasing climatic stress.

Our findings underscore the importance of physiological traits, such as pre-dawn leaf water potential (Ψ_{p0}), in validating SDM predictions. The strong correlation between CMI-based habitat suitability and drought tolerance metrics emphasizes the need to integrate macro-climatic data with species-specific functional traits for urban forestry planning.

Future research should refine SDM predictions by incorporating microclimatic factors, urban heat island effects, and soil moisture availability, alongside experimental validation of tree performance in urban settings. By integrating ecological modeling with plant physiology, we can enhance urban tree selection strategies, ensuring that species planted today will thrive in the cities of tomorrow.

CRedit authorship contribution statement

Kevin W E Martin: Writing – review & editing, Writing – original draft, Visualization, Validation, Software, Resources, Methodology, Investigation, Formal analysis, Conceptualization. **Henrik Sjöman:** Writing – review & editing, Writing – original draft, Methodology, Investigation, Formal analysis, Data curation, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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