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Climate change increases global risk to urban forests

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Climate change threatens the health and survival of urban trees and the various benefits they deliver to urban inhabitants. Here, we show that 56% and 65% of species in 164 cities across 78 countries are currently exceeding temperature and precipitation conditions experienced in their geographic range, respectively. We assessed 3,129 tree and shrub species, using three metrics related to climate vulnerability: exposure, safety margin and risk. By 2050 under Representative Concentration Pathway 6.0, 2,387 (76%) and 2,220 (70%) species will be at risk from projected changes in mean annual temperature and annual precipitation, respectively. Risk is predicted to be greatest in cities at low latitudes—such as New Delhi and Singapore—where all urban tree species are vulnerable to climate change. These findings aid the evaluation of the impacts of climate change to secure long-term benefits provided by urban forests.

Urban areas span ~3% of the Earth's land surface area[1] and accommodate more than 4.2 billion people (55% of the global population)[2]. Within cities, urban forests (all trees and shrubs in a city, present in streets, parks, woodlands, abandoned sites and residential areas[3,4]) provide environmental services and socio-economic benefits, such as carbon sequestration and natural cooling via microclimate processes[5]. Cities are expected to expand in size around the globe, with predictions of 6.6 billion people living in cities by 2050 (~70% of the predicted global population)[2]. As the human population grows, so too will the societal demands on urban forests.

Planting and preserving climate-resilient urban forests can play an essential role in people's connection to nature[5] and help mitigate the adverse effects of global climate change by: (1) shading buildings and paved surfaces as well as reducing energy usage for cooling[6]; (2) dissipating urban heat through evapotranspiration; and (3) capturing greenhouse gases and storing carbon through photosynthesis[7]. However, the pace at which climate is changing[8] poses a serious threat to the persistence of urban forests globally.

Natural and urban ecosystems are already impacted by climate change, resulting in suboptimal tree growth and increased mortality[9,10]. Climate change is increasing the frequency and severity of extreme events—such as heatwaves, fire and drought[8,11,12]—which contribute to extensive tree dieback and mortality globally[9,13]. Additionally, features of urban environments, including impervious surfaces and the urban heat island (UHI) effect, can locally exacerbate climatic extremes[8].

Urban tree dieback and mortality have environmental and socio-economic consequences for governments and urban residents due to the loss of both ecosystem services and investments in planting and maintenance[13,14]. Urban greening policies target the strategic delivery of ecosystem services and benefits[15]. Unfortunately, studies of urban tree vulnerability to climate change are rare and limited in scope and broad applicability[16]. This limits the capacity to assess climate risk for species that are currently experiencing conditions that may exceed their climatic tolerance[17]. Given the comparatively slow growth rates of many trees and the importance of promoting tree longevity in the landscape, successful urban greening must be strategically planned with future climatic conditions in mind to secure the persistence of urban forests into the future[16].

Here, we present a global climate-risk analysis for urban forests. We assessed the potential impacts of future climate change on 3,129 tree and shrub species present in 164 cities across 78 countries. We calculated three climate-impact metrics: (1) exposure, the extrinsic degree to which a city is exposed to changes in climate; (2) safety margin, the intrinsic sensitivity of each species to climate change in each city according to its climatic tolerance based on current geographical distributions; and (3) risk, calculated as the difference between exposure and safety margin[17,18]. Because of the asynchrony between the speed of contemporary climate change and the time required for long-lived tree and shrub species to respond[19,20], known as the macroclimatic debt[21], we expect that high proportions of species in cities are already at risk or partially decoupled from macroclimatic constraints as a result of costly management practices (for example, water supply). Hence, contemporary urban planning and tree species selection are required to ensure a successful climate mitigation strategy for the future.

Exposure to climate change

Exposure is the degree to which climate is projected to change in cities[22,23]. Here, it is measured using the magnitude of change in climate in a given city between baseline (average during 1979–2013) and future (2050 or 2070) climatic conditions. Under the Representative Concentration Pathway (RCP) 6.0 (for RCP 4.5 see Supplementary Table 1) and according to an ensemble of ten General Circulation Models (GCMs), all 164 studied cities are predicted to undergo

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Table 1 | Summary of climate change exposure, safety margin and risk to urban forests for five climate variables across the world's cities

Variable	Exposure		Current safety margin					Climate risk in 2050				
	2050	2070	Species	Species 100%	Cities 100%	Species 50%	Cities 50%	Species	Species 100%	Cities 100%	Species 50%	Cities 50%
MAT	2.1 °C (0.6)	3.0 °C (0.8)	1,759 (56%)	532 (17%)	2	610 (19%)	78	2,387 (76%)	1,200 (38%)	12	854 (27%)	133
MTWM	1.7 °C (0.5)	2.6 °C (0.7)	1,724 (55%)	465 (15%)	2	684 (22%)	82	2,140 (68%)	862 (28%)	19	941 (30%)	106
MTCM	1.3 °C (0.5)	2.0 °C (0.7)	2,699 (86%)	1,676 (54%)	0	2,600 (83%)	121	2,435 (78%)	1,233 (39%)	2	2,258 (72%)	34
AP	−57 mm (78.3)	−62 mm (88.7)	2,030 (65%)	789 (25%)	2	897 (29%)	91	2,220 (70%)	1,006 (32%)	3	944 (30%)	99
PDQ	−1 mm (8.2)	−2 mm (12)	1,880 (60%)	665 (21%)	4	846 (27%)	92	1,849 (59%)	661 (21%)	0	852 (27%)	101

Exposure to predicted mean (standard deviation) changes in MAT, MTWM, MTCM, AP and PDQ across 164 cities in 2050 and 2070. Current safety margin and climate risk in 2050: the number of tree and shrub species (and proportion in brackets) exceeding their safety margins and at high risk under climate change in at least one city, 100% of cities and >50% of cities where they are planted; the number of cities with 100% and >50% of their species at risk; species ($n=3{,}129$), cities ($n=164$). Climate projections for 2050 and 2070 were derived from RCP 6.0 and 10 GCMs.

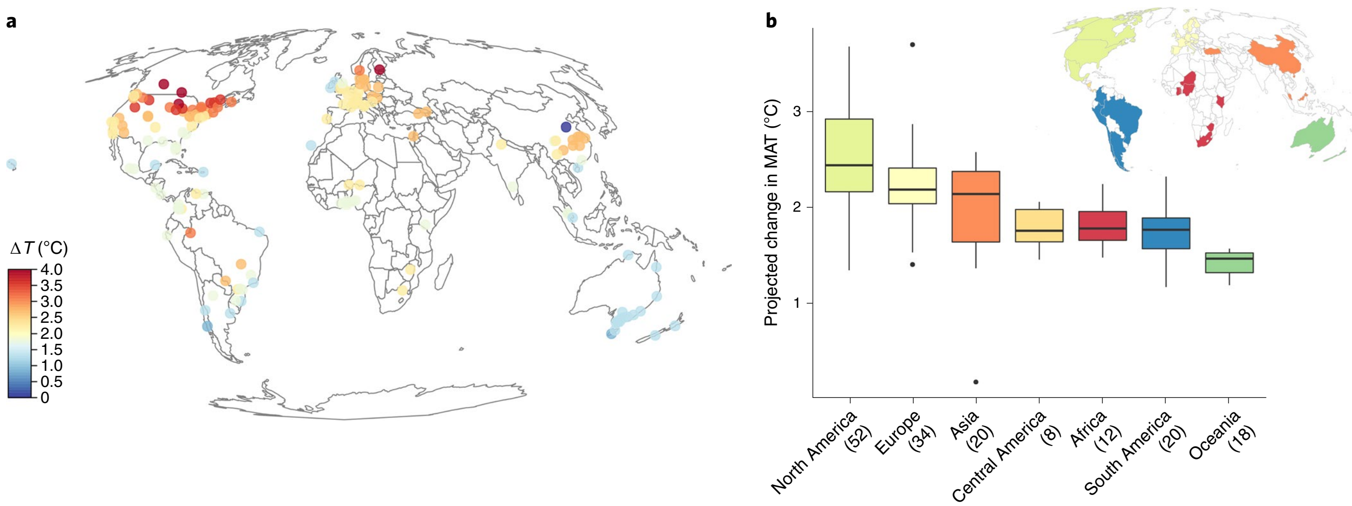

Fig. 1 | Exposure to future climate change across the world's cities. a,**b**, Exposure of 164 cities to predicted changes in MAT in 2050 relative to baseline MAT between 1979 and 2013 (**a**); boxplot of changes in MAT averaged across cities in seven geographical regions (as coloured in inset map); numbers in brackets indicate the number of cities for each region (**b**). Plots display data for RCP 6.0 averaged across 10 GCMs.

increases in all temperature variables (mean annual temperature, MAT; maximum temperature of the warmest month, MTWM; and minimum temperature of the coldest month, MTCM) (Table 1 and Supplementary Table 1), with the highest increases predicted to occur in Helsinki (Finland), Winnipeg (Canada) and Minneapolis (United States). The increases in MAT and MTWM are predicted to exceed 2 °C for 54 cities by 2050 and increase to 119 cities by 2070. Cities are predicted to become drier by 2050 for both annual precipitation (AP, $n=138$) and precipitation of the driest quarter (PDQ, $n=96$). On average, cities towards the equator will be exposed to larger decreases in AP, whereas cities at high latitudes will be subject to larger increases in MAT, MTWM and MTCM (Supplementary Table 2, Fig. 1, Supplementary Figs. 1 and 2 and Extended Data Fig. 1).

Species climatic safety margin

The safety margin describes intrinsic species sensitivity to climate change and indicates potential tolerance to changing climate conditions[18,24] of tree and shrub species within a given city. The safety margin is calculated as the difference between baseline climate conditions (for example, MAT or AP) for the city and the species' tolerance limit in relation to the direction of change for the climate variable being examined (for example, the upper limit in case of warmer MAT or the lower limit in case of drier AP) (Supplementary Fig. 3). For each climate variable, we found species that are currently exceeding their safety margins in all cities in which they are planted: (1) MAT, 532 species (17% of all study species); (2) MTWM, 465 (15%); (3) MTCM, 1,676 (54%); (4) AP, 789 (25%); and (5) PDQ, 665 (21%) (Supplementary Data 1). For all climate variables, the plant families with the largest number of species at risk were Myrtaceae, Fabaceae and Rosaceae, while 26 smaller families had 100% of their species at risk. We also identified cities that currently have all their species exceeding their safety margins, including Barcelona (Spain), Niamey (Niger) and the city-state of Singapore; across all 164 cities, the mean proportion of species subject to unsafe baseline climate conditions was 53% (Table 1, Fig. 2, Supplementary Fig. 4 and Extended Data Fig. 2).

Notably, many of the species identified as at risk in cities had relatively narrow safety margins under baseline climate conditions. A narrow safety margin indicates that baseline climate conditions are close to the species' upper or lower tolerance limit in relation to the direction of change (for example, baseline MAT is too close to the species' warm limit under the expectation of a warmer climate). Median values of safety margins were 0.2 °C for MAT, 0.3 °C for MTWM, −4.4 °C for MTCM, −56 mm for AP and −8 mm for PDQ. For MAT, 1,277 species (41%) had exceeded their safety margin by <1 °C, while 149 species (5%) exceeded their safety margin by >10 °C. Similarly, for MTWM and MTCM, 1,189 (38%) and 153 (5%) species, respectively, exceeded their safety margin by <1 °C (Fig. 2, Supplementary Fig. 4 and Extended Data Fig. 2).

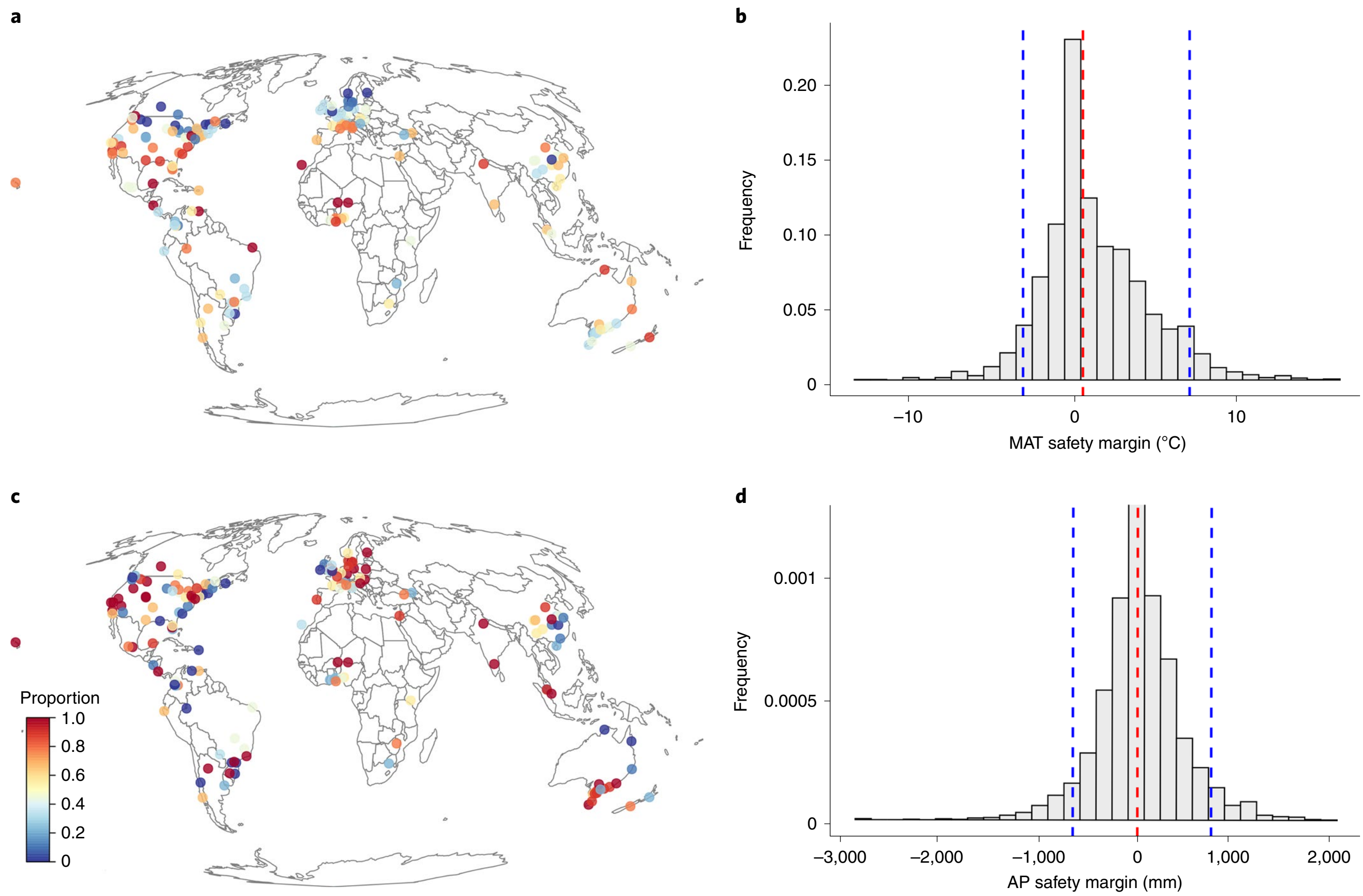

Fig. 2 | Contemporary tree and shrub species safety margin across the world's cities. a,c, Proportion of species currently exceeding their safety margin for MAT (**a**) and AP (**c**) in 164 cities. **b,d**, Frequency distribution of mean values of MAT (**b**) and AP (**d**) safety margins of each species ($n=3,129$) across all cities. Red lines indicate the median and blue lines the 5th/95th percentiles. A positive safety margin ($S>0$) indicates species with an upper (MAT) or lower (AP) climatic tolerance limit greater than that of baseline climatic conditions; a negative value ($S<0$) indicates species under 'unsafe' climatic conditions.

Risk to climate change

Risk refers to the potential for adverse consequences on biological systems[25,26] and is defined here as the difference between cities' exposure to future climate change and its urban forest species' safety margins. By 2050, under RCP 6.0 (for RCP 4.5, see Supplementary Table 3), projected changes in climate will result in an increase in numbers of species at risk (city's future climate will exceed the species' safety margin) in at least one city where they are planted in terms of changes in MAT, MTWM and AP. However, warmer and wetter projections of MTCM and PDQ in some cities will benefit some species by decreasing their future risk (Table 1, Fig. 3 and Extended Data Fig. 3).

By 2050, between 20% and 40% of urban forest species are projected to be at risk in all cities where they are currently planted, depending upon the climate variable considered: (1) MAT, 1,200 (38%); (2) MTWM, 862 (28%); (3) MTCM, 1,233 (39%); (4) AP, 1,006 (32%); and (5) PDQ, 661 (21%). Similar to safety margin, the plant families with the largest number of species at risk were the Myrtaceae, Fabaceae and Rosaceae, while 62 families had 100% of their species at risk (for example, Dipterocarpaceae, Cunoniaceae and Taxaceae). Conversely, we found 742 (24%; MAT), 989 (32%; MTWM), 694 (22%, MTCM), 929 (30%; AP) and 1,280 (41%; PDQ) species at no risk by 2050 in all cities where they are currently planted (Supplementary Data 1).

We found a tendency for the mean climate change risk to increase towards the equator (Fig. 3 and Supplementary Table 4). For all climate variables, except MTCM, the proportion of species at risk in each city is predicted to increase by 2050 and 2070 (Table 1 and Supplementary Table 3), with 65% being the mean proportion of species at risk across all 164 cities by 2050 under RCP 6.0 (Fig. 3 and Supplementary Figs. 5 and 6). Comparing risk profiles across climate variables by 2050, 1,231 (39%) species were identified to be at risk for all five climatic variables simultaneously and 2,022 (65%) species were predicted to be at risk because of changes in at least three climatic variables. No risk was observed for 62 species (1%) in any city where they are currently planted (Supplementary Fig. 7 and Supplementary Data 1). By 2050 under RCP 6.0, the magnitude of risk for the species reached median values of 1.8 °C (MAT), 1.4 °C (MTWM), 5.6 °C (MTCM), −103 mm (AP) and −9 mm (PDQ). We found 1,006 (32%) and 1,060 (34%) species at risk by <1 °C increase of MAT and MTWM, respectively (Supplementary Fig. 5).

For each country, we obtained their 2019 readiness score quantified by the Notre Dame Global Adaptation Initiative (ND-GAIN)[27]. ND-GAIN is an index of a country's vulnerability to climate change and its capacity to strengthen resilience[27]. We found climate risk for urban forests was higher in cities projected to undergo decreases in precipitation, increases in temperature and in countries with low ND-GAIN scores (for example, Pretoria, South Africa and New Delhi, India) (Supplementary Table 5). Cities in countries with low ND-GAIN scores may have limited capacity to mitigate climate change impacts on their urban forests.

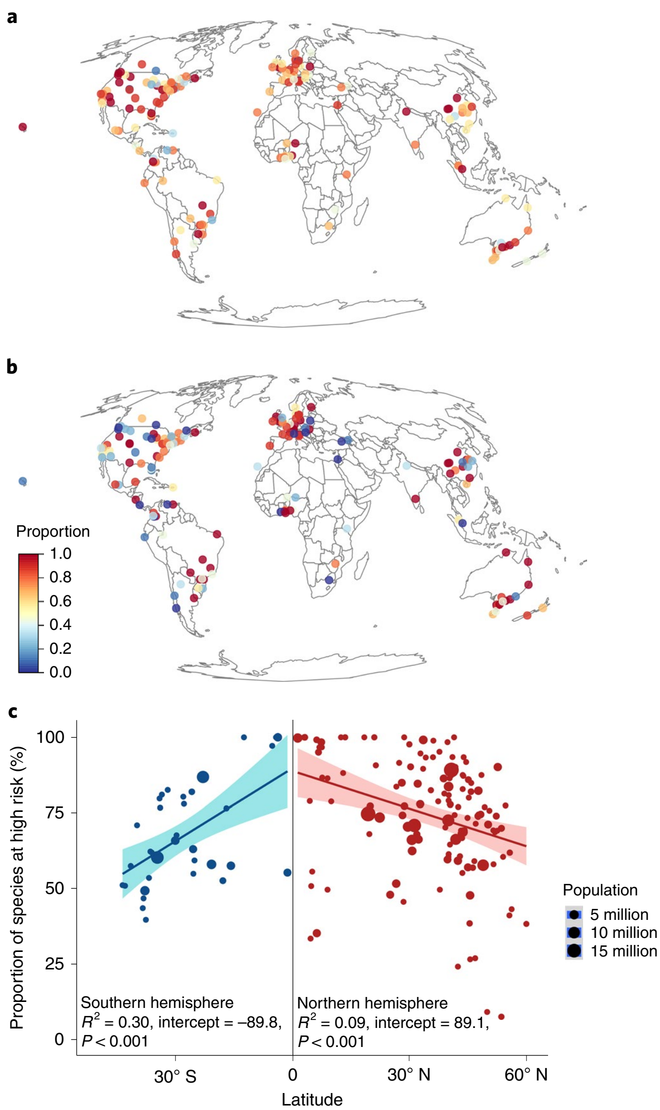

Fig. 3 | Tree and shrub species at risk of future climate change impacts across the world's cities. a,**b**, Proportion of species predicted to be at risk from projected changes in MAT (**a**) and AP (**b**) by 2050 in 164 cities. Each point represents the proportion of species at risk in a given city. **c**, Relationship between the proportion of species at risk and cities' latitude (northern hemisphere, $n = 129$ cities; southern hemisphere, $n = 35$). Shaded ribbons indicate the 95% confidence interval for predictions from a linear model. Point size indicates human population size[47]. Data for 2050 and RCP 6.0.

Discussion

Here, we assessed the climate risk of 3,129 urban tree and shrub species in 164 studied cities across 78 countries and found that 56% and 65% of the species are currently exceeding the temperature and precipitation conditions experienced in their geographic range, in at least one city where they are planted. By 2050 and under RCP 6.0, the proportions of species at risk are predicted to increase to 76% and 70% given the projected changes in MAT and AP, respectively.

The long-term stability of urban forests depends on the identification and use of species that are resilient to climate change and are able to survive and thrive[28]. We found that cities currently harbour many species growing beyond their safety margins, suggesting that there are additional management actions, such as irrigation, and biological factors (for example, trait plasticity) facilitating species' presence in cities and decoupling them from macroclimatic constraints. Being planted in a city, however, does not necessarily mean that a species is performing well in that location. Species whose safety margins are exceeded may be able to survive locally through various compensatory effects but may not have the capacity to function and remain healthy under those conditions[29,30]. Urban forest monitoring would provide valuable and necessary information on individual species performance in local contexts, which can be used to iteratively improve urban tree management.

Our climate risk assessment method achieves two key goals. First, the metrics are interpretable and reproducible in any city with access to tree occurrence data. Second, the approach identifies species most at risk currently and under future climate change (Supplementary Fig. 8). The safety margin and risk metrics can guide prioritization for urban forest monitoring and planning in the coming decades. For example, species in current plantings far exceeding their safety margin may be prioritized for monitoring and potential substitution with more resilient species in future planting programmes, whereas species identified as low risk may represent a valuable resource for creating climate-proof urban forests (Supplementary Data 1). Yet climate risk must be considered in the context of many other important factors in species selection, such as site suitability or invasiveness[31]. Our method provides a path forward to inform local governments, prioritize monitoring and mitigation and support societal benefits of urban forests in a warmer world.

While we have assessed the global climatic risk of urban forests, there are some limitations to consider when interpreting findings derived from our method. We used occurrence records that we related to bioclimatic variables to approximate species realized climatic niches. However, biotic factors (for example, competition and facilitation), other abiotic factors (for example, soil and nutrients) and dispersal limitations within species native ranges are not accounted for, meaning that one may underestimate or overestimate the fundamental climatic niche and thus the climate tolerance of a species. Although we used global occurrence records, species distribution data may not fully reflect climatic constraints[32]. Occurrence records at the margin of a species geographic range may reflect peculiar but highly suitable microclimate or occurrence within climate refugia. Furthermore, an aggregate species-level assessment may not account for population or individual variation in climate vulnerability. Thus, our approach may not fully reflect genetic adaptive capacity and phenotypic trait plasticity of species, which may facilitate their resilience to climate change. In urban environments, other environmental factors can mitigate (for example, presence of water sources) or exacerbate (for example, pollution and limited rooting space) the effects of climate change. In addition, given that in many cities comparatively few tree species are abundant, a weighted climate risk metric could be used to correct for any influence of rare species on risk profiles. Finally, our estimates of future risk do not consider the effects of urban population growth and urban land use changes that could further amplify risk, suggesting that our estimates are conservative.

Urban forests are often water stressed or closely coupled to regional precipitation and water balance; hence, species growing under hydrologically stressful conditions are more vulnerable to extreme climate events[31], resulting in dieback and higher mortality rates[33]. Urban forests that experience declines in precipitation will be more vulnerable than those facing higher rainfall, although significant increases in precipitation might also represent a risk factor, that is flooding[34]. Also, depending on the location of trees within cities, changes in UHI and water availability may narrow species safety margins and increase their future risk. Management actions, such as irrigation or stormwater capture, can aid in mitigating the effects of low precipitation by providing supplemental water during periods of severe climate stress[35] and by promoting evapotranspiration (local cooling effect), which will be crucial to mitigate heatwaves in cities[36]. However, it may become increasingly difficult to mitigate the adverse effects of climate change through management actions to offset soil water deficits, particularly under limited urban water supply and in places where water is increasingly scarce[37,38]. These types of costly management actions may explain why so many tree species are currently present in cities with climates that already exceed their current safety margins at the dry margin for precipitation.

Risk associated with increases in MTWM highlights that extreme heat represents a significant threat to urban forests. Cities with the highest risk for heatwaves might be those with a current high UHI effect[39]. However, we found no correlation between baseline climate variables and current daytime average maximum land surface temperatures (a proxy for the UHI effect[39]), probably a result of a decoupling between macroclimate and microclimate in cities. Predicted changes in extreme seasonal variables (MTWM and PDQ) may impose thermal and hydrological stress on plants. However, warmer temperatures in MTCM indicate that species in temperate climates will be relieved from cold stress as the urban environment may become more favourable in the future. Nonetheless, many temperate tree species require a winter cold period (vernalization) for proper functioning[40] and future winter warming may represent a risk for those species. In contrast, MTCM of tropical and subtropical species may not be indicative of cold tolerance risk.

The mitigation of climate change impacts in cities through management actions ultimately will depend on available resources and the capacity to respond to climatic change as it occurs. Importantly, future risk was higher in cities located closer to the equator where economic resources to mitigate climate change are generally more limited[41]. Furthermore, we found cities with high proportions of urban forest species at risk located in countries identified as vulnerable by the ND-GAIN index (for example, India, Niger, Nigeria and Togo).

Despite lower exposure to future climate change in cities at low latitude, our finding of a higher proportion of urban forest species at risk in cities at low latitudes compared to high latitudes, particularly in the northern hemisphere, highlights a potential mismatch between species planted in low-latitude cities and baseline climatic conditions. Cities in tropical climate zones may provide comparatively more benign climate conditions due to less frequent and intense temperature and precipitation regimes, which may limit species choice elsewhere. Presently, species selection during urban planning is largely based on past and current climate, without accounting for future climate change[16] and on management considerations, prioritizing characteristics such as canopy size or aesthetics[42], which may lead to inadequate consideration of potentially narrow safety margins. Therefore, considering future climate change in urban forest species selection as a prospective strategy should become a priority in cities worldwide but particularly so in low-latitude cities near the equator.

To maintain healthy urban forests in a changing climate, it will be necessary to address economic constraints in establishing and maintaining urban plantings and fill the knowledge gaps in appropriate species selection. To further improve species choice in relation to climate change resilience, information on physiology-based environmental tolerances, as well as ecological functional approaches[43] and trait-based analysis[44–46] are needed. Urban forest monitoring will be essential in guiding species selection and management actions. We highlight the importance of using prospective—rather than retrospective—strategies to preserve urban forests to ensure resilience to climate change. We emphasize the importance of taking immediate actions in terms of the climate emergency[8] to secure the survival and persistence of urban forests globally and the benefits provided by these socio-ecological systems.

Online content

Any methods, additional references, Nature Research reporting summaries, source data, extended data, supplementary information, acknowledgements, peer review information; details of author contributions and competing interests; and statements of data and code availability are available at https://doi.org/10.1038/s41558-022-01465-8.

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Methods

Urban forests composition and urban areas. We obtained data of tree and shrub species present in cities from the Global Urban Tree Inventory (GUTI) database[48]. This database compiles presence data for 4,734 tree and shrub species found in 473 urban areas globally and includes data from published and unpublished tree inventories, online data portals and tree species lists contained in studies published in the scientific literature. Details on the compilation of these data are reported elsewhere[48].

Across the 473 cities, the average number of species per city reported in GUTI was 92 species (s.d. ± 106), with 72 cities having fewer than 10 species. A small number of recorded species for a city probably represents under-sampling of the diversity of species and their respective climate niches than is present. To assess possible sampling bias of climate niches for cities with small numbers of species, we randomly sampled the full set of species in the dataset to get a mean climate variable expected for *X* number of species (that is, simulating cities with varying numbers of species). We then assessed the stabilization of the mean (and variance around the mean) as we increased the number of species sampled. High instability of the mean at low numbers of species would indicate potential bias in the range of climate niches represented by the sample. On the basis of this analysis, we removed cities with fewer than 50 species (Supplementary Fig. 9) as well as cities that were identified as municipalities or local areas within major cities. The dataset used for the analyses included 164 cities from 78 countries and 3,129 tree and shrub species (165 families).

For all 3,129 tree and shrub species, we obtained occurrence records from two sources: (1) the Global Biodiversity Information Facility (https://www.gbif.org/; 18 December 2019 GBIF occurrence download https://doi.org/10.15468/dl.cpwlwc); and (2) sPlotOpen, an environmentally balanced, open-access, global dataset of vegetation plots (German Centre for Integrative Biodiversity Research (iDiv)[49]). Vascular plant species recorded in this dataset represent cover or abundance of naturally co-occurring species within delimited areas[50]. For sPlotOpen, we only retained occurrence information (plot coordinates) and for GBIF, we only retained occurrence records with geographical coordinates. Additionally, occurrence records were filtered and cleaned by removing spatially invalid or suspect records that could lead to miscalculation of species' climatic niches and duplicate records using the CoordinateCleaner package[51] in R v.4.0.5 (ref. [52]). We retained only species with more than 20 occurrence records. We found 2,555 species (82%) shared between GBIF and sPlotOpen (data from 95,104 vegetation plots). The average number of occurrence records per species (GBIF + sPlotOpen) was 1,041 (±518), with a maximum of 92,331 occurrences (*Quercus robur*). Taxonomy was standardized and verified against GBIF and then against The Plant List (TPL; www.theplantlist.org) using the Taxonstand package[53] in R[52].

Polygons defining the spatial boundaries of 6,018 urban areas (cities) globally were obtained from ref. [54] as a shapefile (WGS84; 1:10 million; EPSG:4326). These data were projected to the Mollweide projection, an equal-area pseudocylindrical map projection (ESRI:54009). Additionally, we obtained population size[47] of all 164 cities, daytime average maximum land surface temperatures (representative of the UHI effect)[39] for 122 cities and for each country the 2019 readiness score quantified by ND-GAIN. ND-GAIN is an index of a country's vulnerability to climate change and its capacity for investment in adaptation actions[27]. This index measures a country's exposure, sensitivity and ability to adapt to the negative impact of climate change based on six life-supporting sectors (food, water, health, ecosystem services, human habitat and infrastructure)[27].

Climate data. Baseline and future climate data were obtained from CHELSA v.1.2 climatologies at high resolution for the Earth's land surface areas[55] at a spatial resolution of 30 arcsec (~1 km at the equator). A detailed description of the generation of these data is given in ref. [55]. We selected five climate variables; two of them describing mean conditions: (1) MAT and (2) AP; and three variables describing extremes of climate: (3) MTWM, (4) MTCM and (5) PDQ (Supplementary Table 6). These variables are known for their biological relevance and influence on species distributions, ecological interactions and species survival[56,57]. All climate data were projected to the Mollweide projection system (ESRI:54009) at a 1 km resolution using bilinear interpolation. Throughout the text, we refer to 'baseline climate' as the average climate conditions during the baseline period 1979–2013.

Future climate data were downloaded as projections for ten GCMs: (1) bcc-csm1-1; (2) CCSM4; (3) CESM1-CAM5; (4) CSIRO-Mk3-6-0; (5) GFDL-CM3; (6) HadGEM2-AO; (7) IPSL-CM5A-MR; (8) MIROC-ESM-CHEM; (9) MIROC5; and (10) NorESM1-M (Supplementary Table 7). We extracted values of the five climate variables from all ten GCMs and estimated the median for all our analyses. By selecting multiple GCMs, we aimed to capture the uncertainty and variability around future climate scenarios. We selected two time periods: 2050 (average for 2041–2060) and 2070 (average for 2061–2080) and the two RCPs 4.5 and 6.0, which project a peak in emissions around 2040 and 2080, respectively, followed by a decline[58]. Of all GCMs, CSIRO-Mk3-6-0 showed the greatest variability for AP and PDQ (Supplementary Fig. 10). Climate in urban areas is complex and its future projections can be uncertain. However, recent research has enhanced model projections[39,59,60]; therefore, we downloaded global multimodel projections of local urban climates at a resolution of 0.9° latitude × 1.25° longitude[59] for the time period 2040–2060 and RCP 8.5 and estimated the MTWM using the same set of GCMs.

When we compared future climate changes between GCMs and global multimodel projections of local urban climates, we found the latter were 0.42 °C (median) warmer than future projections from CHELSA (Supplementary Fig. 11). This finding gives confidence in our estimation of the cities' future climate for 2050 and RCP 6.0. However, we highlight that the global multimodel projections of local urban climates do not consider the effects of future urban population growth and future urban land use changes. Therefore, additional effects of future changes in human population and urban land use are not included in our analyses and could further amplify the risk, suggesting that our future estimates are conservative.

Importantly, we acknowledge that climate data based on coarse-grained spatial interpolations from weather stations that are shielded from direct solar radiation, as used here, can fail to identify areas where conditions are more benign or cooler due to the buffering effect of vegetation cover (microclimatic processes)[61] or areas where harsh conditions can be exacerbated by the UHI due to lack of vegetation and presence of impervious surfaces[62]. We found that the current daytime average maximum land surface temperatures (UHI; see details below) can be 8.4 °C (median) warmer than air temperature based on future climate changes in 2050 as provided by GCMs (Supplementary Fig. 12). Therefore, the risks we calculated are probably conservative, leaving the possibility of greater risks than what we are reporting if urban warming is intensified in the future. Finally, we highlight that future projections of UHI and urban precipitation changes are still lacking at a global extent, limiting the incorporation of these urban effects.

Species' realized climate niche and cities' climate. For all species, we extracted values of the aforementioned climate variables from all global occurrence records to characterize species' realized climate niches under baseline climatic conditions. For each city, we placed a grid ($1 \times 1\,\text{km}^2$) over its area and extracted the values of all five variables at each cell for both baseline and future climates using the function 'exact_extract' from the exactextractr package[63]. For global multimodel projections, we extracted climate data from the grid cells closest to the cities' polygon, where the median distance was 25.6 km.

We calculated the niche breadths for all species (Supplementary Data 2) and the upper and lower limits of the temperature and precipitation variables, respectively, on the basis of the global geographic range for each species, whereas cities' climate values were estimated using all grid cells of each city. Spatial autocorrelation of climate variables associated with the species occurrences was assessed using the raster package[64] on the basis of Moran's *I*. We calculated the upper and lower bounds of the distribution of values across the species range to determine whether cities are likely to exceed species' limits. For this, we selected the threshold of the 95th percentile of MAT and MTWM and the 5th percentile of MTCM, AP and PDQ. We used these thresholds to assess the extremes of these variables as indicative of species safety margin (that is, species' thermal and drought stress tolerance for survival and growth)[17] and towards the main direction of change for the variable being examined (for example, the warm limit in case of warmer MAT or the dry limit in case of drier AP). Throughout the text, when referring to these climate variables, we imply the use of the 95th (MAT and MTWM) and 5th (MTCM, AP and PDQ) percentiles, accordingly (Supplementary Fig. 3).

Climate change impact metrics. We selected three climate change impact metrics for our analysis: exposure, safety margin and risk[18,23]. These metrics were calculated for all five climate variables, time periods (baseline and future (2050 and 2070)) and RCPs (4.5 and 6.0).

Exposure (*E*) is the degree to which a city is exposed to climatic change[22] and is a measure of how much the climate is projected to change (for example, warmer or drier) between current and future time periods in a given location; thus, it is calculated as the difference between the city's future and baseline climate as follows:

$$E = \text{City}_{\text{FutureClimate}} - \text{City}_{\text{BaselineClimate}}$$

A positive exposure ($E > 0$) indicates that warmer (or wetter) conditions are expected under future climate change scenarios, while negative exposure ($E < 0$) indicates that colder (or drier) conditions are expected under future climate change. Here, we are more specifically interested in the positive exposure for MAT, MTWM and MTCM, as expected under warmer climates, but negative exposure for AP and PDQ, as expected under drier climates.

The safety margin (*S*) describes a species' sensitivity to climate change (warmer and drier, on average, here) and indicates its potential tolerance to changing climate conditions that may exceed either of the species' upper or lower climatic limits (its upper limit for MAT and MTWM and or its lower limit for MTCM, AP and PDQ) within a given city and indicates how much warmer (or drier) a city could become before the upper or lower tolerance limits of its resident species have been exceeded and was calculated as follows:

$$S = \begin{cases} \text{Species}_{\text{ClimateVariable}[i]} - \text{City}_{\text{BaselineClimate}}\ (\text{MAT, MTWM}) \\ \text{City}_{\text{BaselineClimate}} - \text{Species}_{\text{ClimateVariable}[i]}\ (\text{MTCM, AP, PDQ}) \end{cases}$$

For *S*, a species' climatic limit ($\text{Species}_{\text{ClimateVariable}[i]}$) was measured as the 95th (MAT and MTWM) and the 5th (MTCM, AP and PDQ) percentiles of the species' climate niche based on its global occurrence records and baseline climatic conditions from CHELSA. The difference between $\text{Species}_{\text{ClimateVariable}[i]}$ and the long-term average climatic conditions experienced in the focal city ($\text{City}_{\text{BaselineClimate}}$) is calculated as the 'safety margin' (S) for each focal species-by-city combination[17]. That is, a positive safety margin ($S > 0$) indicates that the species has a climatic tolerance limit which exceeds current baseline climatic conditions in the focal city (for example, cooler or wetter and thus safe under warmer and drier future conditions); whereas a negative value ($S < 0$) indicates that the species is already now experiencing 'unsafe' climatic conditions under the baseline (for example, warmer than the warm limit or drier than the dry limit) that the species can actually withstand according to its known limits for temperature or precipitation) (Supplementary Fig. 3).

The risk (R) refers to the potential for adverse consequences on biological systems[26] and is calculated as the difference between the city's extrinsic exposure to future climate change and the species' intrinsic safety margin. Thus, if the exposure to future climate is greater than the current safety margin for the focal species in a focal city (that is, high risk), then $R > 0$ for MAT and MTWM and $R < 0$ for MTCM, AP and PDQ. Yet, if the exposure (E) to future climate change is still within the range of values allowed by the safety margin (S), then $R < 0$ for MAT and MTWM and $R > 0$ for MTCM, AP and PDQ, and it is considered 'safe' under future conditions (that is, low risk) (Supplementary Fig. 3). Risk to climate change (R) was calculated as:

$$R = \begin{cases} E - S_{(\text{MAT,MTWM})} \\ S + E_{(\text{MTCM,AP,PDQ})} \end{cases}$$

Linear regressions were fitted to evaluate the relationship between: (1) climate exposure and latitude of cities; (2) species' risk and cities' latitude (assessing northern and southern hemispheres independently); and (3) species' risk and UHI, using independent linear models (the lm function in R). We used this approach because linear mixed-effects models did not converge. The relationships between species' risk and ND-GAIN scores and climate exposure were analysed using linear mixed-effects models (the lmer function from the lme4 package[65]) followed by analysis of variance, using country and species as random intercept terms. Models were developed for each climatic variable as a response variable and model performance was evaluated through the calculation of the F-statistic at a significance level of $P < 0.05$. All analyses were conducted using the statistical software R v.4.0.5 (ref. [52]) and all maps were generated using maptools package[66].

Data availability

The data generated and analysed for this study have been deposited on Figshare: https://figshare.com/projects/Climate_change_increases_global_risk_to_urban_forests/144039

Code availability

All data were edited and analysed in R v.4.0.5 (ref. [52]) and Microsoft Excel v.16.17.27 (201012). The complete codes used to generate and visualize the results reported in this study have been deposited on Figshare: https://figshare.com/projects/Climate_change_increases_global_risk_to_urban_forests/144039

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Author contributions

M.E.R., R.V.G., P.D.R., S.A.P. and M.G.T. conceived the article. M.E.R., R.V.G., L.J.B., P.D.R., S.A.P. and M.G.T. designed the research. M.E.R., J.B.B., D.A.N., R.V.G., J.L. and B.R. collected, provided code and analysed data. M.E.R. wrote the first draft of the article. All authors contributed to the discussion of the content and reviewed or edited the manuscript before submission. All authors, except for M.E.R., M.T.G., J.L. and R.V.G., are listed alphabetically.

Competing interests

The authors declare no competing interests.

Additional information

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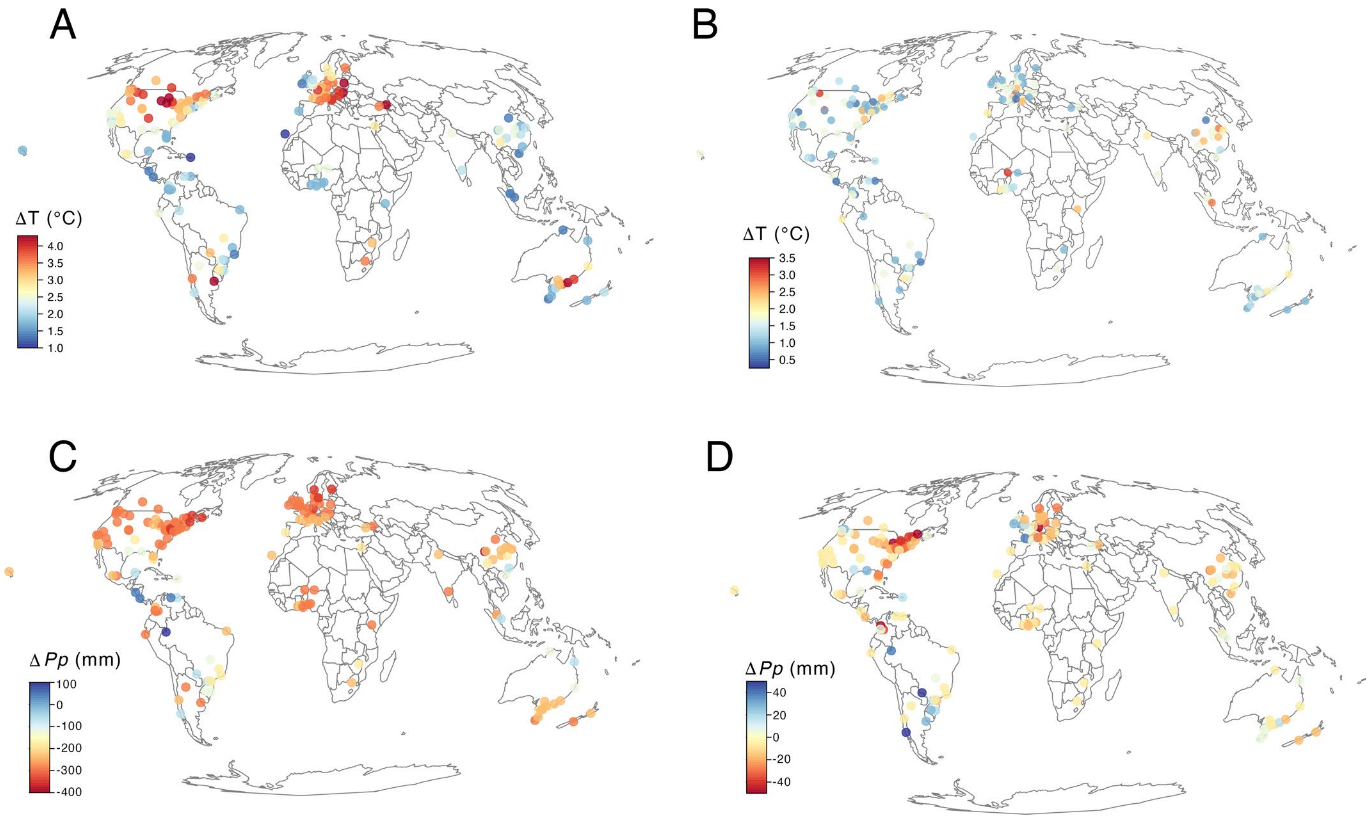
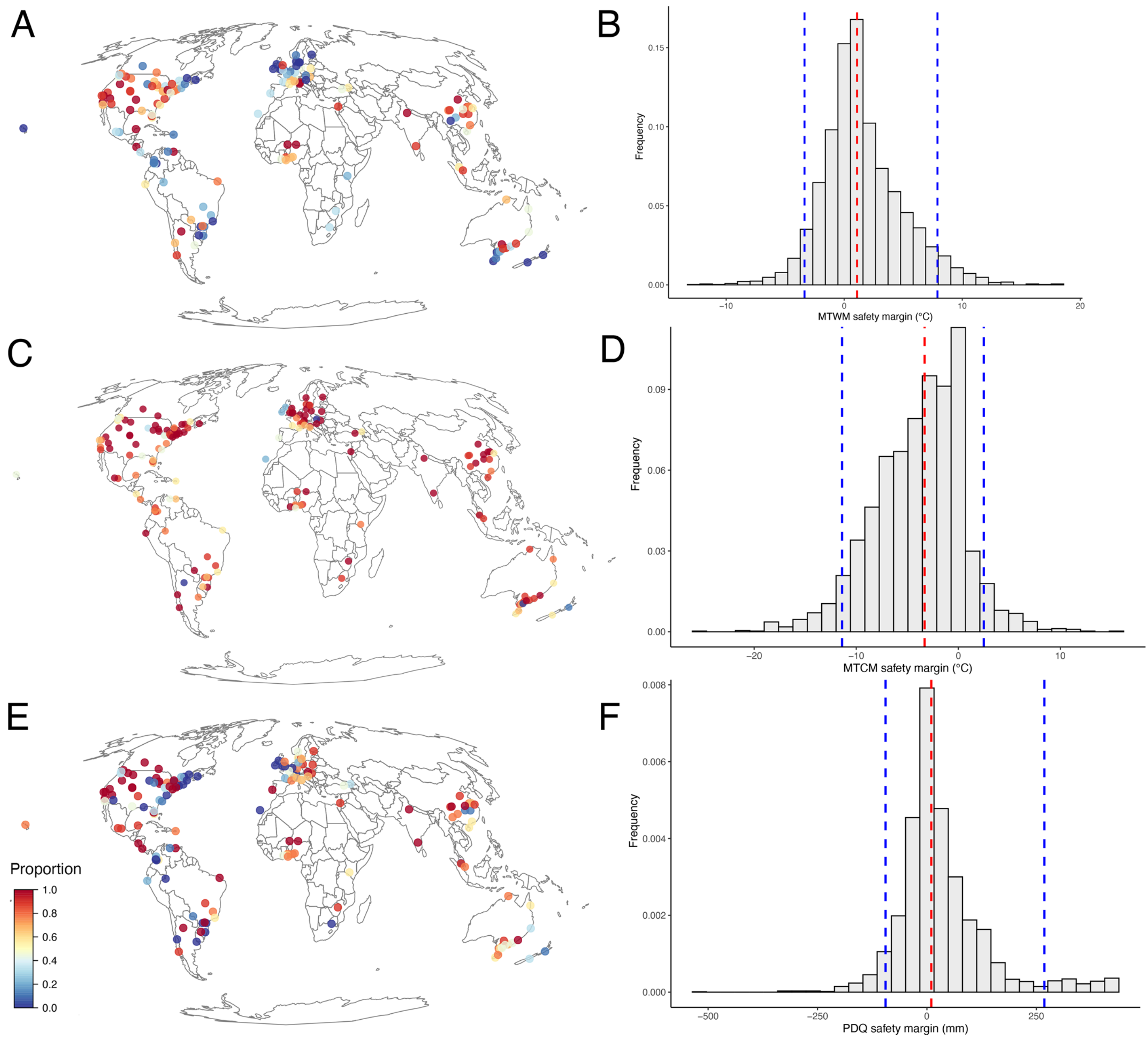
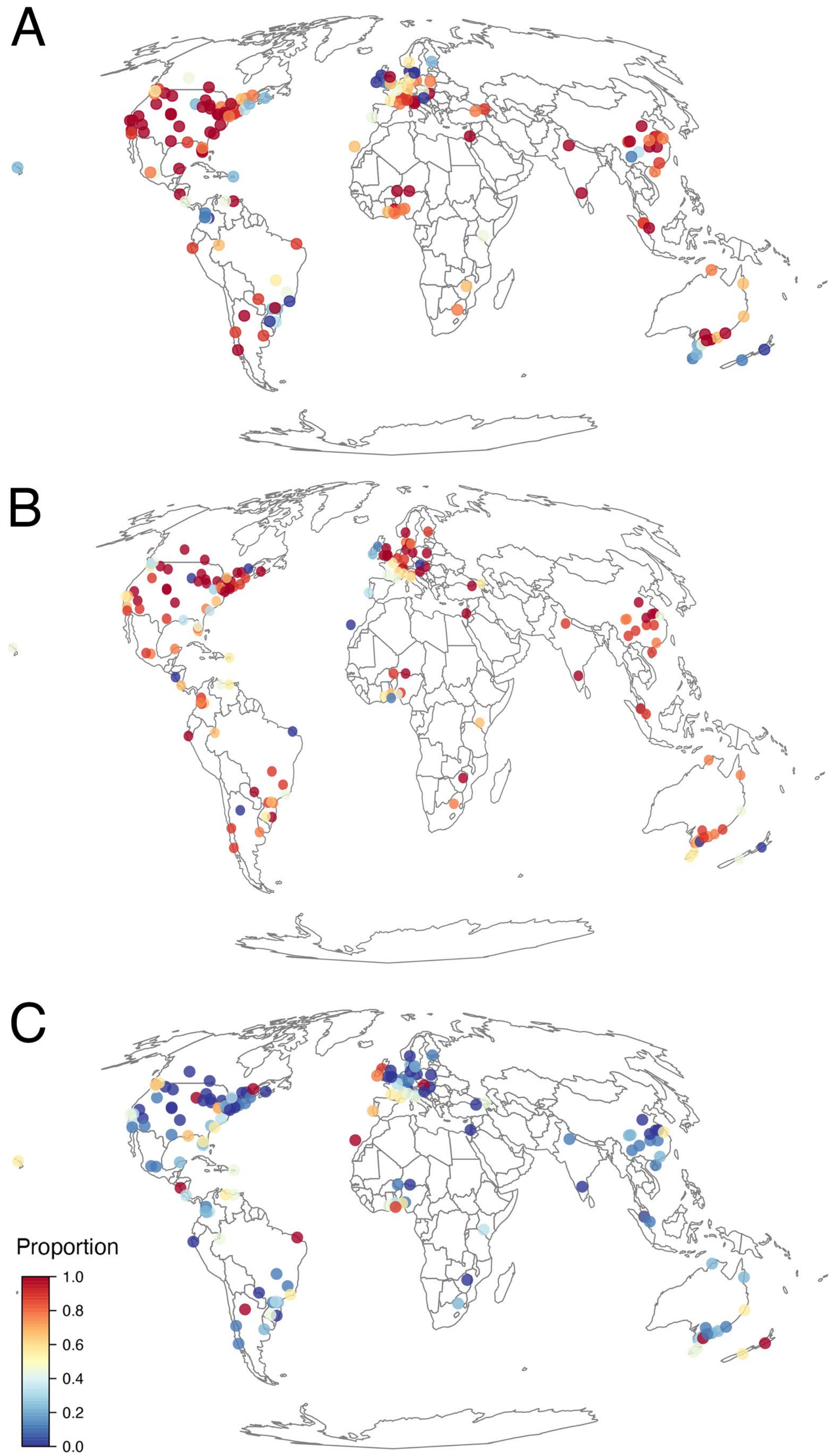


Extended Data Fig. 1 | Exposure to future climate change across the world's cities. Changes (i.e. exposure) in maximum temperature of the warmest month (**A**), minimum temperature of the coldest month (**B**), annual precipitation (**C**), and precipitation of the driest quarter (**D**) predicted to occur by 2050. Data for Representative Concentration Pathway 6.0.



Extended Data Fig. 2 | Contemporary tree and shrub species safety margin across the world's cities. Proportion of tree and shrub species presently exceeding their current safety margin for maximum temperature of the warmest month (MTWM; A), minimum temperature of the coldest month (MTCM; **C**), and precipitation of the driest quarter (PDQ; **E**) in 164 cities where they are planted. Frequency distribution of mean values of MTWM (**B**), MTCM (**D**) and PDQ (**F**) safety margin of each species ($n = 3{,}129$). Red and blue lines indicate the median and 5th/95th percentiles, respectively. A positive safety margin ($S > 0$) indicates that the species has a climatic tolerance limit that exceeds climatic conditions; whereas a negative value ($S < 0$) indicates that the species is subject to 'unsafe' climatic conditions outside its climatic tolerance limits.



Extended Data Fig. 3 | Tree and shrub species at risk of future climate change impacts across the world's cities. Proportion of plant species predicted to be at risk of changes in maximum temperature of the warmest month (**A**), minimum temperature of the coldest month (**B**), and precipitation of the driest quarter (**C**) in 164 cities where they are planted. Data for 2050 and Representative Concentration Pathway 6.0.