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Global trends in urban forest irrigation: Environmental influences, challenges and opportunities for sustainable practices across 109 cities worldwide

Manuel Esperon-Rodriguez [a,b,*], Rachael V Gallagher [a], Alessio Russo [c], Sally A Power [a], Pedro Calaza-Martínez [d], Tiago Capela Lourenço [e], Paloma Cariñanos [f,g], Ana Alice Eleuterio [h], Zhengfei Guo [i], Gervais Lee [j], Pierre Masselot [k], Robert I. Mcdonald [l,m,n], Christian Messier [o,p], Camilo Ordoñez [q], Mostafa Parpanchi [r], Rossano Schifanella [s,t], Charlie Shackleton [u], Mahmuda Sharmin [v], Ingjerd Solfjeld [w], Annick St-Denis [p], Jens-Christian Svenning [x], Maria Martha Torres-Martinez [y], Björn Wiström [z], Pengbo Yan [aa], Jun Yang [bb], Mark G Tjoelker [a]

[a] *Hawkesbury Institute for the Environment, Western Sydney University, Locked Bag 1797, Penrith, NSW 2751, Australia*
[b] *School of Science, Western Sydney University, Locked Bag 1797, Penrith, NSW 2751, Australia*
[c] *School of Architecture and Built Environment, Queensland University of Technology, Brisbane, Australia*
[d] *Spanish Association of Public Parks and Gardens (AEPJP), Higher Technical School of Mountains, Forestry and Natural Environment Engineering, Polytechnic University of Madrid, Madrid 28040, Spain*
[e] *Centre for Ecology, Evolution and Environmental Changes (CE3C) & Global Change and Sustainability Institute (CHANGE), Faculdade de Ciências, Universidade de Lisboa, Lisbon 1749-016, Portugal*
[f] *Department of Botany, Faculty of Pharmacy University of Granada, Granada, Spain*
[g] *IISTA-CEAMA, Andalusian Institute for Earth System Research University of Granada, Granada, Spain*
[h] *Instituto Latino-Americano de Economia, Sociedade e Política, Universidade Federal da Integração Latino-Americana, Brazil*
[i] *Department of Geography, The University of Hong Kong, Hong Kong, China*
[j] *Fenner School of Environment & Society, The Australian National University, Canberra ACT 2601 Australia*
[k] *Environment & Health Modelling (EHM) Lab, Department of Public Health Environments and Society, London School of Hygiene & Tropical Medicine, 15-17 Tavistock Place, WC1E 7HT, London, United Kingdom*
[l] *The Nature Conservancy, Berlin, Germany*
[m] *CUNY Institute for Demographic Research, NY, NY, United States*
[n] *Humboldt University, Berlin, Germany*
[o] *Institut des sciences de la forêt tempérée, 58 rue principale, Département des sciences naturelles, Université du Québec en Outaouais, Ripon, Québec J0V 1V0, Canada*
[p] *Centre d'étude de la forêt, Département des sciences biologiques, Université du Québec à Montréal, 141 avenue du Président-Kennedy, Montréal, Québec, H2×1Y4, Canada*
[q] *Department of Geography, Geomatics and Environment, University of Toronto at Mississauga, Mississauga, ON, Canada*
[r] *University of Milano-Bicocca, Milano MI 20126, Italy*
[s] *University of Turin, Via Giuseppe Verdi 8, 10124, Italy*
[t] *ISI Foundation, Turin, Italy*
[u] *Department of Environmental Science, Rhodes University, P.O. Box 94, Makhanda 6140, South Africa*
[v] *Department of Forestry and Environmental Science, Shahjalal University of Science and Technology, Sylhet, 3114, Bangladesh*
[w] *Faculty of Landscape and Society, Norwegian University of Life Sciences (NMBU), N-1432 ÅS. Norway*
[x] *Center for Ecological Dynamics in a Novel Biosphere (ECONOVO), Department of Biology, Aarhus University, C, DK-8000, Aarhus, Denmark*
[y] *Postgraduate Program in Neotropical Biodiversity, Instituto Latino-Americano de Ciências da Vida e da Natureza, Universidade Federal da Integração Latino-Americana, Foz do Iguaçu, Brazil*
[z] *Department of Landscape Architecture, Planning and Management, Swedish University of Agricultural Sciences, Slottsvägen 5, 23053 Alnarp, Sweden*
[aa] *School of Tourism Ecology and Environment, Guilin Tourism University, Guilin 541006, China*
[bb] *Department of Earth System Science, Institute for Global Change Studies, Ministry of Education Ecological Field Station for East Asian Migratory Birds, Tsinghua University, Beijing 100084, China*

* Corresponding author.
E-mail address: m.esperon-rodriguez@westernsydney.edu.au (M. Esperon-Rodriguez).

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ABSTRACT

Urban forests are critical for climate adaptation and liveability, but effective irrigation management—key to their sustainability—remains poorly documented at the global scale. This study addresses this critical knowledge gap by analysing urban forest irrigation practices across 109 cities in 21 countries, offering one of the first global assessments of irrigation approaches, challenges, and opportunities. Using survey data, we examined water sources, irrigation frequency, constraints, and enabling conditions. Our results show that weather conditions were the leading factor influencing irrigation scheduling in 44 % of cities, while 56 % reported no formal water restrictions. Despite the importance of water conservation, 55 % of respondents reported having no water usage monitoring systems, and 73 % lacked financial incentives to promote water-efficient irrigation. A large majority (80 %) did not use recycled wastewater, and 58 % did not conduct water quality testing. Only 15 % of cities regularly used water-efficient irrigation technologies, and 47 % had no plans to implement smart systems. Over half (56 %) rated their current irrigation practices as only moderately successful. Budget constraints and infrastructure limitations were the most frequently reported challenges, followed by climate change-related concerns. While environmental variables such as mean annual temperature and irrigation need influenced specific practices, local governance and institutional actions had stronger effects. Cities in the Global South reported distinct strategies and constraints compared to those in the Global North. Our findings provide actionable insights for climate-resilient urban water strategies and underscore the need for targeted policies, capacity-building, and efficient technologies to enhance urban forest sustainability worldwide.

1. Introduction

Global average temperatures reached a record 14.8 °C in 2024—1.34 °C above the 20th-century mean—underscoring the urgency of climate adaptation (NOAA, 2024). With urban areas hosting over half the global population and projected to reach 70 % by 2050 (UN, 2018), cities are increasingly exposed to climate extremes including heatwaves, droughts and floods (Dharmarathne et al., 2024; Esperon-Rodriguez et al., 2025b; Guerreiro et al., 2018; Hanson et al., 2011; IPCC, 2023; UNEP, 2023). Cities in lower- and middle-income countries face particular vulnerabilities due to rapid and often unplanned urbanisation, which amplifies the effects of urban heat islands and socio-economic inequality (Dyer et al., 2024; Steele et al., 2023; Wahba Tadros et al., 2021).

Nature-based solutions, particularly urban forests, offer promising and cost-effective strategies to enhance urban climate resilience and sustainability (Fang et al., 2023; Sahay, 2025). Urban forests—comprising the entire assembly of trees in a city, including trees in streets, trees in parks, trees in public and private land, and all woodlands and groups of trees (FAO, 2016)—support human health, reduce energy use, regulate stormwater, and mitigate extreme heat through shading and evapotranspiration (Ballinas & Barradas, 2016; Escobedo et al., 2019; Keeler et al., 2019). However, urban trees face harsh growing conditions, such as limited water availability, compacted soils, soil sealing, limited rooting volumes, and increasingly frequent climate extremes (Bullock & Gregory, 2009; Esperon-Rodriguez et al., 2022; Jim, 1993; Miron et al., 2022; Mullaney et al., 2015; Rosenberger et al., 2024). Thus, supplemental irrigation is often critical to sustaining urban trees, particularly during establishment and in hot, dry climates (Czaja et al., 2020; FAO, 2022; Fini & Brunetti, 2017).

Despite the critical role of irrigation in urban forest management, collective understanding of how irrigation practices vary across cities worldwide remains limited, especially regarding the adoption and effectiveness of sustainable irrigation management strategies. Inconsistent or poorly managed irrigation practices may fail to alleviate water stress in urban greenery, while excessive irrigation may also result in tree decline due to waterlogged soils (Bijoor et al., 2014; Grey et al., 2018; Grijseels et al., 2023). Cities also have to contend with numerous competing pressures associated with urban water demand and supply (Hoekstra et al., 2018), providing strong motivation for sustainable urban forest irrigation practices. However, common trends and barriers regarding the adoption of effective and sustainable urban forest irrigation strategies across different cities remain poorly understood (Esperon-Rodriguez et al., 2025a), with previous studies having focused on irrigation needs and challenges at local or regional scales (e.g., Gebul, 2021; Gober et al., 2009; Litvak et al., 2014). Furthermore, although cities are increasingly experimenting with smart irrigation technologies—such as automated systems and IoT-based soil moisture monitoring (Froiz-Míguez et al., 2020; Hui et al., 2023)—there is limited knowledge about their adoption, particularly in the Global South, where budgetary and infrastructural constraints may hinder implementation (Nitoslawski et al., 2019; Russo & Escobedo, 2022). Thus, while research has advanced knowledge of urban greenery planning and management in individual regions or countries (e.g., Lara-Valencia et al., 2022; Livesley et al., 2021; Pan et al., 2023), urban irrigation practices remain an understudied aspect of global comparative urban forestry research, where the lack of comprehensive assessments of irrigation practices across cities worldwide represents a missed opportunity for practitioners to collaboratively address shared challenges and advance best practices. While global efforts have begun to map irrigation in agriculture, including spatial and temporal trends (Mehta et al., 2024), a critical lack remains of equivalent data or systematic assessments for irrigation practices in urban forestry.

This study represents the first global exploration of urban forest irrigation practices, filling a critical gap in our understanding of how cities manage water for urban greenery under varying climatic and socio-economic conditions. Uniquely, it also explores the environmental and geographic drivers shaping these practices across diverse urban contexts, while identifying common trends and barriers regarding the adoption of effective irrigation practices. For this, we surveyed 109 cities in 21 countries to investigate how environmental factors (e.g., temperature, aridity, latitude) and socio-economic contexts influence irrigation strategies. This work contributes to global urban forestry literature by (1) systematically documenting irrigation practices and barriers across diverse regions, (2) evaluating the influence of climate variables and regional context on irrigation management, and (3) assessing the adoption of sustainable and smart irrigation technologies. Our findings reveal key challenges, identify opportunities for enhancing irrigation management, and provide new insights to guide policy and management strategies to support climate-resilient urban forests

This study focuses on identifying patterns in irrigation practices across global cities, together with their potential influences and enabling conditions. Specifically, we aim to (1) understand how shifting future climate envelopes will influence global urban forest irrigation requirements, (2) determine whether cities with similar climates or regions adopt comparable irrigation strategies, and (3) examine how environmental variables, such as climate, latitude and aridity influence irrigation practices worldwide. We hypothesised that cities in warmer, drier climates would irrigate more frequently and adopt more water-efficient technologies, while cities in wetter climates would rely more on natural rainfall. We also expected regional differences in irrigation practices and capacity, particularly between cities in the Global North and Global South.

2. Methods

To summarise our approach, we identified global cities with populations over 200,000 and contacted local governments to participate in an online survey on urban forest irrigation practices. The survey included questions addressing water sources, irrigation frequency, restrictions, and perceived effectiveness. We obtained spatial, demographic, economic, and climate data for all participating cities from global databases (**Supplemental Table S1**). Future climate projections and potential evapotranspiration data were used to estimate irrigation needs, while environmental variables were extracted and summarised per city. Multiple Correspondence Analysis was used to explore clustering of irrigation practices across climates and regions, while Principal Component Analysis helped identify key environmental and geographic variables. Multinomial Logit Models were then applied to examine how climate and location influence urban irrigation practices. This structured approach integrates survey data with environmental and socio-economic variables to provide a comprehensive analysis of global urban irrigation patterns (Fig. 1).

2.1. Study area and city selection criteria

We identified 525 urban areas (hereafter referred to as cities) in 40 countries with populations exceeding 200,000 inhabitants, based on data from the World Cities Database (World Cities, https://simplemaps.com/data/world-cities; accessed March 2024). This population threshold was chosen because large cities typically offer a comprehensive representation of diverse urban landscapes, infrastructure, and population densities associated with urbanisation (Dyer et al., 2024). These cities are more likely to have a significant environmental footprint, including substantial water consumption for irrigation, and are also more likely to possess the resources and infrastructure necessary for implementing and monitoring advanced irrigation systems (Mahjabin et al., 2018; Parkinson et al., 2017; Yigzaw & Hossain, 2016). Using this list of large cities, we contacted municipalities, counties, or local government areas via generic email addresses obtained from official websites. Additionally, we used personal contacts and networks to reach out to cities with populations under 200,000. All participants were asked to respond to an online survey to collect data on global urban irrigation practices.

2.2. Survey design and implementation

The survey included 17 questions related to sources of water used for irrigation of urban forests (i.e., the entire assembly of public trees in a city), irrigation frequency and restrictions, along with questions about challenges and effectiveness of their practices (**Supplemental Table S2**). In constructing the survey questions, we aimed to comprehensively assess global urban irrigation practices while addressing our primary research aims. To investigate whether cities with similar climates have similar irrigation practices, we included questions about water sources, irrigation frequency, methods, and technologies used. These questions allowed for comparison of practices across different climatic regions. To examine the influence of environmental and human demographic factors on urban irrigation practices, we incorporated questions about water restrictions, monitoring systems, educational programs, and financial incentives. These questions helped elucidate how different environmental and socio-economic factors might shape irrigation practices in different cities.

We specifically targeted personnel from city or municipal government departments responsible for urban forest management, particularly those involved in watering and irrigation practices. To ensure relevant expertise, we included a screening question asking participants to confirm their role in urban forest irrigation planning and/or decision-making. All respondents reported working directly in urban forest management and contributing to irrigation strategies. Their professional experience ranged from 3 to 25 years, with an average of nine years. The survey was available in 11 languages (i.e., Bengali, Chinese, English, French, German, Italian, Norwegian, Persian [Farsi], Portuguese, Spanish, and Swedish) and was open from May to September 2024. We received responses from 109 cities in 21 countries (Fig. 2, **Supplemental Tables S3-S4**).

The 109 cities surveyed included 86 cities (71 %) from the Global North and 23 cities (21 %) from the Global South. The highest number of responses came from Europe (47 cities, 43 %), followed by North America (28 cities, 26 %), South America (13 cities, 12 %), Asia (11 cities, 10 %), and Oceania (10 cities, 9 %). In terms of climate zones, most responses were from cities with temperate climates (56 cities, 51 %), followed by continental (35 cities, 32 %), arid (10 cities, 9 %), and tropical (8 cities, 7 %) climates (**Supplemental Tables S3-S4**).

The study and protocol were approved by the Human Research Ethics Committee (HREC) of Western Sydney University under approval number H15948. The HREC is constituted and operates in accordance with the National Statement on Ethical Conduct in Human Research 2007 (Anderson, 2011). Participants were provided with detailed information about the nature and purpose of the research. Informed consent was obtained from the participants to contribute to the current

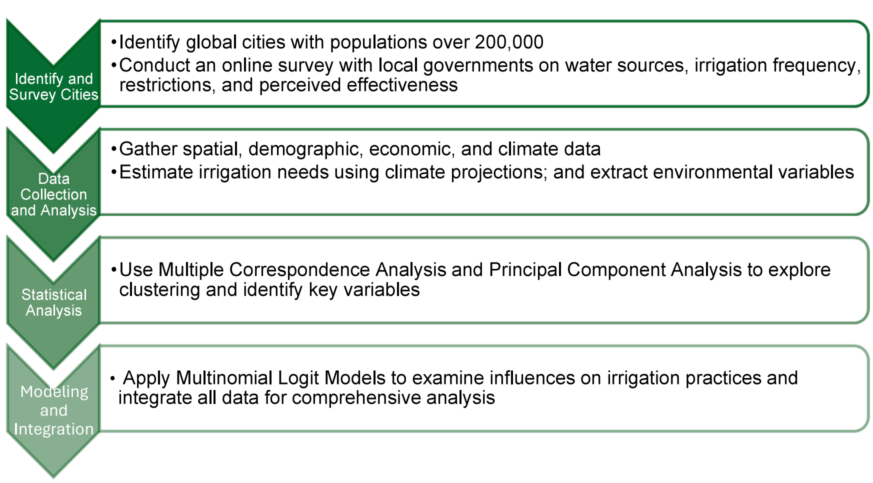

Fig. 1. The flowchart outlines the key steps in the methodology.

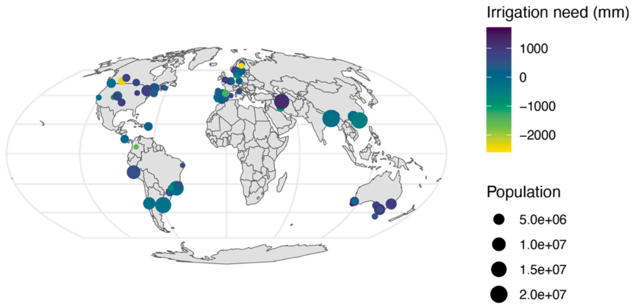

Fig. 2. Location of 109 cities in 21 countries that participated in an online survey on global urban irrigation practices of urban forests. The colour scale represents future water irrigation need, calculated as the difference between future potential evapotranspiration and future annual precipitation (average conditions during 2041–2060). Positive values (i.e., darker colours) indicate the amount of water needed for irrigation. The size of the points is related to city population, with larger points indicating higher population sizes. For details on demographic and economic characteristics, climates, and irrigation needs for each city, see **Supplemental Tables S3-S4**.

study prior to their involvement in the project.

2.3. City data

We obtained polygons defining the spatial boundaries of 109 cities as a shapefile (v4.0.1, WGS84; 1:10 million; EPSG:4326) from Natural Earth (Schneider et al., 2003; https://www.naturalearthdata.com; accessed January 2025). These data were derived from NASA SRTM and tailored to register with Natural Earth Vector, with urban polygons derived from MODIS satellite data. City area data were also extracted from this dataset.

Population data for 2024 were sourced from the World Cities Database (World Cities, https://simplemaps.com/data/world-cities; accessed January 2025), which compiles information from authoritative sources including the NGIA, US Geological Survey, US Census Bureau, and NASA. Using the cities' area and population, we estimated the population density of each city. Gross Domestic Product (GDP) data for 2022 were obtained from the Global Cities by GDP database (Global Cities, https://www.kaggle.com/datasets; accessed January 2025), providing economic output and population statistics for major metropolitan areas. When city-specific GDP data were unavailable, we used values from the next higher administrative level (**Supplemental Table S3**).

2.4. Climate and potential evapotranspiration data

Climate data for baseline (average of conditions during 1970–2000) and future (average of conditions during 2041–2060, centred in 2050) conditions were obtained from WorldClim Version 2.1 (Fick & Hijmans, 2017) at a spatial resolution of 30 arc-seconds (~1 km^2). Future climate projections were based on the Shared Socioeconomic Pathway SSP3–7.0, a medium-high reference scenario that assumes reduced air pollution controls and increased aerosol emissions, filling a gap in previous Representative Concentration Pathways (Meinshausen et al., 2020, 2024). We selected five global circulation models (GCMs) to account for model uncertainty: (1) GFDL-ESM4; (2) IPSL-CM6A-LR; (3) MPI-ESM1-2-HR; (4) MRI-ESM2-0; and (5) UKESM1-0-LL. These GCMs are part of the Coupled Model Intercomparison Project Phase 6 (CMIP6), which informs the IPCC Sixth Assessment Report (IPCC, 2023). We focused on two bioclimatic variables: mean annual temperature (MAT; °C) and annual precipitation (AP; mm). The Köppen-Geiger climate classification for each city was derived from Peel et al. (2007).

Global Aridity Index (hereafter Aridity) and potential evapotranspiration (PET) data for future conditions (average of conditions during 2041–2060, centred in 2050) were obtained from Zomer et al. (2024) at a 30 arc-second (~1 km^2) spatial resolution. To ensure consistency with climate projections, Aridity and PET data were based on the SSP3–7.0 and the same five GCMs used for climate variables. We calculated the irrigation water need (*IN*) using future projections of PET and annual precipitation (AP) with the following formula:

$$IN = PET_{Future} - AP_{Future} \quad (1)$$

A positive *IN* value indicates the amount of water needed for irrigation, while a negative value suggests that precipitation exceeds evapotranspiration, potentially negating the need for irrigation. We acknowledge this method does not account for effective rainfall (i.e., the portion of precipitation actually available to plants), soil characteristics, or irrigation efficiency. Additionally, the annual estimate may not capture seasonal variations in water needs by vegetation (Critchely & Siegert, 1991). Despite these constraints, this approach provides a first-order approximation of future irrigation requirements, valuable for broad-scale planning and comparative analyses across urban areas.

For each city, we extracted MAT, AP, Aridity and PET values using the 'exact_extract' function from the *exactextractr* package (Baston et al., 2021) in *R*, applying a regular grid at 1 km^2 resolution. We then calculated the average value across all extracted grid cell data to derive a single mean value for each city (**Supplemental Table S4).** Exposure to future change for each climate variable (ΔMAT and ΔAP) and city was calculated as the difference between future climate projections (2041–2060; median across five GCMs) and baseline climate conditions (1970–2000):

$$\Delta MAT = MAT_{Future} - MAT_{Baseline} \quad (2)$$

$$\Delta AP = AP_{Future} - AP_{Baseline} \quad (3)$$

2.5. Statistical analyses

To assess whether cities sharing similar climates or geographic regions employ comparable irrigation strategies, we analysed survey data on irrigation practices using Multiple Correspondence Analysis (MCA). This method was chosen because all survey questions yielded categorical responses, making MCA an appropriate technique for handling such data (Abdi & Valentin, 2007). First, we pre-processed the data to accommodate multiple selections per question. For each question, we split the responses into separate categories, for example, treating combinations like "Sprinkler irrigation & Drip irrigation" as distinct categories. This involved creating new columns for each possible response across all questions. For instance, if a question had responses like "Sprinkler irrigation", "Drip irrigation", and "Sprinkler irrigation & Drip irrigation", we created separate columns to represent each of these responses as binary variables. To maintain consistency with MCA requirements, we treated each unique value (including combinations) as a single category.

In our survey, all questions required a response, consequently, there were no missing responses in our dataset. For questions that allowed respondents to provide their own response under an "other" category, we treated these responses as a distinct category by creating a new column for "other" responses. This approach allowed us to capture the diversity of responses while maintaining the categorical structure required for MCA.

We then performed MCA on the pre-processed dataset (i.e., including the responses to all the survey questions) using the 'MCA' function from the *FactoMineR* package (Lê et al., 2008) in *R*, with default settings. MCA is particularly suited for this task because it provides insights into how different categories relate to each other and to the cities (Abdi & Valentin, 2007). By using MCA, we aimed to visualise how cities cluster together based on their irrigation practices and to identify if cities with similar climates (i.e., similar Köppen-Geiger climates) or regions (i.e., continents) also had similar responses (i.e., clustered together).

To evaluate relationships among climate variables, geographic predictors, and economic/demographic factors, we conducted a Principal Component Analysis (PCA) (Jolliffe, 1986). This analysis included climate variables (mean annual temperature, MAT, and annual precipitation, AP), the global aridity index (Aridity), potential evapotranspiration (PET), irrigation water need (*IN*), latitude, longitude, city GDP, and population density. These variables were chosen to assess how climate, geographic location, and economic/demographic factors might influence urban irrigation practices globally. We hypothesised that climate would drive water needs, while geographic location, GDP, and population density would affect resource availability.

By examining the loadings and the magnitude and direction of vectors in relation to the first two principal components (Legendre & Legendre, 2012), we identified a subset of four non-correlated climate-related variables for further modelling analyses: mean annual temperature (MAT), global aridity index (Aridity), irrigation water need (*IN*), and latitude (non-transformed; i.e., positive and negative values) (**Supplemental Figure S1**). This selection was based on the PCA results, which helped us to reduce dimensionality while retaining key variables that capture the underlying patterns in the data. Additionally, we considered whether each city is located in the Global North (i.e., developed countries primarily located in the Northern Hemisphere) or Global South (i.e., the world's developing countries and least developed countries), as this distinction can influence urban development patterns, resource availability, and cultural practices, potentially affecting responses to the survey on irrigation practices. Cities in the Global North often have more developed infrastructure and greater economic resources compared to those in the Global South. As a result, irrigation practices in the Global North are typically supported by well-developed infrastructure, robust institutional frameworks, and access to advanced technologies (Kowalski, 2021; Odeh, 2010). In contrast, in the Global South, irrigation is often shaped by resource constraints, informal governance structures, and the need to adapt to rapid urbanisation and climate variability (Yasmin et al., 2023). These differences in infrastructure and resources directly influence the management of water resources and, consequently, urban irrigation practices worldwide.

We note that non-transformed latitude provides a continuous measure of geographical position that captures more nuanced environmental and ecological gradients than the binary Global North/South classification alone. The North/South categorisation, while useful for broadly representing socioeconomic differences, cannot account for latitudinal variations in climate, day length, seasonality, and other factors that directly influence plant physiology, water requirements, and, consequently, irrigation strategies. Therefore, including latitude allowed us to detect geographical patterns in irrigation practices driven by continuous environmental gradients that would be obscured by a simple division into 'North' and 'South,' adding substantial explanatory power to the models.

To investigate how environmental variables influence global irrigation practices, we analysed the effects of mean annual temperature (MAT), Aridity, irrigation needs (*IN*), and latitude on survey responses employing a Multinomial Logit Model (MLM) and using the 'mblogit' function from the *mclogit* package (Elff et al., 2022) in *R*. MLM is appropriate when analysing categorical dependent variables with more than two unordered categories (Kropko, 2007). MLM was selected because the dependent variable has multiple, unordered categories and our study aimed to examine the influence of multiple independent variables (MAT, Aridity, *IN*, and latitude) on the choice of different irrigation practices. MLM allowed for estimating the probability of each category of the dependent variable based on the predictor variables (Kropko, 2007). This approach enabled a comprehensive analysis of factors influencing global urban irrigation practices among cities, accounting for various environmental and geographical conditions.

We developed 17 models (one for each question), where the dependent variable was the categorical response to a given question (**Supplemental Table S5**). Models were fitted using maximum likelihood estimation, and model assumptions were checked, including independence of irrelevant alternatives, independence of observations, and multicollinearity (Legendre & Legendre, 2012). All variables were standardised using the 'scale' function in *R*, which centred each variable at its mean and scaled it to have a standard deviation of 1. Consequently, the units of the standardised variables are expressed in standard deviations from the mean, allowing for comparison across different metrics. Model performance (i.e., explanatory power) was evaluated through the calculation of the *z*-statistic values at a significance level of $P < 0.05$. All analyses were conducted using the statistical software *R* v.4.2.0 (R Core Team, 2022).

3. Results

3.1. Climate exposure, future aridity, potential evapotranspiration and irrigation water need

All cities assessed here were projected to undergo increases in MAT, as projected by future climate models by 2050. On average, MAT was projected to increase by 2.5 °C (± 0.6), with the highest increases of >3.5 °C in six Canadian (Boucherville, Calgary, Granby, Montreal, Verdun, and Winnipeg) and four Swedish (Boden, Luleå, Skelleftea, and Umeå) cities. Fifty-three cities (49 %) were projected to have increases in AP, while 56 cities (51 %) were projected to experience decreases in AP across the suite of climate models examined. Four cities were projected to experience decreases of >100 mm in AP: San Juan, Puerto Rico (−226 mm), Santiago, Chile (−199 mm), Busselton, Australia (−120 mm), and Vitória, Brazil (−105 mm) (Fig. 3; **Supplemental Table S4**).

We found 34 cities (31 %) with negative *IN* (irrigation need) values, indicating that the projections of AP exceed PET projections and suggesting these cities might not need additional irrigation water under the conditions modelled. In contrast, 75 cities (69 %) had positive *IN* values; four cities (Ahvaz and Khomeyn in Iran, and Albacete and Murcia in Spain) had values above 1000 mm, suggesting a significant irrigation need and indicating that the future PET far exceeds the future annual precipitation (Fig. 2; **Supplemental Table S4**).

3.2. Global urban irrigation practices

Our global survey across 109 cities in 21 countries uncovered marked variability in irrigation practices across cities, reflecting differences in infrastructure, environmental conditions, and policy frameworks. A clear majority of cities (58 %) rely primarily on municipal

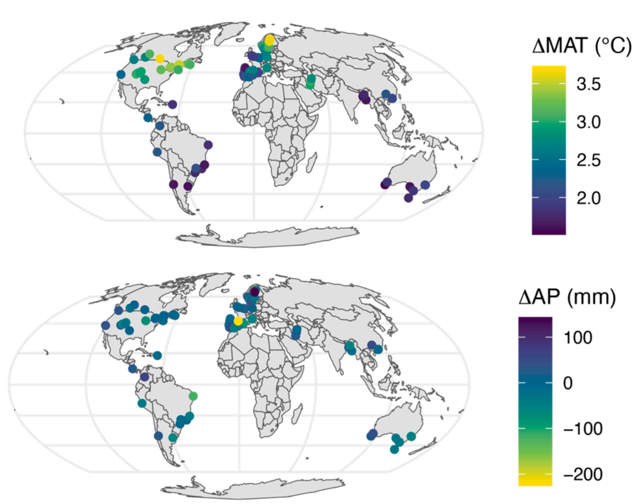

Fig. 3. Projected changes in mean annual temperature (ΔMAT) and annual precipitation (ΔAP) by 2050 across 109 cities in 21 countries. Projections represent the difference between future climate conditions (average 2041–2070; median across five global circulation models and SSP3–7.0) and baseline conditions (average 1981–2010).

water supply to irrigate urban trees, underscoring urban forests' dependence on centralised water systems. In contrast, more sustainable sources, such as rainwater harvesting, are underutilised, reported by only 7 % of respondents, suggesting untapped potential for water-saving innovations. Irrigation frequency also varied widely. While only 5 % reported daily irrigation, most cities either irrigate “as needed” (31 %) or followed practices not captured by predefined options (38 %), likely because irrigation is selectively applied to vulnerable groups such as newly planted trees. This selectivity highlights the adaptive management strategies employed in resource-limited contexts (**Supplemental Table S2**).

Manual watering remains the most common irrigation method (38 %), indicating continued reliance on labour-intensive approaches, particularly where automated systems may be financially or technologically inaccessible. Weather conditions were the leading factor influencing irrigation scheduling (44 %), pointing to a reactive approach shaped by short-term environmental cues rather than predictive models or long-term planning. Interestingly, water availability was the least influential factor (7 %), which may reflect a combination of stable water supply in some cities and lack of water metering or cost-based incentives in others (**Supplemental Table S2**).

Adoption of water-saving technologies showed encouraging signs, with 41 % of respondents using them at least occasionally and only 3 % reporting no use at all. However, widespread adoption remains limited. A lack of regulatory pressure may contribute to this trend—56 % reported no formal water restrictions, and only 5 % operated under strict irrigation regulations. This absence of policy intervention presents a clear opportunity for local governments to promote conservation through stronger guidelines. Monitoring remains another critical gap—55 % of respondents reported having no water usage monitoring systems in place, while only 10 % employed advanced systems (Fig. 4). This shortfall likely limits cities' ability to optimise irrigation strategies or track the impacts of water conservation measures. Mulching was the most widely used technique to reduce water loss (40 %), whereas shading—a passive but potentially effective method—was rarely used (10 %). These trends may reflect differences in awareness, feasibility, or available resources to implement different conservation methods (**Supplemental Table S2**).

We also identified significant gaps in approaches to relevant education and incentives. Half of the cities reported no current educational programs on water-efficient irrigation, and 73 % lacked financial incentives to promote such practices. Only 1 % of respondents reported strong incentive programs, suggesting missed opportunities for capacity building and behavioural change. Smart irrigation systems, which optimise water use based on sensor inputs or predictive algorithms, are not yet widely adopted. Nearly half of respondents (45 %) had no plans to implement such systems, while only 25 % intended to do so in the near future (Fig. 4). This hesitancy could stem from limited technical capacity, budgetary constraints, or uncertainty about the systems' effectiveness. Although 35 % of respondents evaluated irrigation effectiveness through monitoring and performance metrics, 38 % reported no assessment mechanisms at all—pointing again to the need for better data-driven management (**Supplemental Table S2**).

Key challenges reported by cities included limited budgets (23 %), infrastructure constraints (22 %), and the increasing impacts of climate change (20 %). Despite these obstacles, more than half (56 %) rated their current irrigation practices as moderately successful, suggesting that cities are adapting to their constraints, albeit with potential for improvement. Finally, the survey highlighted critical opportunities for innovation in water sourcing. A large majority (80 %) do not use recycled wastewater, and 58 % do not conduct water quality testing—highlighting the need for more integrated and sustainable urban water management strategies (**Supplemental Table S2**).

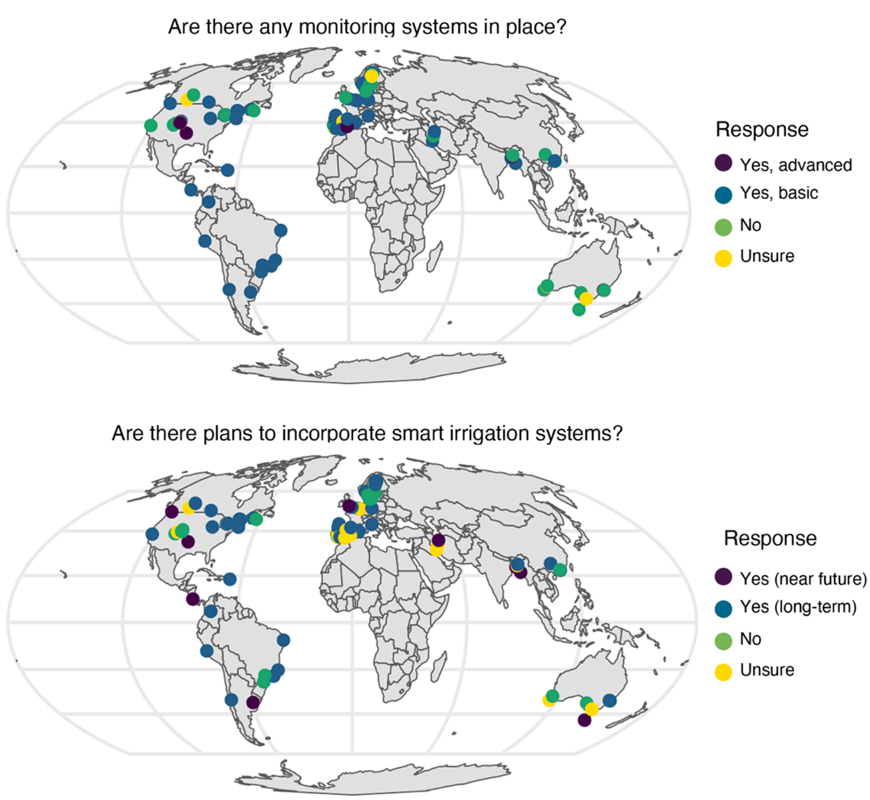

Fig. 4. Responses from 109 cities in 21 countries to two survey questions on global urban irrigation practices of urban forests. The top panel shows responses to: “*Are there any monitoring systems in place to track the water usage of urban forests?*” The bottom panel presents responses to: “*Are there any plans to incorporate smart irrigation systems in the management of urban forests?*”.

3.3. Trends and effects of mean annual temperature, aridity, and latitude on irrigation practices

3.3.1. Climate and geographic patterns in survey responses

The results of the Multiple Correspondence Analysis (MCA) did not reveal any clear patterns linking cities with similar climates or geographic regions to similar irrigation practices. Specifically, the responses to the online survey varied widely across different locations, indicating that factors other than climate or regional characteristics may play a more significant role in shaping irrigation decisions (Fig. 5).

3.3.2. Drivers of irrigation practices in urban forest across 109 worldwide cities

Our results indicate that municipal water supply is significantly more relied upon for irrigating urban trees than rainwater harvesting or other sources. Latitude emerged as a key factor predicting the choice between rainwater harvesting and municipal supply, suggesting that geographic location, rather than climate, influences irrigation source preferences. Irrigation frequency showed minimal significant differences compared to daily irrigation, except when comparing “never” to “daily” where mean annual temperature (MAT) was a significant predictor. This suggests that cities in warmer climates are more likely to irrigate at least occasionally, highlighting the influence of temperature on irrigation decision-making (**Supplemental Table S5**).

Manual watering was significantly more common than sprinkler systems, indicating a continued reliance on labour-intensive methods. Cities with higher irrigation needs (*IN*) were more likely to use drip irrigation instead of sprinkler systems (Fig. 6), reflecting a shift towards water-efficient practices in response to water scarcity. Additionally, scheduling irrigation based on water availability was more common than using weather-based scheduling, with both *IN* and Aridity being significant predictors. This underscores that current and anticipated water limitations are more influential than geographical or climatic factors in scheduling decisions (**Supplemental Table S5**).

3.3.3. Water management and regulation

Adoption of water-efficient irrigation technologies varied across cities, with occasional use being more frequent than consistent use.

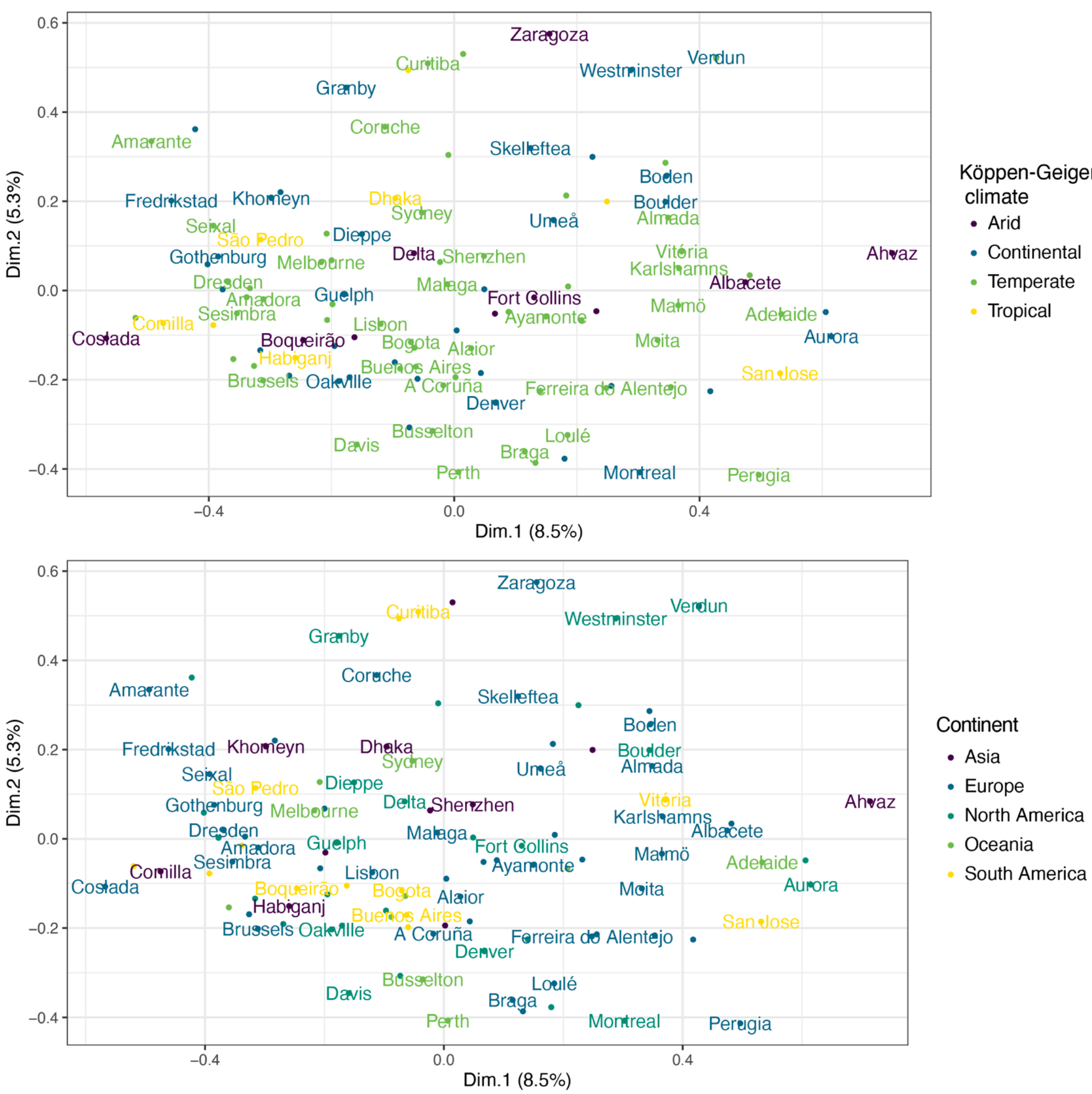

Fig. 5. Multiple Correspondence Analysis (MCA) of urban irrigation practices across 109 cities in 21 countries, based on responses to a 17-question online survey on global urban irrigation practices of urban forests. Both panels display the same distribution of cities, clustered according to their survey responses. In the top panel, cities are coloured according to their Köppen-Geiger climate classification, while in the bottom panel, cities are coloured according to their continental location. The axes represent the first two dimensions of the MCA, with values in parentheses indicating the proportion of inertia (variance) explained by each dimension.

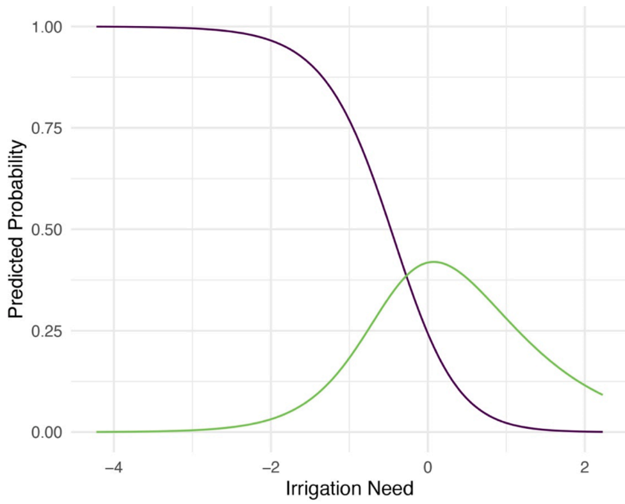

Fig. 6. Predicted probabilities of using drip irrigation and manual watering as functions of standardised irrigation needs (i.e., the difference between future projections of potential evapotranspiration and annual precipitation). The lines represent the predicted probabilities of adopting each irrigation method, with drip irrigation shown in purple and manual watering in green. As irrigation need increases (moving to the left on the *x*-axis), the probability of manual watering increases. Note that irrigation need is standardised; therefore, the values are relative to the mean and standard deviation of irrigation need.

Latitude was marginally associated with uptake, suggesting regional differences in infrastructure or awareness. Regarding regulatory frameworks, strict irrigation restrictions were more frequently reported than moderate or absent ones. MAT significantly influenced the distinction between "other" and "strict" regulations, indicating that cities with warmer climates may be more likely to implement strict water-use policies. Irrigation volumes were more often based on plant water needs rather than arbitrary or "other" criteria, reinforcing the localised, plant-specific nature of decision-making in urban forest management over broad environmental predictors (**Supplemental Table S5**).

3.3.4. *Water conservation and efficiency measures*

Advanced water usage monitoring systems were more prevalent than the absence of any monitoring, although many cities still lacked such systems. Latitude was marginally associated with monitoring level, while cities in the Global South were significantly more likely to lack monitoring entirely. This suggests infrastructure disparities between regions. Among strategies to reduce evaporative loss, mulching was notably more common than shading or applying no measures. While environmental predictors were generally not significant, Aridity was associated with the selection of mulching over "other" methods, reflecting concern about increasing water scarcity as an influence on water conservation practices (**Supplemental Table S5**).

3.3.5. *Awareness, incentives, and innovation in irrigation*

Educational efforts showed regional variation, with frequent programs more likely in some areas and latitude emerging as a significant predictor. In contrast, financial incentives for water-efficient practices were generally absent and showed no significant relationship with the variables tested, implying that such incentives might depend more on local governance and policy than environmental drivers. Plans to adopt smart irrigation systems were influenced by both MAT and geography. Warmer cities were more likely to implement such systems in the near future, and cities in the Global South were more uncertain about future adoption, pointing to potential barriers, such as cost or technical capacity. Irrigation effectiveness was more commonly assessed through regular monitoring than through "other" means, although no predictors were significant in this case (**Supplemental Table S5**), possibly reflecting a lack of standardised evaluation frameworks.

3.3.6. *Challenges and outcomes in urban forest irrigation*

Budget constraints, infrastructure limitations, and climate change were perceived as greater challenges than water availability. Being in the Global South significantly predicted these differences, highlighting regional disparities in perceived barriers. MAT was also marginally significant in distinguishing between climate change and water availability as a challenge, again reflecting the influence of temperature on urban forestry operations. Most cities rated their irrigation practices as “moderately successful,” with this category significantly more common than “very successful”. Latitude was marginally associated with these differences, indicating that perceptions of success may vary geographically (**Supplemental Table S5**).

Water quality testing was largely absent, with both latitude and Global South status being significant predictors. Respondents from warmer or drier cities, or from the Global South, were more likely to be unsure about whether testing was conducted, suggesting a gap in awareness or infrastructure. Notably, cities with higher irrigation needs were significantly more likely to use wastewater as an alternative source, indicating a proactive approach to addressing water scarcity. This trend was especially pronounced in Global South cities, again highlighting regional differences in adaptation strategies (**Supplemental Table S5**).

4. Discussion

4.1. *Climate exposure, future aridity, potential evapotranspiration and irrigation water need*

Our study shows that while projected increases in mean annual temperature (MAT) are widespread, changes in annual precipitation (AP) are more variable across cities, with implications for irrigation needs. Importantly, more than two-thirds of the respondent cities (75 cities, 69 %) were projected to require irrigation by 2050, even in the absence of AP declines, due to rising evaporative demand. This aligns with previous research showing that temperature increases can intensify water stress regardless of precipitation trends (Farquhar & Roderick, 2005). Furthermore, we note that AP alone may not be the best indicator of plants’ water deficit, as it does not capture the nuances of seasonal growth requirements (Zeppel et al., 2014), highlighting the importance of accounting for both the timing and amount of precipitation when assessing future irrigation requirements.

Irrigation is critical during tree establishment and under extreme heat and drought conditions (Eisenman et al., 2024; Gao & Santamouris, 2019). Building on previous regional studies (e.g., Livesley et al., 2021; Pataki et al., 2011; Pincetl et al., 2019), our results provide global empirical evidence based on projected irrigation demands. Our global assessment not only highlights the scale of the challenge, especially in water-limited regions, but also underscores the potential for irrigation to compete with other human water needs (Hoekstra et al., 2018; McDonald et al., 2014). Our results showed that even cities without projected AP declines may face substantial irrigation needs, a nuance not captured in previous assessments that focused primarily on precipitation metrics (Shepherd, 2005). This finding emphasises the importance of using multiple hydrological and climatic indicators—including PET and aridity indices—for more accurate urban forest planning.

Cities in semi-arid and arid zones face the double burden of increased water stress and limited irrigation feasibility due to financial and infrastructural constraints (Di Baldassarre et al., 2018). To address this, our findings support the promotion of drought-tolerant species and alternative water sources such as treated wastewater (Bichai et al., 2018; Esperon-Rodriguez et al., 2025a). However, few cities reported using such strategies, suggesting a disconnect between climatic projections and adaptive practices.

4.2. Global urban irrigation practices

Our global-scale assessment across 109 cities in 21 countries revealed significant variability in irrigation strategies across cities, shaped by infrastructure, cultural preferences, and governance models rather than solely by climate. While municipal water remains the dominant source, the heavy reliance on this reflects a missed opportunity to diversify water supplies. The limited uptake of rainwater harvesting and greywater reuse suggests that sustainable alternatives are underutilised despite their feasibility (Reznik et al., 2019; Ssekyanzi et al., 2024).

Notably, the widespread use of manual watering—even in technologically advanced cities—points to established practices that may hinder efficiency. This persistence reflects its flexibility (requiring no permanent irrigation infrastructure) and the challenges of alternative systems (e.g., seasonal freezing necessitates winter adaptation). This supports previous findings noting that institutional legacy often determines urban green space management more than innovation potential (Green et al., 2016). Moreover, the low prevalence of monitoring and scheduling systems reveals a critical gap in data-driven management. Similar gaps were previously noted in European cities where lack of real-time data limited adaptive responses (Berland et al., 2017). Encouragingly, mulching was widely used, although its effectiveness varies by context (Coello et al., 2017; Cogliastro et al., 1993). The minimal implementation of complementary shading strategies suggests unexploited synergies for water conservation and biodiversity enhancement (Di Pirro et al., 2022).

Policy gaps were also evident. The scarcity of educational programs and incentives mirrors global findings from UNESCO (2020), which stress the need for behavioural change alongside infrastructural investment. Testing and use of alternative water sources, such as treated wastewater, remain negligible despite strong advocacy in recent research (Bichai et al., 2018; Filali et al., 2022). Overall, our findings revealed a clear mismatch between projected climate-driven irrigation demand and current urban forestry irrigation capacity. This highlights a need for integrated policies that combine infrastructure upgrades, public engagement, and ecological knowledge to close the adaptation gap.

Although we hypothesised a North–South divide in technology and irrigation efficiency, the evidence was mixed. Cities in the Global South did report more challenges and aspirations for smart irrigation, and resource availability alone did not explain variability in practice. These results are consistent with research showing that institutional inertia and policy frameworks often outweigh technological capacity in determining irrigation outcomes (Playán et al., 2018). Our results also reinforce the idea that effective water management depends as much on governance and human behaviour as it does on hydrological systems (Loucks & Van Beek, 2017). These findings suggest that future frameworks for urban irrigation should integrate climate science with socio-political analysis to foster more equitable and effective adaptation strategies.

4.3. Trends and effects of mean annual temperature, aridity, and latitude on irrigation practices

One of the key findings of our survey was the absence of consistent irrigation practices among cities with similar climates or geographic regions. This result challenges findings from previous studies that climate is the dominant driver of urban water management practices (Brown et al., 2009). Instead, our results reinforce the complexity and contextual dependency of urban irrigation, where local governance, institutional capacity, and socio-economic factors are highly influential (Alaerts, 2020; Molle, 2007). This aligns with previous findings arguing that climate adaptation strategies often diverge even within similar urban environments due to differing political and financial landscapes (Meerow & Newell, 2017).

Although most environmental variables had limited explanatory power in our models, mean annual temperature (MAT) was an important exception, showing a complex effect on urban forest irrigation practices. This likely reflects MAT's direct relationship with plant water demand and heat stress, which may drive adaptive management responses in ways that other environmental factors do not. Notably, we observed that higher MAT correlated with less frequent irrigation, a pattern that could reflect deliberate adaptation strategies in warmer cities—such as planting drought-tolerant species or relying more heavily on seasonal precipitation (Esperon-Rodriguez et al., 2022; Gill et al., 2007)—or conversely, a lack of capacity to adequately irrigate under high heat conditions. This raises the possibility that some cities may appear efficient to low water use (i.e., less frequent or low-volume irrigation) not due to climate-smart design, but due to under-resourced management systems. The finding that warmer climates had fewer strict water regulations suggests potential regulatory lag in the face of escalating heat-related water demands. Other studies have similarly highlighted that regulation often fails to keep pace with climate risk in urban green space governance (Bai et al., 2018; Meerow & Newell, 2017).

The negative association between MAT and plans to adopt smart irrigation technologies suggests a mismatch between climate exposure and investment in innovation. While it could reflect financial or technical barriers, it might also indicate differing perceptions of urgency or risk prioritisation, especially in places where water stress is viewed as normative (Döll & Siebert, 2002). The positive link between MAT and wastewater use, however, signals a promising avenue where water-scarce cities are innovating under restriction (Bichai et al., 2018; Furniss, 2011). This is consistent with findings from Mediterranean and Middle Eastern cities, where high heat and low rainfall have spurred the use of treated wastewater for non-potable purposes (Angelakis & Snyder, 2015). The association of MAT with uncertainty around water quality testing suggests a critical monitoring gap. As cities with warmer climates become more reliant on marginal water sources (e.g., wastewater, stormwater), rigorous testing becomes not just a precaution, but a necessity to avoid ecological or public health risks (Salgot & Folch, 2018). Future studies should systematically examine whether these monitoring gaps are due to infrastructure limitations, unclear governance, or financial barriers.

Although aridity was not a significant predictor in most models, its contextual importance should not be overlooked. Prior work has shown that increased aridity—particularly when coupled with high vapor pressure deficits—can drastically impair urban tree physiology and increase watering demand (Grossiord et al., 2020). Our findings that irrigation need significantly influenced the use of efficient irrigation systems (e.g., drip) and alternative sources (e.g., wastewater) supports the argument that water scarcity is a primary driver of adaptive responses, in line with resource-efficiency theories of innovation (Turral et al., 2011).

Latitude showed only marginal effects, such as distinguishing between basic and advanced monitoring systems or influencing perceptions of irrigation success. However, its weak predictive power overall reinforces the view that irrigation practices are shaped less by absolute geographic position and more by context-specific combinations of infrastructure, policy, and cultural factors. Nonetheless, cities at higher latitudes may experience more pronounced seasonal cycles, leading to punctuated irrigation demands and different temporal management regimes (García-Ruiz et al., 2011). This warrants further place-based exploration, particularly in comparing humid continental versus subtropical cities. Cultural, historical, and institutional legacies may also explain why cities in similar climates diverge significantly in irrigation practices (Brown et al., 2009; Ordóñez et al., 2019). Thus, while environmental variables help delineate irrigation pressures, non-environmental factors are likely to be stronger determinants of capacity, response, and innovation.

4.4. Caveats and limitations

While our study offers novel insights into global irrigation practices, several limitations are acknowledged. First, our sample is primarily concentrated in latitudes between 25° N and 49° N, with limited representation from equatorial and high-latitude cities. This distribution may limit our ability to detect irrigation strategies specific to extreme climates (e.g., tropical or cold temperate), where water needs and management approaches differ markedly. This gap highlights the need for future research that better captures latitudinal extremes and more equitably represents cities from the Global South. Future research can explore how environmental conditions interact with regional non-environmental factors—such as infrastructure, governance, or access to technology—to shape irrigation decisions. Additionally, while our sample of 109 cities spans diverse regions, its modest size limits statistical power. Several factors may have contributed to this: (1) barriers from local authorities in openly sharing information and data (i.e., legal barriers) (Moorthie et al., 2022; Rajamäe Soosaar & Nikiforova, 2025); (2) the possibility that the survey did not reach the appropriate department or personnel; (3) IT systems blocking access to the online survey; (4) irrigation management falling under the jurisdiction of entities other than the city council; or (5) internal approval policies that require time to authorise information sharing. Consequently, our results should be interpreted as descriptive patterns, not causal inferences, and may represent certain dominant or emerging trends.

Second, our study captures a single time point, which limits our ability to track changing practices over time. A longitudinal design would enable deeper analysis of how cities evolve their practices in response to climate events, policy shifts, or technological change. Furthermore, although we integrated climate, demographic, and economic predictors, we did not include local water policies, infrastructure quality, or utility pricing, all of which can significantly affect irrigation decisions. Third, while precipitation amount (i.e., annual precipitation) was analysed, we did not assess precipitation frequency or seasonal distribution, both of which critically influence irrigation needs (Smith et al., 1985), especially in tree establishment phases. For instance, an increase in AP may coincide with a decline in growing-season rainfall, thus exacerbating tree stress even if total precipitation increases (Choat et al., 2012). We also did not include variables such as soil type or vegetation cover, which are known to influence irrigation scheduling and effectiveness and may significantly influence irrigation practices. However, obtaining reliable and globally consistent datasets for these variables in urban environments remains a challenge due to heterogeneity and local management practices. Additionally, we acknowledge the inherent uncertainties in climate modelling, particularly around extreme event prediction and regional downscaling. Future studies could benefit from incorporating model ensembles or uncertainty quantification frameworks to better assess variability in projected irrigation needs.

Importantly, our study did not distinguish irrigation practices for young versus mature trees, or for street trees versus park trees—groups that may differ significantly in water requirements, vulnerability, and management regimes (Brandt et al., 2021; Rissanen et al., 2025; Roman & Scatena, 2011). Furthermore, our analysis of intelligent irrigation technologies was limited to adoption rates and did not quantify their actual impact on water savings. Similarly, although economic constraints were commonly cited, we did not explore other potential factors, such as technical compatibility, maintenance costs, or policy and regulatory challenges. These aspects represent important future research directions to understand not just whether, but how and why such technologies are (or are not) implemented in cities. Finally, while our statistical models describe correlations, they do not imply causality. Potential interactions between environmental and non-environmental variables (e.g., climate and governance) were not explored and represent a rich direction for future work. Despite these caveats, our study provides a critical global overview of urban irrigation practices and lays the groundwork for broader, more integrated research.

4.5. Future recommendations

Our findings suggest that urban irrigation practices are more strongly influenced by local traditions and decision-making processes than by environmental constraints alone. This opens significant opportunities for cities to improve water efficiency, particularly through targeted policy reforms, technological upgrades, and capacity-building initiatives. Scaling up the adoption of alternative water sources is key to achieving more resilient urban irrigation. For instance, treated wastewater represents a viable option for many cities (Ramaiah et al., 2022), while stormwater harvesting, either passively (e.g., swales and curb cuts) or actively (e.g., underground cisterns), has shown promise in improving both water use efficiency and urban biodiversity (Fam et al., 2008; Wendling & Holt, 2020). Although these systems require substantial initial investment (Pokhrel et al., 2022), their long-term benefits—particularly in water-stressed regions—can outweigh costs, as demonstrated in Australian and United Arab Emirates case studies (Giwa & Dindi, 2017; Marlow et al., 2013).

These alternative strategies are particularly relevant for cities located in dryland regions, where maintaining healthy urban forests is becoming increasingly difficult due to chronic water scarcity (FAO, 2022). Moreover, in many water-scarce cities, the high cost of irrigation and limited recognition of the long-term social and environmental benefits of urban trees hinder sustained investment in green infrastructure (FAO, 2022). With climate change projected to expand the extent and severity of dryland areas globally (Koutroulis, 2019), ensuring urban forest resilience in these regions is not only increasingly important but also urgent. In this context, resilient dryland water governance must evolve to better account for the complex synergies and trade-offs between water security, environmental health, and broader goals of sustainable development (Stringer et al., 2021), without excluding the vital role of urban forests.

Future efforts should also focus on shared governance frameworks. Adopting shared policies and practices among cities can help mitigate water scarcity while promoting sustainable urban forestry (Rambhia et al., 2023). Building regional or global networks for knowledge exchange, particularly among cities with similar climate profiles, could accelerate best-practice diffusion and help address gaps in public education and regulatory support. Matching irrigation scheduling to actual plant water requirements, especially during heatwaves and droughts, can enhance both water savings and tree survival (Halper et al., 2012; Nouri et al., 2019). This will require more real-time monitoring, remote sensing integration, and adaptive management frameworks (Esperon-Rodriguez et al., 2025a). Lastly, future research should more deeply investigate the socio-economic, policy, and infrastructural drivers behind urban irrigation choices. A clearer understanding of "how" and "why" cities adopt certain practices—not just "what" they adopt—will be vital to designing effective future interventions.

5. Conclusions

This study provides the first global-scale assessment of urban forest irrigation practices, filling a critical knowledge gap in understanding how cities manage water for urban greenery under varying climatic and socio-economic conditions. Our findings reveal the complexity and heterogeneity of irrigation strategies across 109 cities in 21 countries and demonstrate that environmental factors—particularly mean annual temperature, aridity, irrigation needs, and latitude—play a measurable but uneven role in shaping irrigation decisions.

Climate alone did not uniformly predict irrigation practices. Instead, local management traditions, infrastructure limitations, and regional socio-economic contexts emerged as key drivers. Notably, cities in the Global South often reported distinct practices and challenges compared to those in the Global North, underscoring the importance of context-specific approaches to urban forest management. Despite increasing awareness of the need for sustainable water use, significant gaps remain. Only 15 % of cities reported consistent use of water-efficient technologies, and nearly half had no plans to implement smart irrigation systems. These findings highlight an urgent need for integrated strategies that combine innovative technologies, supportive governance, financial incentives, and capacity-building to accelerate the adoption of efficient, adaptive irrigation practices.

Our study provides actionable insights for urban planners and policymakers. These include developing species-specific irrigation guidelines, enhancing data-driven decision-making through better monitoring systems, fostering collaboration between cities with similar environmental conditions, and increasing the use of drought- and heat-tolerant tree species. Future research should build on this foundation by examining the long-term impacts of climate change on urban irrigation demand and tree health, exploring the potential in using tree species with no or limited need for supplementary irrigation, quantifying the effectiveness of smart irrigation technologies, and exploring the institutional, financial, and policy mechanisms that support their implementation—particularly in resource-constrained settings. A deeper integration of social and governance dimensions will be essential to fully understand and improve urban irrigation systems globally.

CRediT authorship contribution statement

Manuel Esperon-Rodriguez: Writing – review & editing, Writing – original draft, Visualization, Validation, Software, Resources, Project administration, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization. **Rachael V Gallagher:** Writing – review & editing, Validation, Supervision, Investigation, Formal analysis, Conceptualization. **Alessio Russo:** Writing – review & editing, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Sally A Power:** Writing – review & editing, Validation, Investigation, Formal analysis. **Pedro Calaza-Martínez:** Writing – review & editing, Investigation, Data curation. **Tiago Capela Lourenço:** Writing – review & editing, Investigation, Data curation. **Paloma Cariñanos:** Writing – review & editing, Investigation, Data curation. **Ana Alice Eleuterio:** Writing – review & editing, Investigation, Data curation. **Zhengfei Guo:** Writing – review & editing, Investigation, Data curation. **Gervais Lee:** Writing – review & editing, Investigation, Data curation. **Pierre Masselot:** Writing – review & editing, Investigation, Data curation. **Robert I. Mcdonald:** Writing – review & editing, Investigation, Data curation. **Christian Messier:** Writing – review & editing, Investigation, Data curation. **Camilo Ordoñez:** Writing – review & editing, Investigation, Data curation. **Mostafa Parpanchi:** Writing – review & editing, Investigation, Data curation. **Rossano Schifanella:** Writing – review & editing, Investigation, Data curation. **Charlie Shackleton:** Writing – review & editing, Investigation, Data curation. **Mahmuda Sharmin:** Writing – review & editing, Investigation, Data curation. **Ingjerd Solfjeld:** Writing – review & editing, Investigation, Data curation. **Annick St-Denis:** Writing – review & editing, Investigation, Data curation. **Jens-Christian Svenning:** Writing – review & editing, Investigation, Data curation. **Maria Martha Torres-Martinez:** Writing – review & editing, Investigation, Data curation. **Björn Wiström:** Writing – review & editing, Investigation, Data curation. **Pengbo Yan:** Writing – review & editing, Investigation, Data curation. **Jun Yang:** Writing – review & editing, Investigation, Data curation. **Mark G Tjoelker:** Writing – review & editing, Validation, Supervision, Resources, Project administration, Methodology, Investigation, Formal analysis, Conceptualization.

Declaration of competing interest

None.

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Supplementary materials

Supplementary material associated with this article can be found, in the online version, at doi:10.1016/j.scs.2025.106510.

Data availability

Data will be made available on request.

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