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Time to Adapt Urban Trees of European Cities in Response to Climate-Driven Changes

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Abstract

Urban trees mitigate climate impacts, but their long-term suitability under future climates remains poorly quantified at the city scale across Europe. We combine published tolerance limits with kernel density estimation-derived thresholds from urban species occurrence records to build climate envelopes for the 26 most common European urban tree species. These climate envelopes are applied to CHELSA climate projections for multiple periods until 2100 under SSP1-2.6, SSP3-7.0, and SSP5-8.5 to assess changes in climatic suitability and species persistence across 1,165 European cities. Results reveal strong and geographically differentiated shifts: many cities in Central and Southern Europe are projected to lose suitable species, with reductions of up to 46% of their municipal tree inventories, whereas cities in Northern and parts of Western Europe gain climatic suitability and access to a broader pool of species. Our city-level projections provide a robust basis for climate-adaptive urban tree planning and policy development across Europe.

Introduction

Urban trees are increasingly exposed to climatic stress as global warming accelerates (Hansen et al. 2025, IPCC 2022), especially in Europe (C3S 2025). Rising temperatures (Friesen & Taubenböck, 2025), shifting precipitation regimes (André et al. 2024), and more frequent extreme weather events (IPCC 2021) already challenge their vitality. As urban forests or trees are also exposed to more severe conditions compared to natural forests (Esperon-Rodriguez et al. 2022, Franceschi et al. 2023), the expected changes are particularly challenging for European cities. Reduced soil aeration and impaired belowground activity limit nutrient and water uptake, while urban trees generally develop smaller and less fine-rooted systems than their forest counterparts (Day et al. 2010, Jim 2023). Due to a usually high share of impervious surfaces surrounding urban trees, water and air exchange between the soil and the atmosphere is severely restricted. Furthermore, the groundwater level in cities is often lowered (Giglou et al. 2023, Zhou et al. 2024) due to drainage systems, construction activities, and drinking water extraction, which leads to faster drought stress (Franceschi et al. 2023). The increased temperature in urban areas due to the urban heat island (UHI) effect (Oke 1982; Iungman et al. 2024) leads to a higher tree water consumption (Ji et al. 2024, Klein 2014). In addition, urban trees are negatively impacted by elevated radiative temperatures from impervious surfaces and building facades, which exacerbate heat stress, as well as by increased exposure to air pollutants (Livesley et al. 2016).

At the same time, city trees provide essential ecosystem services that mitigate the negative impacts of urbanization and climate change, making their preservation critical for sustainable cities (Rahman et al. 2024, Rötzer et al. 2021). They filter pollutants, bind particulate matter, and store carbon (Blanusa et al. 2015, Livesley et al. 2016). Through shading and evapotranspiration, they reduce ambient temperatures (Li et al. 2025, Livesley et al. 2016), regulate humidity, improve stormwater retention, and stabilize the urban microclimate and water balance (Berland et al. 2017, Ow & Gosh 2017). Urban trees also support biodiversity and promote human health and well-being (Ren et al. 2022, Giacinto et al. 2021, Yao et al. 2022).

To preserve these functions under future climate conditions, urban planning require species selection strategies grounded in reliable projections of climatic suitability. In forest science, ecological niche modelling approaches are widely used to assess future species distributions (Dyderski et al. 2018, Illés & Móricz 2022, Mauri et al. 2022). These methods aggregate average climatic conditions across known occurrences in forests to delineate species-specific niches and predict future range shifts (Martes et al. 2024, Wesseley et al. 2024, Heubel et al. 2025). However, occurrences in managed forests often reflect silvicultural practices rather than natural climatic tolerances, creating mismatches between observed and potential ranges (Leuschner & Ellenberg 2017). Moreover, urban environments impose additional stressors and constraints (see above; Roloff 2016), limiting the transferability of forest-based species assessments to cities. For these reasons, climate-envelope models remain an appropriate framework for

estimating climate-driven changes in urban tree suitability (Fäth et al. 2025), provided that both fundamental and urban-realized climatic tolerances are considered (Esperon-Rodriguez et al. 2022).

Despite growing attention, Europe still lacks a consistent, continent-wide and city-specific assessment of future climatic suitability of widely planted urban tree species that integrates urban distribution data, physiological tolerance ranges from literature, and climate projections.

This study addresses this gap by evaluating the future climatic suitability of the 26 most common urban tree species in Europe. Combining urban occurrence records and published climatic tolerance limits, we construct combined climate envelopes to project future suitability across 1,165 European cities through 2100 (Fig. 1). The analysis treats cities as single units rather than conducting intra-urban spatial predictions. By integrating municipal tree inventories for ten cities, the study additionally assesses potential future shifts as well as long-term persistence in urban tree species pools. Overall, this work provides an evidence base for climate-adaptive urban forest planning and long-term ecosystem resilience under changing climatic conditions. In this study we do not model the ecological niche in the classical Hutchinsonian sense, but a climatic feasibility space derived from observed occurrence and published tolerance limits, hereafter termed climate envelope.

Results

Persistent suitability of urban tree species

The results highlight substantial long-term suitability losses for a broad set of commonly used urban tree species under higher emission scenarios. Figure 2 presents the persistent climatic suitability of each species until 2100 across the emission scenarios SSP1-2.6, SSP3-7.0, and SSP5-8.5, distinguishing between the extended (yellow) and core (green) envelopes. Suitability follows a bottleneck approach (Wessely et al. 2024), meaning that species must remain climatically suitable across all three time periods. We find that one consistent gradient appears across all scenarios: SSP1-2.6 maintains comparatively large shares of suitable cities, often exceeding 40%. Under SSP3-7.0, these fractions drop markedly, accompanied by a rise in partly suitable and unsuitable areas. SSP5-8.5 amplifies these trends further, with many species showing high proportions of unsuitable cities even when some suitability occured in earlier periods. Nearly all tree species display strong declines in suitable areas from SSP1-2.6 to SSP3-7.0 and even more pronounced reductions under SSP585.

In contrast, more heat-tolerant taxa, including *Robinia pseudoacacia, Quercus robur, Quercus petreae, Populus nigra, Populus tremula, Aesculus hippocastanum, Acer pseudoplatanus, Alnus glutinosa, Platanus L*, retain at least for 20% of the cities a suitable share, although even these species show narrowing persistence under SSP5-8.5. Figure 2b, which also evaluates the extended envelope (yellow part) per city, mirrors the same overall patterns with systematically higher suitability compared to Fig. 2a. Here, similarly, a systematic contraction of climate-robust habitat is observed.

Geographic shifts in species suitability

Across the European continent, the spatial pattern of suitability change differs strongly between emission scenarios and envelope definitions (Fig. 3). Under SSP1-2.6, gains and losses are spatially heterogeneous, whereas SSP5-8.5 is dominated by losses, particularly in Central and Southern Europe, with substantially larger magnitudes of change and a pronounced north–south gradient. Considering the extended envelope, SSP1-2.6 still allows locally stable or positive changes in Northern and parts of Eastern Europe, while southern regions already decline. Under SSP5-8.5, most cities experience losses, indicating a contraction of climatically suitable species pools although the northeast still shows

gains. The core envelope shows a stronger response and most European cities lose suitability, indicating a rapid loss of optimal climatic conditions, with limited gains remaining mainly in Northern and Northeastern Europe.

Overall, the results indicate a northeastward redistribution of suitability rather than a uniform decline, with northern cities acting as relative refugia while cities in Central and Southern Europe undergo widespread reductions in the number of suitable species. The course of each of the three time periods is shown in Supplementary Information Figures S1 and S2.

Net changes in urban species pools

Under SSP1-2.6, the distribution of net changes in climatically suitable tree species per city remains narrow and concentrated around zero (Fig. 4). Most cities gain or lose one to five species, and large shifts are virtually absent. The overall pattern indicates that net changes remain small and that gains and losses tend to offset each other. This suggests that the low-emission pathway preserves a relatively stable balance of suitable species across the European continent, even when individual cities experience minor adjustments.

Under SSP5-8.5, the structure of the distribution changes fundamentally. The magnitude of losses and gains is increasing, and the side of species losses becomes dominant. The number of losses reaches up to 20 species. Species gains continue to occur, but they are limited to a small group of cities and remain low in magnitude. The resulting distribution is strongly asymmetric and shows that the high-emission pathway does not simply reduce average suitability across Europe. Instead, it introduces a structural imbalance where losses vastly outweigh gains in the investigated species pool. This imbalance reflects a complete breakdown of the equilibrium observed under SSP1-2.6 and signals a fundamental shift in the climatic capacity of cities to sustain diverse tree species.

These distributions reveal aspects of climate impacts that do not appear in the temporal trajectories alone. Although average trends show that many species decline toward the end of the century under SSP5-8.5, the histograms make visible how unevenly these declines are distributed across cities (also see Fig. 3). Some cities remain relatively stable despite high-emission conditions, while others experience disproportionately large reductions in suitable species. A similar pattern emerges when considering only the core envelope (Fig. 4b). While the magnitude of both gains and losses is generally smaller compared to the extended envelopes, the overall structure of the distributions remains consistent. Under SSP1-2.6, most cities experience only minor net changes regarding the surveyed species pool, indicating a largely stable climatic suitability for the core envelope of many tree species. In contrast, SSP5-8.5 again produces a clear asymmetry, with losses exceeding gains in a large proportion of cities. The comparison therefore highlights that SSP5-8.5 leads not only to an overall contraction of suitable species pools but also to an increasing disparity between cities in the severity of climatic constraints.

Changes in municipal tree inventories

In the previous analyses, we considered the full set of 1,165 cities included in our dataset. Here, we focus on ten representative cities for a more detailed evaluation. Using official municipal tree registries, we re-examined the species covered in our study regarding the absolute number of trees per city. These cities span the European continent from Helsinki in the northeast to Valencia in the southwest and capture a broad climatic and biogeographic gradient. We first quantified the proportion of trees in each municipal registry that fall within the set of species included in our analysis. The coverage varied markedly across cities. Approximately 65% of Berlin's recorded trees are represented in our species list, whereas only about 7% of Valencia's registered trees are addressed. We then assessed how well our model-based climatic tree species suitability for 2011–2040 aligns with observed occurrences in the municipal tree

inventory, serving as a city-specific plausibilisation of the approach (Tables S8 and S9). Table 1 contains two complementary evaluation strategies. As a “best-case” scenario, we used SSP1-2.6 in combination with the extended envelope definition (yellow). In a second and highly strict approach, we applied SSP5-8.5 together with the core envelope (green). The extended envelope scenario yielded substantially higher plausibilisation rates, reflecting the broader range of permissible temperature–precipitation combinations and the larger climatically suitable area under this scenario. The stricter core envelope approach revealed that actual urban species distributions extend beyond the limits suggested by combined presence data and published tolerance limits.

Table 1

Plausibilisation and projected changes in municipal tree inventories for ten focal cities by 2100. Overview of total tree number in recent inventories, plausibilized species counts for 2011–2040, projected losses, and remaining trees by 2100 under SSP1-2.6 + extended ("best-case scenario") and SSP5-8.5 + core ("worst-case scenario") conditions. Values indicate the number of trees expected to persist climatically suitable, the number lost, and the corresponding percentage loss per city.

Berlin	Total number of trees in inventory	Emission scenario and envelope approach	Number of trees from plausi- bilized species for 2011–2040	Number of trees lost by 2100	Number of persistent trees by 2100	Percentage lost by 2100
	835473	**SSP1-2.6 extended**	**540159**	**0**	**540159**	**0.0**
		SSP5-8.5 core	410656	317570	93086	38.0
Bordeaux	59205	SSP1-2.6 extended	20127	2885	17242	4.9
		SSP5-8.5 core	13201	7138	6063	12.1
Frankfurt	161791	SSP1-2.6 extended	97286	570	96716	0.4
		SSP5-8.5 core	94650	75218	19432	46.5
Helsinki	48082	SSP1-2.6 extended	22040	1	22039	0.0
		SSP5-8.5 core	20516	157	20359	0.3
Innsbruck	13525	SSP1-2.6 extended	8303	0	8303	0.0
		SSP5-8.5 core	8056	113	7943	0.8
London	889936	SSP1-2.6 extended	538374	0	538274	0.0
		SSP5-8.5 core	522487	148114	374373	16.6
Paris	202338	SSP1-2.6 extended	107401	70	107331	0.0
		SSP5-8.5 core	105073	39074	65999	19.3
Valencia	152314	SSP1-2.6 extended	11245	10674	571	7.0
		SSP5-8.5 core	0	0	0	0.0
Vienna	226666	SSP1-2.6 extended	133243	0	133243	0.0
		SSP5-8.5 core	125864	97565	28299	43.0
Würzburg	43769	SSP1-2.6 extended	25785	0	25785	0.0
		SSP5-8.5 core	23881	10437	13444	23.9

Figure 5 shows these results for each of the your possible variants. Under SSP1-2.6 with the extended envelope definition, almost no tree loss is expected in the validated species pool per city. The highest projected losses occur in Valencia with 7% and Bordeaux with 5%, the two southernmost cities in our analysis. All other cities retain their validated tree species pools. This pattern also holds under the core envelope definition, although the number of unvalidated trees increases when the more restrictive envelope concept is applied. A pronounced shift emerges under the SSP5-8.5 scenario. Across both envelope definitions, cities are projected to lose a substantial share of their current trees. Under the core envelope concept, Berlin may lose 38% of its validated trees, Vienna 43%, and Frankfurt 46%. Although losses are smaller when the less strict extended envelope is used, reduction in the numbers of tree species remains considerable, typically between 10 and 20%.

Discussion

Time to adapt. This phrase captures the central tension emerging from our results. Under low-emission pathways, European cities still retain a temporal buffer in which climatic suitability for many common urban tree species remains largely intact, allowing for gradual and proactive adaptation. Under high-emission conditions, however, this window narrows rapidly. Climatic constraints intensify, suitability contracts, and adaptation shifts from a strategic choice to an urgent necessity. Our analysis reveals a coherent picture of accelerating climatic constraints on urban trees across Europe, with marked differences considering the different emission pathways and latitude. Across the full set of 1,165 cities, climatic suitability declines systematically from SSP1-2.6 to SSP3-7.0 and becomes most pronounced under the SSP5-8.5 scenario. Many species that remain fully suitable across large fractions of Europe in the coming decades under SSP1-2.6 experience a strong reduction in suitable areas under SSP3-7.0 and a widespread transition to unsuitability under SSP5-8.5. Even when extended climatic envelopes are considered, the overall contraction of habitat remains substantial. Only a comparatively small group of heat- and drought-tolerant species retains persistent suitability in at least one fifth of the cities, even within the set of 26 species examined in this study. These system-wide trends are accompanied by strong reductions in the number of suitable species per city which is in line with Esperon-Rodriguez et al. (2022). Under SSP5-8.5, the urban species pool contracts steadily from 2011 to 2100, particularly in warmer regions where cities such as Valencia and Bordeaux begin with fewer suitable species and lose suitability more rapidly. Cities with intermediate climates, including Berlin, Paris, London, and Vienna, follow a moderate but consistent downward trajectory. Northeastern cities mainly maintain or gain climatic suitability, but responses diverge toward the end of the century depending on envelope definition and emission pathway. The resulting patterns demonstrate that a high-emission future increasingly narrows the climatic envelope within which European cities can sustain diverse urban tree communities, when considering the 26 analysed tree species. The distributional analyses further show that these changes are not spatially uniform. Under SSP1-2.6, the majority of cities experiences only minor shifts and gains and losses tend to balance each other, in other words, there would be ‘time to adapt’. Under SSP5-8.5, the entire structure of the distribution changes. Losses become dominant, many cities lose between five and 19 species, and the range of possible outcomes widens substantially, i.e. there is an urgency to adapt. This indicates a fundamental disruption of the equilibrium observed under the low-emission pathway and highlights that a high-emission future imposes structurally unequal burdens on urban areas. Our detailed examination of ten representative cities provides additional insight into local outcomes based on municipal tree inventories. Under SSP1-2.6, almost all cities retain most of their modelconsistent trees, especially when the extended envelope definition is applied. Under SSP5-8.5, the situation shifts substantially. Central European cities such as Berlin, Vienna, and Frankfurt may lose more than one third of all trees listed in their inventories when evaluated with the core envelope concept. Even under the less restrictive extended envelope, losses of between 10 and 20% remain common. These results confirm that the broad continental patterns of declining suitability translate into substantial reductions in existing urban tree populations at the city scale. Taken together, the findings highlight an important governance challenge. European cities host a disproportionately large share of the continent’s population and therefore depend critically on urban trees, which provide essential ecosystem

services such as cooling, improved air quality, recreation, and psychological well-being (Rötzer et al. 2021; Ren et al. 2022, Giacinto et al. 2021, Yao et al. 2022). Yet, they remain marginally represented in climate decision-making, which is largely determined at national and international levels (Hoornweg et al. 2011). Our results show that global mitigation pathways will directly determine the ecological stability of urban environments and the ability of cities to sustain green infrastructure that supports local quality of life. The strong divergence between SSP1-2.6 and SSP5-8.5 serves as a reminder that decisions made beyond the municipal scale have immediate consequences for urban residents. Beyond the ecological implications, the projected restructuring of urban tree communities entails substantial long-term economic consequences. Replacing vulnerable species, redesigning planting schemes, and maintaining climate-resilient urban forests require sustained financial investment and long planning horizons (Lehmann et al. 2025). Evidence from IPCC assessments and urban adaptation studies suggests that delayed action substantially increases future costs, as reactive measures tend to be more expensive and less effective than proactive adaptation (IPCC 2022; Valverde et al. 2022). Implementing timely transformation of urban tree structures therefore depends not only on technical feasibility, but also on sustained political commitment and societal support. Without such commitment, cities risk deferring adaptation costs into the future, where they are likely to accumulate and further constrain municipal budgets.

These insights call for deeper integration of cities into climate governance, combined with local adaptation strategies that anticipate the magnitude of change expected over the coming decades (Barber 2013; Zeppel 2013). Diversified species portfolios, climate-resilient planting, dynamic management of urban forests, and systematic monitoring of tree performance will become essential components of urban planning. Although cities cannot determine global trajectories on their own, they play a central role in shaping how climate change is experienced by the majority of Europe’s population. A coordinated approach that aligns local adaptation with ambitious global mitigation is therefore crucial to preserve the ecological and social functions of urban trees in the twenty-first century (Glassmann & Schnabel 2018).

Regarding the selection of specific tree species and their future potential, more parameters are used in exurban forestry, like soil variables, risk of calamities, and water balance simulations (Keenan 2015, Baumbach et al., 2024). Although such additional variables (e.g., water balance; Yao et al. 2025) are difficult to predict under different emission scenarios, they provide valuable insights into which tree species are most suitable for specific locations (Konings et al. 2024). In cities, soil horizons are compacted and disturbed due to artificial substrates, the absence of organic litter layers, covered humus layers in the subsoil, and interruptions in capillarity caused by erosion and deposition (Greinert 2015; Greinert et al. 2024). Consequently, urban soils are heavily altered by human activity and often only partially fulfil their natural functions, such as providing plants with water, oxygen, and nutrients, filtering pollutants, or anchoring roots (Deeb et al. 2020; O'Riordan et al. 2021). Beyond that, anthropogenic interventions, such as regular maintenance, pruning, soil improvement, and targeted irrigation, significantly influence urban tree health (Vogt et al., 2015). Such actions can alter vitality indicators and mask trees' natural responses to environmental stressors (Ibsen et al. 2023). Furthermore, pests and diseases that thrive in the urban microclimate, also potentially exacerbate tree decline and mortality (Dale & Frank 2014). This approach does also not account for genetic and epigenetic adaptive capacity at the individual level, which may enable short-term responses to environmental stress (Miryeganeh & Armitage, 2025). Against this background, we restrict the modelling to climate data as the only spatially consistent constraints at the city scale. In urban environments, soil properties and water supply are largely engineered and adjustable locally, influencing establishment success but not the transferable limits of species viability across cities or future climates. Climate therefore defines the feasible species range, while site conditions rather determine performance within it. However, extreme events such as droughts, heatwaves, and storms are key drivers of increased tree mortality, both in exurban (Bigler & Vitasse 2021; Schuldt et al. 2020) and urban areas (Marchin et al. 2022; Jääskeläinen et al. 2025). Especially regarding the latter, there is a large uncertainty in projecting urban heat waves for the next decades under

climate change (Zheng et al. 2021). Therefore, this study relied on average climatic values, following the concept of climate envelopes, where mean values serve as indicators for tree growth, vitality, and long-term climatic suitability (Wessely et al. 2024; Esperon-Rodriguez et al. 2022). However, this approach does not capture the variability of extreme events or small-scale urban microclimates. In this context, also the relatively coarse spatial resolution (1km) of the climate data becomes apparent from the perspective of end-users, such as city administrations. As a result, this limits the ability to capture small-scale intra-urban differences on a “street-level”, potentially overlooking significant variations in local conditions, like intra-urban heat islands, that influence urban forest conditions (Frank & Backe, 2023). Consequently, cities were analysed as aggregated administrative units, which may limit the applicability of the results for local-scale decision-making. Nevertheless, from the perspective of climatology, using this comparatively high resolution already represents a clear advantage. Applying convection-resolving (Hohenegger et al. 2020) or dedicated urban climate models (e.g., PALM4U; Maronga et al. 2020) at comparable spatial resolution would be computationally infeasible for the number of cities analysed, making our approach a practical and efficient alternative. Conceptually, our framework follows the logic of climate-constraint approaches that evaluate species vulnerability by comparing environmental conditions with species-specific tolerance limits. For example, Holzmann et al. (2026) assessed the climate vulnerability of tropical insects by relating experimentally derived thermal tolerance limits to current and projected temperature regimes. In contrast to traditional species distribution models (Esperon-Rodriguez et al., 2022; Wessely et al., 2024), this study integrates published tolerance limits to account for the natural occurrence of tree species. This approach is particularly important in urban contexts, where occurrence data are strongly shaped by planting decisions, historical management, and site availability and thus do not necessarily reflect the species’ climatic preferences. In addition, occurrence data available through municipal inventories only captures tree species on public land, while private trees with deviating species composition are systematically omitted (Hutt-Taylor & Ziter 2022; Chambers-Ostler et al. 2024; Leichtle et al. 2021). Relying solely on urban presence data could therefore produce biased climate envelopes that over- or underestimate climatic tolerance. Furthermore, it must also be noted that even in exurban forests there are substantial discrepancies between current species distributions and their potential natural ranges (Leuschner & Ellenberg 2017) caused by forest management. To address this limitation, we employed a combined climate envelope approach that incorporates both the natural distribution range derived from literature and observed urban occurrences that were additionally compared to occurrences by independend municipal tree inventories. By combining literature-derived climatic envelopes, representing the species’ fundamental climatic envelope, with urban occurrence data, approximating the realized urban envelope, our approach captures both the species’ potential climatic tolerance and its realized performance under urban-specific stressors such as heat islands or altered precipitation regimes. This dual perspective ensures that the resulting climate envelopes are ecologically meaningful while also reflecting the conditions experienced by trees in urban environments. The combined approach also provides a form of mutual validation, as each dataset helps to cross-check and constrain the other, increasing confidence in the resulting envelope estimates.

Finally, our results show that the climatic foundation of Europe’s urban trees will shift substantially over the coming decades. Under low-emission pathways, most common urban tree species retain stable climatic suitability and species pools in most cities remain largely intact, i.e. in such a scenario European cities still have ‘time to adapt’. Under high-emission conditions, however, the majority of species experience marked contractions of their suitability ranges and many cities face a sharp decline in their tree register, i.e. there is an urgency to adapt. Regarding the 26 analysed species, a small group of heat- and drought-tolerant taxa persists across large parts of Europe, but this set is too narrow to sustain functional, resilient, and diverse urban forests on its own. Validation using municipal tree inventories confirms that many species planted today already operate at or beyond their climatic limits, which are likely to be exceeded under SSP5-8.5. Consequently, decisions taken today regarding climate mitigation directly influence the future ecological performance of urban trees and, by extension, the liveability of Europe’s cities. Urban planning therefore needs to shift from static species lists to dynamic, climate-responsive strategies. This requires diversifying

planting portfolios, prioritizing climate-robust species, proactively phasing out vulnerable taxa, and implementing long-term monitoring. At the same time, cities play a central role in shaping societal responses to climate change. While cities cannot shape global emission trajectories on their own, they can prepare for the climatic conditions ahead. A coordinated approach that couples ambitious mitigation with targeted local adaptation will be essential to sustain the cooling, hydrological, ecological, and social functions of urban trees throughout the twenty-first century. Importantly, compared to exurban forests, cities operate under fewer ecological constraints and can draw from a substantially broader, though still regulated, pool of taxa, providing greater flexibility and additional time for proactive adaptation. Because the majority of Europe's population lives in cities, urban areas concentrate social, economic, and political influence. This demographic weight gives cities a unique leverage to drive climate action and accelerate adaptation measures. Consequently, integrating urban perspectives into climate governance is not only an ecological necessity but also a strategic opportunity to mobilize change where it matters most.

Methods

Software and hardware

All spatial analyses and data handling to construct the current and future climate envelopes were performed in R 4.4.3, running under Ubuntu 24.04.2 LTS using the packages terra, sf, MASS, dplyr, ggplot2, readr, and stringr. Subsequent analyses, validation steps, and figure generation based on the model output were performed in Python 3 using the packages pandas, numpy, matplotlib, and geopandas. The authors used the access to the computational and data resources provided through the joint high-performance data analytics (HPDA) project "terrabyte" of the German Aerospace Center (DLR) and the Leibniz Supercomputing Center (LRZ).

Climate data

In this study we do not model the ecological niche in the classical Hutchinsonian sense, but a climatic feasibility space derived from observed occurrence and tolerance limits. Therefore, we obtained employed climatic variables from the Max Planck Institute Earth System Model (mpi-esm1-2-hr, Müller et al. 2018), downscaled to a 1 km spatial resolution using the CHELSA V2.1 topographic algorithm as the climatic framework (Karger et al. 2017). The CHELSA data are frequently used to examine tree species distributions in mountain ranges (Bobrowski et al. 2021, Metreveli et al. 2023, Werner et al. 2025), whose climates have a complexity comparable to that of urban areas. Our analysis covered three time periods: 2011–2040, 2041–2070, and 2071–2100. It focused on two variables, mean air temperature (tas) and total annual precipitation (pr), calculated as 30-year averages for each period (Karger et al., 2021), since they have been proven as valuable indicators for the vitality and long-term persistence of trees (Wessely et al. 2024). The climatic projections were based on three different scenarios (IPCC 2022, Riahi et al. 2017): sustainability pathway with strong climate mitigation (SSP1-2.6), moderate mitigation pathway (SSP3-7.0), business-as-usual, fossil-intensive pathway (SSP5-8.5).

Published tolerance limits

To define tree species-specific thresholds out of published tolerance limits, a literature review of tree species profiles and fact sheets was conducted. Key sources, including EuForGen (2024), Forster et al. (2019), Kunz et al. (2020), San-Miguel-Ayanz et al. (2016), Schütt et al. (2006), and the Forestry Compendium of the Centre for Agriculture and Biosciences International (https://www.cabidigitallibrary.org/product/QF) provided critical data on the minimal and maximal tas and pr of the 30 most common tree species in European cities. The selection of the species was based on Rötzer et al. (2024). Based on this, a theoretical suitability matrix was developed (Table S3), incorporating threshold

values for tas_{min}, tas_{max}, pr_{min}, and pr_{max} for all 30 species. The climatic suitability of the selected tree species was then calculated on a pixel basis for the three climate periods, applying the defined thresholds.

Occurrence data

For defining the occurrence data-based climate envelopes, we first obtained occurrence data of the 30 urban tree species listed in Table S3 from the Global Biodiversity Information Facility (GBIF) for the European continent (https://www.gbif.org/; 1 August 2025). To ensure data reliability and spatial precision for subsequent analyses, a systematic screening and filtering workflow was applied to all downloaded datasets, regarding coordinate accuracy, type of record, time of record, and duplicates (S4). Finally, an urban mask was applied using the Global Human Settlement Layer (GHS-SMOD R2023A, Schiavina et al. 2023). Because the urban footprint across Europe occupies a much narrower climatic space than the continent as a whole (Figure S7), restricting the analysis to this domain is essential for deriving a climatically relevant core envelope for urban tree species. Previous work shows that model quality, stability, and, above all, the transferability of species distribution increase significantly with larger sample size. A few hundred records may be sufficient for regional models, but much larger samples are required for robust, comprehensive projections across continents and climate zones (Merow et al. 2013; van Proosdij et al. 2016; Gaul et al. 2020). For these reasons, a strict target value of ≥ 1000 presence points per tree species was chosen in this study in order to map the edges of the climatic envelope and improve the reliability of future projections, resulting in a final set of 26 species. Regarding the filter- and masking results, see Figure S4-5.

Derivation of the urban climatic envelope

For each of the filtered urban occurrence points, climate data (tas and pr) were extracted out of the CHELSA dataset from the period 2011–2040 per tree species. A two-dimensional kernel density estimation (KDE) was applied using the kde2d function from the MASS package in R, which estimates the joint probability density function of the two climatic variables over a regular grid in climatic space (Venables & Ripley 2013). The parameter n = 100 was used to define the resolution of the grid along both the temperature and precipitation axes. Therefore, each grid cell represents a small interval of temperature and precipitation, and the KDE assigns a density value corresponding to the relative frequency of occurrence points falling within that cell. To delineate the core climatic envelope, an upper quantile threshold of 85% of the KDE surface values was applied. This reduces the influence of rare or extreme occurrence points while retaining the main structure of the species' climatic preferences (Broennimann et al. 2012). The resulting KDE surface served as the basis for subsequent masking and combination with published tolerance limits to define combined climate envelopes with the following stages: (i) Raster cells within both the KDE high-density region and the published limits were flagged as the core envelope (green), (ii) cells meeting only one criterion (KDE or published limits) were flagged as extended envelope (yellow), (iii) cells outside both thresholds were considered unsuitable (Fig. 6). This procedure ensured that both empirical observations and pubished tolerance limits for each species were considered in defining the envelope. An overview of every tree species is given in Figure S6.

City-wise projections to future climate scenarios

The combined climate envelopes were applied to future climate projections (2041–2070, 2071–2100) for the different Socio-economic pathway scenarios SSP1-2.6, SSP3-7.0 and SSP5-8.5. For each CHELSA grid cell, annual mean temperature and precipitation sum were evaluated against the species-specific core and extended envelopes following the combined scheme shown in Fig. 6. Resulting suitability rasters were then aggregated to the city scale using the Global Human Settlement Layer (GHS-SMOD R2023A, Schiavina et al. 2023) based on the degree of urbanization "Urban Centre" extent, ensuring that only pixels located within officially delineated urban areas were considered.

A species was classified as suitable for a given city when at least one pixel inside the administrative boundary met the suitability threshold for the extended and core envelope. In this regard, we followed Ossola et al. (2020), who consider a tree species to be suitable even if it occurs at only one single location of a city. For the persistence analysis, we applied the bottleneck approach of Wesseley et al. (2024), identifying those pixels that remained suitable across all three time periods for each scenario before aggregating results to the city level as mentioned before.

City-specific validation and projection of tree inventory

For our validation and forecast of the focused cities' tree inventories, we screened the Global Urban Tree Inventory (GUTI) dataset for Europe (Ossola et al., 2020). This is a collection of municipal tree inventories and tree species lists from more than 470 urban areas located in five continents. This dataset fits perfectly to our study, since the GUTI data was mostly collected between 2010 and 2020 (Ossola et al., 2020). After checking for climatic representativenessand and availability (open access) of the tree inventories, we focussed on ten cities, covering a broad range of climatic and biogeographic gradients in Europe: Berlin, Bordeaux, Frankfurt, Helsinki, Innsbruck, London, Paris, Valencia, Vienna, Würzburg.

To validate the model for each city, the location and presence of every species recorded in the municipal tree inventories were compared with the climate-envelope predictions for the current period (Fig. 6). The proportion assessed as plausible was subsequently incorporated into the future projections and the persistence analysis (Fig. 5).The full workflow is illustrated in Figure S10.

Declarations

Author contributions

J.F., J.Fr. and C.S. conceived the study. J.F. and J.Fr. developed the methodology, implemented the software, performed the formal analysis, carried out the investigation and validation, and prepared the visualizations. J.F., J.Fr., C.S. and K.-H.M. curated the data. S.D., T.U. and H.T. provided resources. J.F. and J.Fr. wrote the original draft of the manuscript. J.F., J.Fr., T.L., K.-H.M., C.S., D.A., A.S.G.d.L., J.S.R., T.E., T.K., D.K., T.U. and H.T. reviewed and edited the manuscript. T.U. and H.T. supervised the study. S.D., T.K. and T.U. acquired funding.

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Competing interests

All authors declare no financial or non-financial competing interests.

Data availability

Species occurrence data used in this study were obtained from the Global Biodiversity Information Facility (GBIF) (https://www.gbif.org/). Climate variables were derived from the CHELSA v2.1 climate dataset and include annual mean temperature (BIO1) and annual precipitation (BIO12) based on the Max Planck Institute Earth System Model *mpi-esm1-2-hr* (https://chelsa-climate.org/). Urban areas used for filtering occurrence records were identified using the

Global Human Settlement Layer Settlement Model (GHS-SMOD R2023A) (Link) provided by the European Commission Joint Research Centre. City boundaries were also derived from the GHS-SMOD Urban Center database (GHS-SMOD R2024A) for 2025 (Link) by selecting spatial units classified as urban centres, which were used to define the extent of cities for the city-level climate suitability analysis.Urban tree inventory datasets used for model validation were obtained from municipal open-data portals. Due to licensing restrictions and the large size of some datasets, the raw data are not redistributed with the repository but can be accessed from the Zenodo repository: https://doi.org/10.5281/zenodo.18886687.

Code availability

The underlying code for this study is available in the Zenodo repository: https://doi.org/10.5281/zenodo.18886687.

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Figures

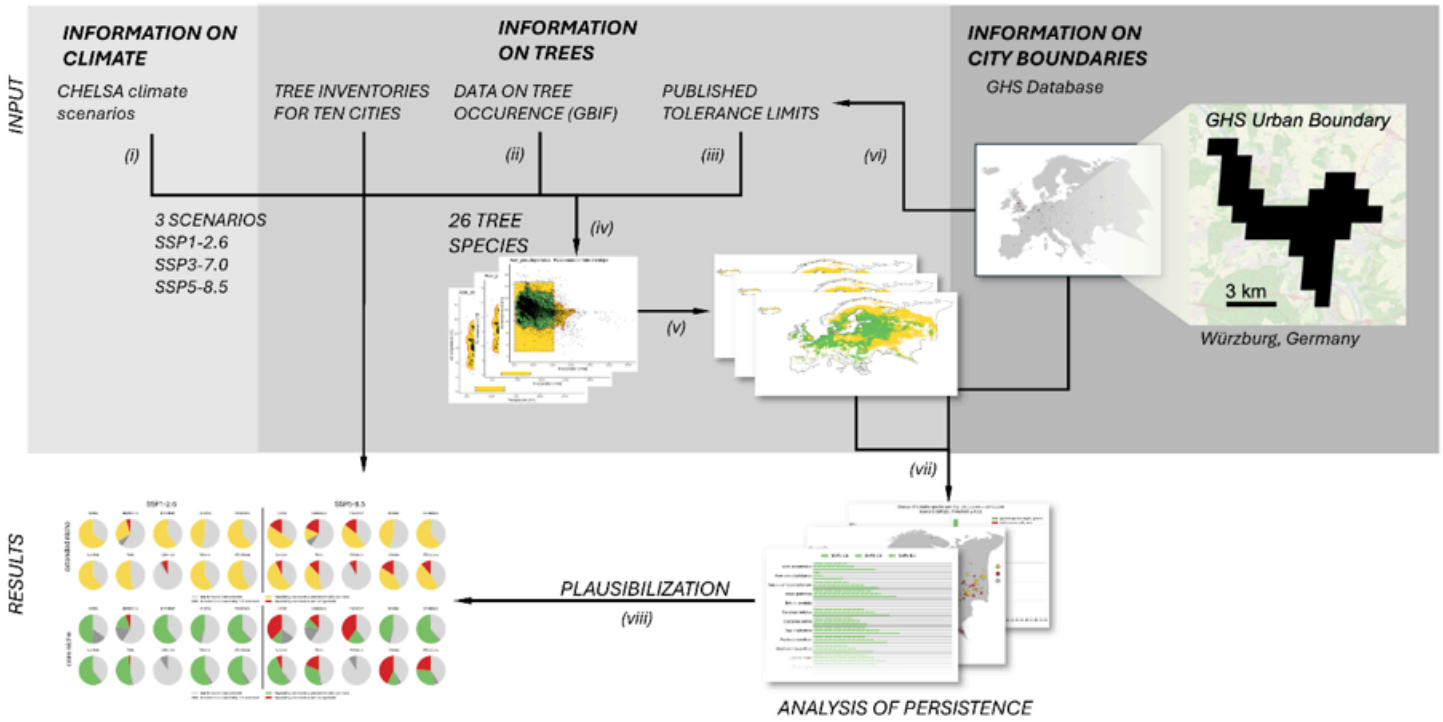


Figure 1

Workflow for deriving climate-based suitability estimates for 26 urban tree species. Overview of the analysis workflow, including (i) extraction of CHELSA climate variables for current and future scenarios, (ii) acquisition and filtering of Global Biodiversity Information Facility (GBIF) occurrence records for European urban areas and (iii) published tolerance limits published tolerance limits from silvicultural manuals and authoritative species descriptions, (iv) construction of species-specific climatic envelopes, (v) spatial projection of climatic suitability across Europe under current and future climate conditions, (vi) integration of urban extent data from the Global Human Settlement Layer, and (viii) evaluation of climatically long-term species persistence and suitability in European cities.

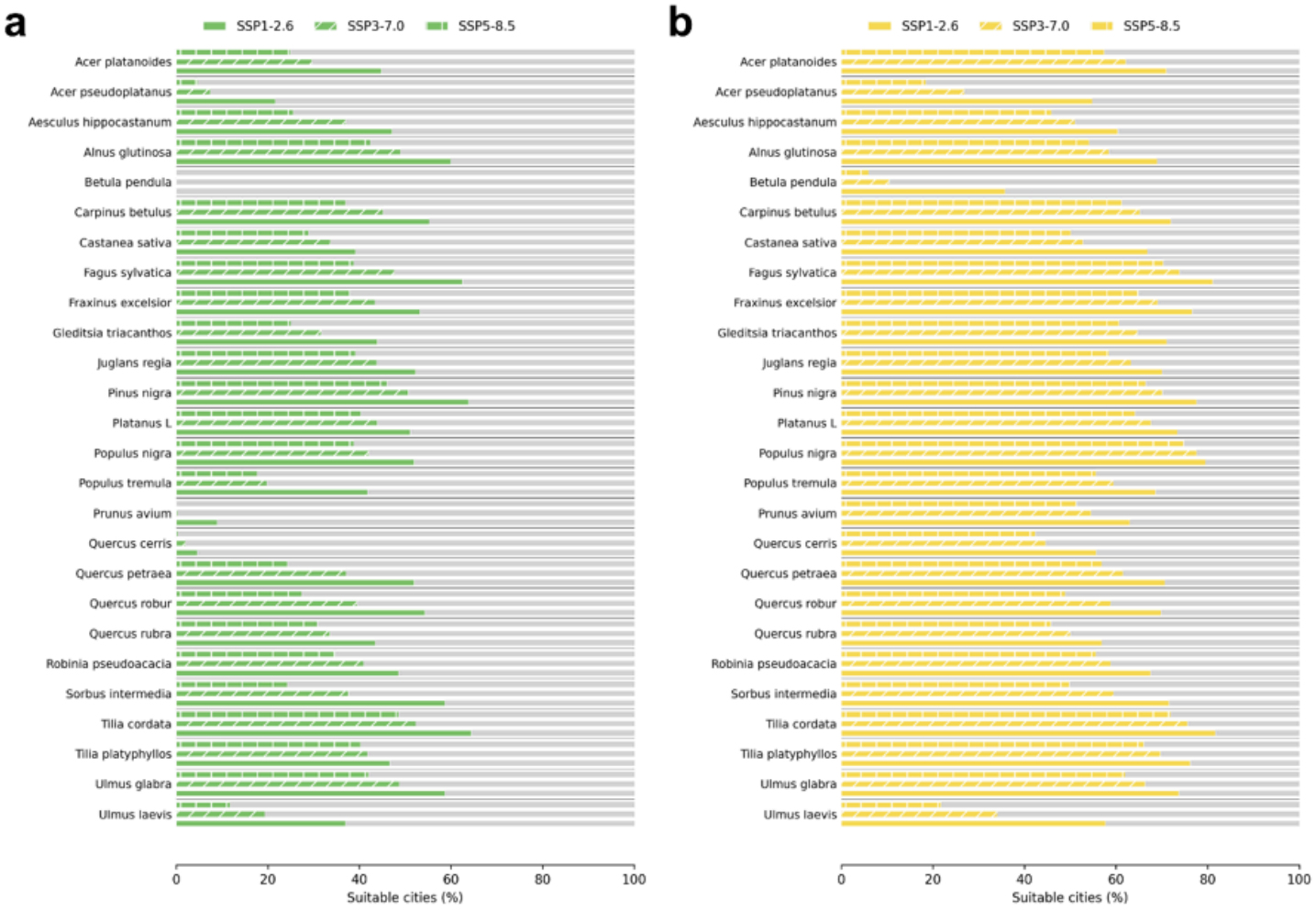


Figure 2

Persistent suitability of 26 urban tree species until the year 2100 across three emission scenarios. Bar charts summarize the proportion of cities where the tree species is considered suitable across all three investigated periods, distinguishing between the core envelope (a; green bars) and the extended envelope (b; yellow bars) as well as the three emission scenarios SSP1-2.6, SSP3-7.0, and SSP5-8.5 across the periods 2011–2040, 2041–2070, and 2071–2100. The visualization highlights how climatic constraints shape climatically suitable conditions for the long-term persistence of urban tree species across Europe's cities.

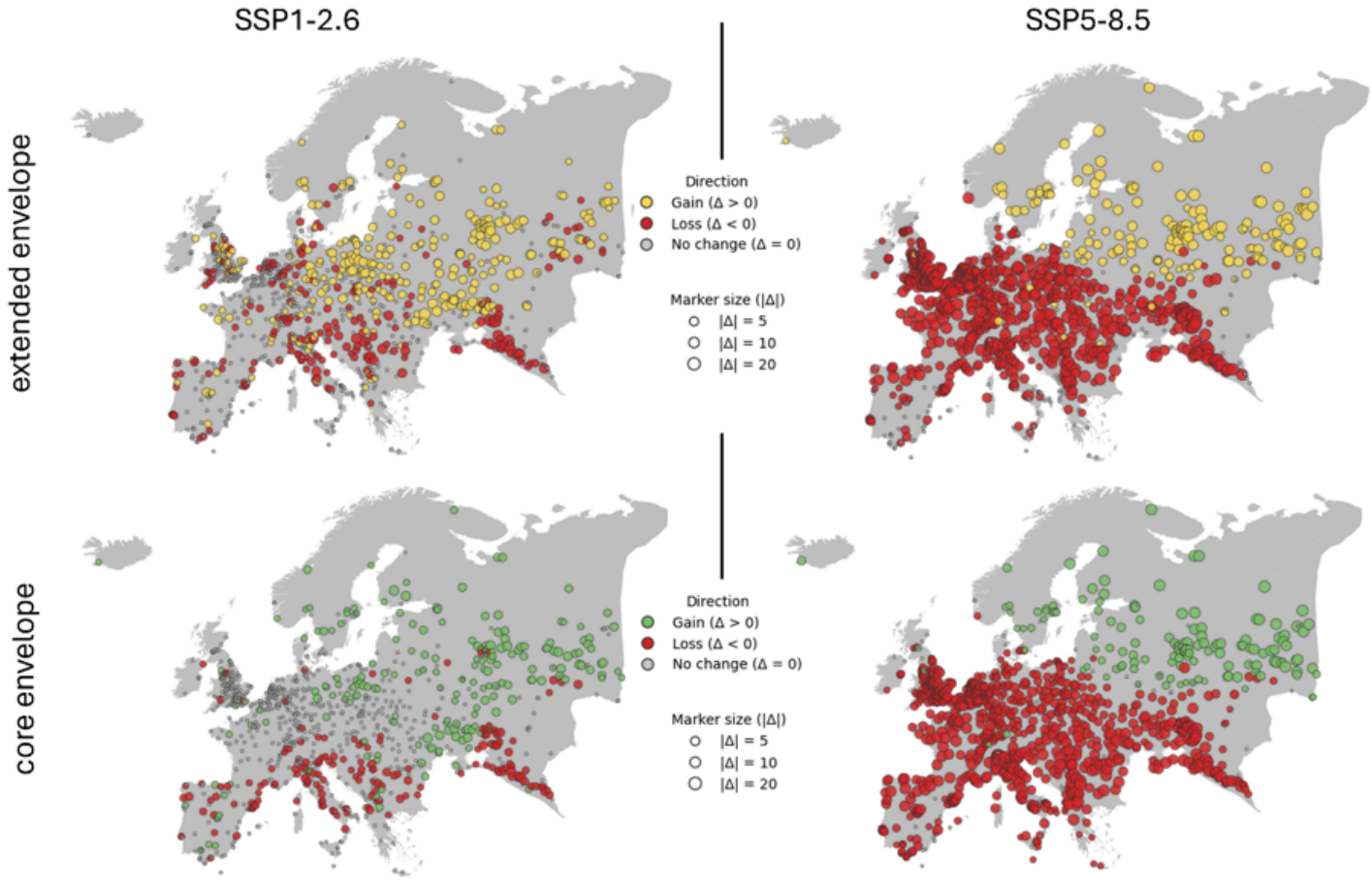


Figure 3

Spatial and temporal patterns of change in the number of climatically suitable tree species across European cities between 2011–2040 and 2071–2100 under SSP1-2.6 and SSP5-8.5. Upper panels show results based on the extended envelope, lower panels on the core envelope. Circles represent each of the surveyed cities, coloured by direction of change (gain, loss, no change) and scaled by magnitude of change (|Δ|). The maps illustrate widespread species losses under strong warming, while gains are mainly restricted to northern and north-eastern Europe.

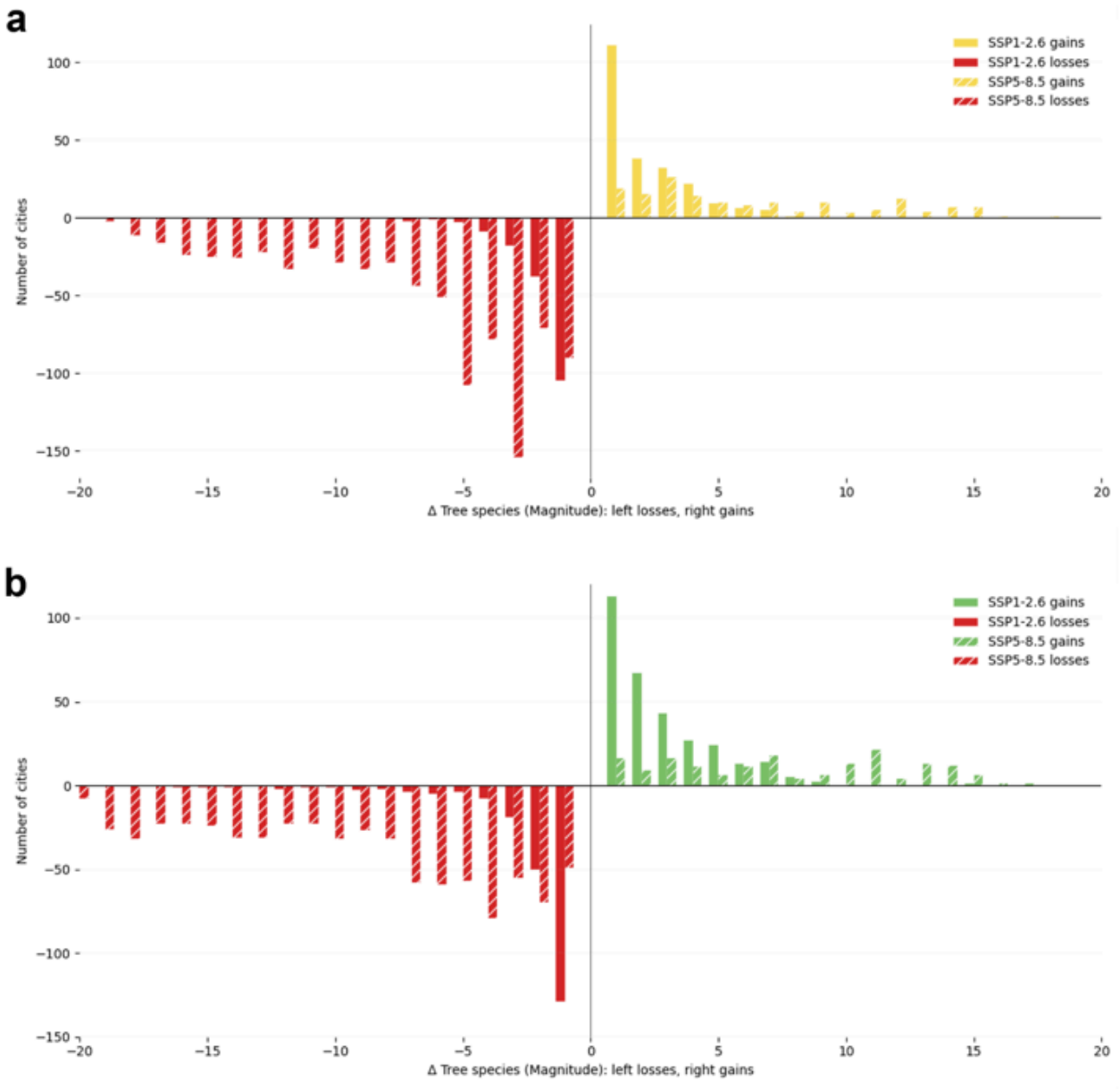


Figure 4

Net changes in climatically suitable tree species considering the extended envelope of the surveyed cities from 2011–2040 to 2071–2100 under SSP1-2.6 and SSP5-8.5. Histogram of species gains (yellow) and losses (red) across all European cities. Bars represent the number of cities experiencing a given magnitude of change.



Figure 5

Persistence and loss of urban tree species in nine European cities under SSP1-2.6 and SSP5-8.5. Pie charts show, for each city and scenario, the proportion of registered urban tree species that are supported by the model and persist across all three periods (yellow/green), supported by the model but become climatically unsuitable in at least one future period (red), modelled but not supported by municipal tree registries (dark grey), or not modelled or not present in the municipal inventory (light grey).

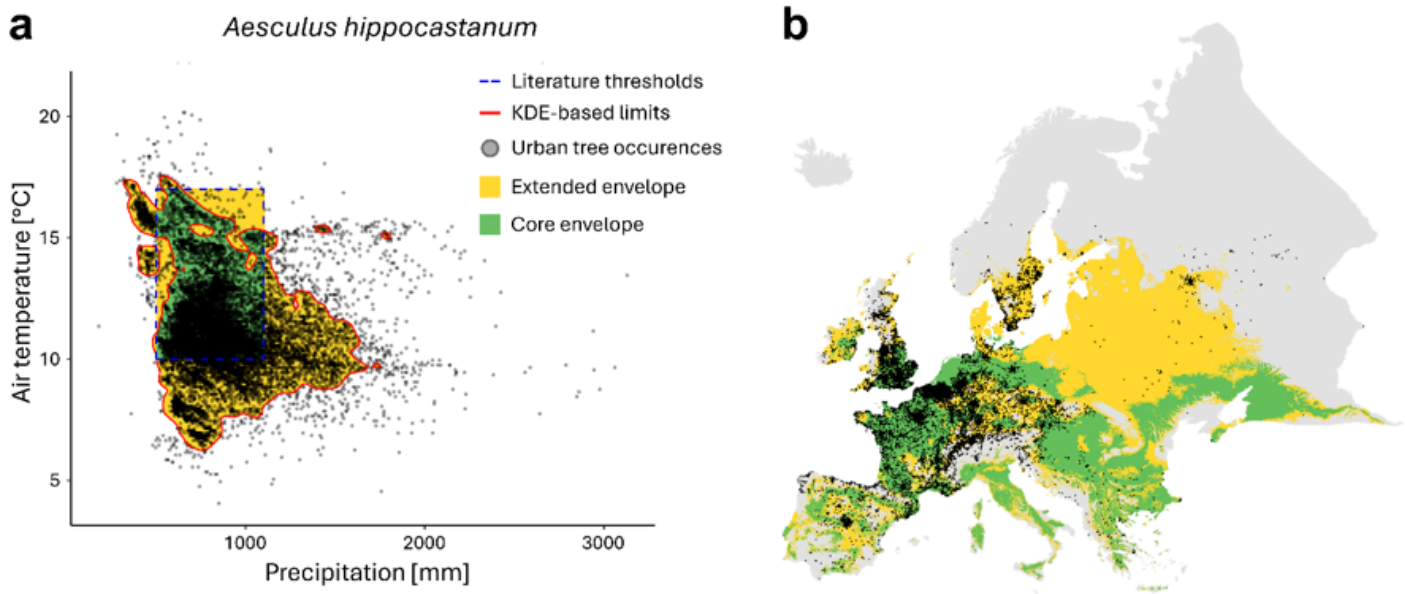


Figure 6

Combined climate envelope and spatial projection for the example *Aesculus hippocastanum*. a: Two-dimensional climate envelope based on mean annual temperature (tas) and annual precipitation sum (pr). Black points show occurrence records after quality control and urban masking according to Figure S4 and S5. The red contour represents the high-density region of the kernel density estimation using the urban occurrence points. The blue and dashed rectangle marks the published tolerance limits. Green shading indicates the core envelope, where KDE and published tolerance limits overlap; yellow shading shows the extended envelope, defined as climatic space covered by either KDE or published limits. b: Spatial projection of core (green) and extended envelope (yellow) under current climatic conditions across Europe. Black dots represent all filtered urban occurrence points for *Aesculus hippocastanum*

Supplementary Files

This is a list of supplementary files associated with this preprint. Click to download.

- SupplementaryMaterial.docx