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(Re)Designing Urban Parks to Maximize Urban Heat Island Mitigation by Natural Means

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Abstract: Urban trees play a key role in mitigating urban heat by cooling the local environment. However, the cooling benefit that trees can provide is influenced by differences in species traits and site-specific environmental conditions. Fifteen dominant urban tree species in parks from Mexico City were selected considering physiological traits (i.e., transpiration and stomatal conductance) and aesthetic and morphological characteristics. Species' physiological performance was measured to explore the potential of trees to reduce urban heat load. Data were collected over a 4-week period in the months of April and May 2020, the warmest and driest months of the year in Mexico City. We used the Thermal UrbaN Environment Energy (TUNEE) balance model to calculate the cooling benefit of each species and the number of individuals necessary to reduce local air temperature. The highest midday transpiration was registered for *Liquidambar styraciflua* L. (0.0357 g m^{-2} s^{-1}) and the lowest for *Buddleja cordata* H.B.K (0.0089 g m^{-2} s^{-1}), representing an energy consumption and cooling potential of 87.13 and 21.69 J m^{-2} s^{-1}, respectively. Similarly, the highest stomatal conductance was recorded for *L. styraciflua.*, whereas the lowest was recorded for *B. cordata*. Based on the species transpiration rates and aesthetic characteristics, we developed a proposal and outline for a 50 × 50 m urban park (i.e., park community) consisting of six species with 19 individuals, and according to the TUNEE model, the proposed arrangement can reduce air temperature up to 5.3 °C. Our results can help urban planners to (re)design urban parks to mitigate urban heat while increasing urban tree diversity in parks.

Keywords: green areas; transpiration; urban heat island; urban landscape; urban trees; urban forests

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1. Introduction

Urbanization, as a radical transformation of the natural environment, creates many distinct effects in the built-up area; one of them is the urban heat island (UHI) effect. UHI occurs when the air temperature is higher in the urban area than in its rural surroundings e.g., [1,2]. This difference in temperature in cities is caused by the redistribution of energy from solar radiation due to extreme changes in land use, causing an alteration in the energy balance [1]. This is partially due to the drastic reduction of the latent heat flux (Q_E) caused by impervious surfaces (e.g., asphalt and concrete), reduced evaporation and the number of green areas, and increases in the sensible heat flux (Q_H), which contributes to the air temperature increase [1].

As a nature-based solution, urban green spaces (i.e., green areas, such as urban parks and forests, green belts, and components such as street trees and water infrastructure in urban contexts [3]) provide multiple environmental services, such as mitigation of the

UHI, reduction of air temperature, air and water purification, wind and noise filtering, and microclimate stabilization [4]. Therefore, these green spaces are crucial to improving urban livability, and thereby the well-being of city dwellers [5,6]. These green spaces also provide a connection with nature and social and psychological services. Recent research shows that green spaces can also aid crime reduction [7–9].

Urban park design, however, is usually planned from an economic perspective [10] or exploring social (e.g., population lifestyle and values) and spatial (e.g., patterns of urban open space) attributes [11]. Urban park design can also be directed to achieve specific goals, such as heat mitigation by using, for example, urban trees to mitigate UHI. However, research assessing the effect of urban tree species on reducing urban heat is site-specific, e.g., [12–14], or has explored relationships between temperature and vegetation using satellite images, e.g., [15–17], which may miss information on individual tree species performance and thus limits its ability to inform species selection.

Urban trees decrease air temperature through transpiration [18,19]. Transpiration (*E*) is the process of water movement through a plant and its evaporation from aerial parts, such as leaves, stems, and flowers [20]. This process is conducted through stomata, which are pores found in the epidermis of leaves, stems, and other organs that are used to control gas exchange, and it is measured through the stomatal conductance [21]. Therefore, using species with high transpiration in parks and gardens can help reduce the UHI effect and thermal pollution, while promoting optimal environmental thermal comfort [19,22].

The quantification of *E* is also important for the management of urban forests because *E* is related to the amount of irrigation needed for an urban tree to survive and perform well in the urban context. Plants exchange near 95% of the absorbed water by *E*, and 5% or less is used in other physiological mechanisms (e.g., photosynthesis) [23]. Urban park design, therefore, requires information on species' physiological responses to environmental conditions where they are planted and growing to identify urban tree species with high *E*. For efficient urban park design, it is required to define the best environmental conditions needed by trees and the optimal conditions for landscape and urban planning (e.g., achieving additional benefits such as enhanced biodiversity). A recently developed approach to assess these conditions is the Thermal UrbaN Environment Energy (TUNEE) balance model, which calculates the cooling benefit that different tree species can produce and the number of individuals of each species necessary to reduce local air temperature [19].

The predicted increases in temperature by the end of the century represent a threat to human populations [24]. Furthermore, the UHI can exacerbate heat waves; therefore, mitigating UHI is crucial since rising temperatures can negatively affect human thermal comfort, which can alter productivity, increase energy consumption using air conditioning systems, and cause health problems and even increase the risk of mortality [25–27]. Here, we used Mexico City as a case study. The UHI intensity in Mexico City can be 6 to 7 °C warmer during nighttime; however, it can also occur during daytime with intensities of up to 10 °C [28]. Further, the electricity consumption in Mexico City in 1996, for example, was 28.4 GW h to the domestic sector, of which 5.69 GW h (20%) was used to cool down inside buildings (e.g., air conditioning, evaporative cooling, fans), while 8.52 GW h was used in commercial and service centers in the metropolitan area [29]. The aim of this work was to propose an approach to (re)design urban parks to mitigate the UHI effect by proposing a tree community that, through its high transpiration rate, can more effectively reduce local air temperature, with a clear direction towards more sustainable, livable cities.

2. Materials and Methods

2.1. Study Area

The Metropolitan Area of Mexico City (MAMC) (19°25′ N, 99°10′ W) is located in an inland-elevated valley at an altitude of ca. 2250 m asl in central Mexico. Climate is highland tropical, with a well-defined rainy season (May–October). Mean annual precipitation (mean of 30 years; 1981–2010) is 600 mm, and almost 89% occurs during the rainy season [30]. Winds are light and predominantly from the northeast. Extreme maximum and minimum temperatures are registered in April and May (30.6 °C) and January and December (0.6 °C), respectively; mean annual temperature is 14.6 °C [31].

The urban area is extensive (~1200 km^2) and heavily developed. As a result, there are urban effects on air quality and climate [32,33], with a marked UHI effect [28–34]. UHI not only occurs at night but also during daytime, with differences of up to 10 °C ($T_{U\text{-}R}$) warmer compared to surrounding nonurban areas [19,28]. By the end of the dry season, the maximum daily air temperature can reach up to 33 °C [28].

We selected eight urban green areas (seven parks) within the MAMC to collect our data: (1) Luis G. Urbina Park (LGUP); (2) Francisco Villa Park (FVP); (3) San Lorenzo Park (SLP); (4) España Park (EP); (5) Mexico Park (MP); (6) Bombilla Park (BP); (7) Los Viveros Park (LVP); and (8) green areas from Ciudad Universitaria, UNAM (CU) (Figure 1). Urban vegetation in public areas is administered by the municipality and is not irrigated systematically.

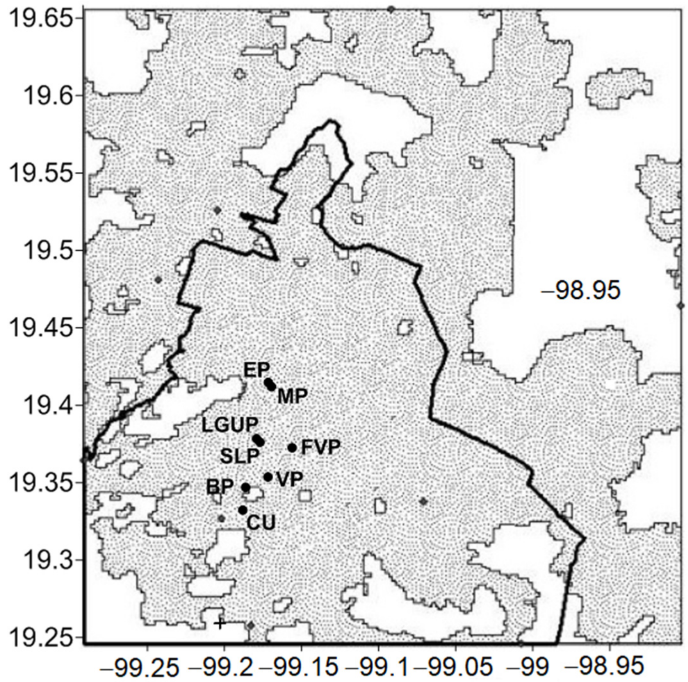

Figure 1. Location of the sites where measurements were collected in the Metropolitan Area of Mexico City (MAMC). The shaded area represents the MAMC and the solid line locates the boundary between Mexico City and the urban area in the State of Mexico. Abbreviation corresponds to LGUP: Luis G. Urbina Park; FVP: Francisco Villa Park; SLP: San Lorenzo Park; EP: España Park; MP: Mexico Park; BP: Bombilla Park; LVP: Los Viveros Park; and CU: green areas from Ciudad Universitaria.

2.2. Species Selection

Fifteen dominant urban tree species were selected based on their presence and abundance in eight urban green areas from Mexico City: *Acacia longifolia* (Andrews) Willd, *Acer negundo* L, *Alnus acuminata* Kunth, *Buddleja cordata* H.B.K, *Celtis occidentalis* L., *Ficus benjamina* L, *Fraxinus uhdei* (Wenz.) Lingelsh, *Lagerstroemia indica* L., *Ligustrum lucidum* W.T. Aiton, *Liquidambar styraciflua* L., *Populus alba* L., *Populus deltoides* W.Bartram ex Marshall, *Quercus rugosa* Neé, *Robinia pseudoacacia* L., and *Ulmus parvifolia* Jacq. Species selection included 11 natives and 4 exotics, and 8 deciduous and 7 evergreen species. Diameter at standard height (DSH), height (H), and crown diameter (CD) varied across species, with *F. benjamina* (DSH and CD) and *F. uhdei* (H) presenting the highest values, whereas *B. cordata* had the lowest values for all three metrics (DSH, H, and CD) (Table 1).

Table 1. Aesthetic characteristics (type of flower and fruit and flowering period), leaf area index (A, m^2 m^{-2}), diameter at standard height (DSH, m), crown diameter (CD, m), leaf size (LS, long (l, cm), wide (w, cm)), leaf habit (LH) and location for 15 dominant urban tree species (n = 4 for A, n = 10 for DBH and CD, n = 40 for LS) from eight urban green areas of Mexico City.

Species	Family	Flower	Flowering	Fruit	A	DSH	H	CD	LS (l, w)	LH	Location (Park)
Acacia longifolia	Fabaceae	Small yellow or golden-yellow	Mainly during winter and early spring	A very elongated pod	3.5	0.48	8.0	9.3	8.5, 1.4	Evergreen	Ciudad Universitaria
Acer negundo	Sapindaceae	Several in a cluster, greenish-yellow	Spring	Samaras 1-seeded, pale yellow	3.2	0.31	8.8	7.5	13.5, 8.6	Deciduous	Luis G. Urbina
Alnus acuminata	Betulaceae	Inflorescences are catkins	Spring and Summer	Long dehiscent, woody brown fruits	2.5	0.29	8.5	6.5	7.6, 3.7	Evergreen / deciduous	Ciudad Universitaria/ Viveros
Buddleja cordata	Loganiaceae	Small fragrant flowers, white, cream, or yellow	Summer and early autumn	Capsule fruit	2.0	0.16	4.0	3.4	12.8, 5.3	Evergreen	Ciudad Universitaria
Celtis occidentalis	Cannabaceae	Gold/Yellow, green, orange, purple/lavender	Spring	Round fleshy berry-like drupes	4.6	0.33	8.5	9.5	11.1, 4.9	Deciduous	Luis G. Urbina
Ficus benjamina	Moraceae	Inflorescences black, green, orange, purple/lavender, red/burgundy	Spring and Summer	Globose to slightly oblong fig	5.4	0.76	11.5	15.0	7.6, 3.4	Evergreen	Bombilla/ Francisco Villa
Fraxinus uhdei	Oleaceae	Small and insignificant, without petals, green, white or yellow	Winter	Brown samaras	4.4	0.25	15.0	11.0	8.1, 3.5	Deciduous	San Lorenzo/ Luis G. Urbina
Lagerstroemia indica	Lythraceae	Numerous and irregular, gold/yellow, pink, purple/lavender, red/burgundy, white	Spring, Summer, and Fall	Brown/copper capsule	2.1	0.15	4.3	5.2	5.5, 3.1	Evergreen	Ciudad Universitaria
Ligustrum lucidum	Oleaceae	Small, perfect, creamy white flowers	Summer	Black, blue druppe	4.0	0.15	13.0	8.1	6.3, 3.1	Evergreen	Ciudad Universitaria
Liquidambar styraciflua	Hamamelidaceae	Yellow-green flowers	Spring and Summer	Brown/copper capsule	4.6	0.27	13.6	11.0	7.5, 6.7	Deciduous	Ciudad Universitaria/ Viveros
Populus alba	Salicaceae	Inflorescence catkin	Spring and Summer	White loculicidal capsules	2.6	0.17	6.0	4.3	3.8, 3.7	Deciduous	Luis G. Urbina/ Bombilla
Populus deltoides	Salicaceae	Inflorescence catkin, green red/burgundy	Spring	Brown/copper, Green or white capsule	3.8	0.47	13.3	9.3	11.1, 8.7	Evergreen	España/ Mexico
Quercus rugosa	Fagaceae	Pistillate catkins pubescent	Spring	Acorn	3.1	0.17	5.5	7.8	13.6, 8.6	Evergreen /deciduous	Viveros/ Francisco Villa
Robinia pseudoacacia	Fabaceae	Fragrant wisteria-like white flowers	Spring and Summer	Brown/copper, purple/lavender legume	3.0	0.19	7.0	8.0	7.5, 4.4	Deciduous	Viveros
Ulmus parvifolia	Ulmaceae	Insignificant and reddish green	Spring, Summer, and Fall	Brown/copper samara	1.5	0.23	5.0	3.0	8.0, 3.7	Deciduous	Viveros

For all 15 species, we collected global occurrence records from the Global Biodiversity Information Facility (GBIF; 1.1.1.2, accessed on 23 May 2022, www.gbif.org; https://doi.org/10.15468/dl.f9ws9k) including records from their native and exotic ranges. Climate data were extracted from each species record aiming to capture species' realized climate niches. Then, we estimated mean values for mean annual temperature (MAT, °C), annual precipitation (AP, mm), the maximum temperature of the warmest month (MTWM, °C) and precipitation of the driest quarter (PDQ, mm) for each species to determine their climate of origin (Supplemental Table S1). Climate data (baseline data representative of 1970–2000) were obtained from WorldClim version 2.1 [35] at 30 arc-seconds (~1 km) resolution.

2.3. Data Collection

We selected 10 individual trees of each species. All trees were inside the parks surrounded by bare soil and some herbaceous vegetation and planted intermixed apparently in unsystematic arrangements. Individual trees for measurements were randomly selected with no overlapping crowns among trees. Tree species' structural parameters and location are shown in Table 1.

Stomatal conductance (g_S, 1/stomatal resistance) was measured with a gas diffusion porometer (LI-1600, LI-COR, Lincoln, NE, USA) on at least five expanded leaves per plant in the mid-level of the tree for at least four individuals in every park. Air temperature (T_A), photosynthetically active radiation (PAR), and relative humidity (RH) were determined next to each measured leaf with a quantum sensor (LI-190SB, LI-COR Ltd., Lincoln, NNE, USA), and a humicap sensor (Vaisala, Helsinki, Finland).

A quantum sensor was installed near and parallel to the leaf maintaining the orientation of the leaf when measuring. Leaf temperature (T_L) was measured with infrared thermographs (thermal camera, PCE-TC3, PCE Instruments, Southampton, UK). The leaf–air vapor pressure deficit (VPD) was calculated from T_A, T_L and RH measurements ($VPD = e_H - e_A$ = {0.6108exp[(17.27 T_L)/(237.3 + T_L)]} − {0.6108exp[(17.27 T_A)/(237.3 + T_A)] [1−RH)}). Additionally, net radiation, air temperature, air humidity, and wind direction and speed were monitored with a net radiometer (NR Lite2, Kipp & Zonen, Delft, The Netherlands), a temperature-humidity probe (HMP35C, Campbell-Scientific, Logan, UT, USA) in a ten-plate radiation shield (41003-5 Campbell Scientific, Logan, UT, USA) and an anemometer and vane set (03001, RM Young, Traverse City, MI, USA), respectively. These instruments were installed 3 m above the highest tree canopy on a telescopic tube connected to a data logger (21X, Campbell Scientific, Logan, UT, USA) and scanned every 30 s and 30 min averages logged. Leaf area index (A) was estimated with a canopy analyzer (LAI-2000, LI-COR Ltd., Lincoln, Dearborn, MI, USA). Four LAI measurements were taken at 1 m height from the ground and with a 90° view cap on a fish-eye lens. LAI is the ratio of the area of leaves to the area of the ground under the crown [36] and was measured on overcast days. LAI data were analyzed using FV2200 software developed for LAI-2200, deploying an isolated crown model and removing the 5th mask (68°). Measurements were performed from 11:00 to 14:00 local hour (h, local time) when transpiration was the highest [37], during the months of April and May 2020, the warmest and the driest months of the year. During measurements, maximum average temperature was 29 °C and 10.2 mm of precipitation were registered the last six days of March.

Transpiration (E) was estimated from VPD and g_S using the relationship e.g., [37]:

$$E = \frac{\rho \varepsilon C_P \; VPD}{\lambda \gamma \; (r_c + r_A)} \tag{1}$$

where γ is the psychrometric constant; λ is the latent heat of evaporation of water; ρ is the air density; ε is the mole fraction of water in air (0.622 kg water per kg air); C_P is the specific heat of dry air at constant pressure; r_S (1/g_S), r_C, and r_A are stomatal, canopy and aerodynamic resistance, respectively. Canopy resistance was calculated as $r_C = 1/Ag_S$, where A is the leaf area index. Aerodynamic resistance was estimated by $r_A = [\ln((z - d)/z_0)]/[k^2 u(z)]$, where z is a reference level, d is the displacement height, z_0 is roughness length, k is the von Karman's constant, and $u(z)$ is the wind speed at level z [38]. We considered that species presenting high values of E, g_S, PAR, VPD, and T_A were more efficient at mitigating UHI because these high values increase water output [39] and thus the cooling potential decreases local air temperature [19]. We acknowledge that the use of this model may introduce an error since the vegetation plot does not formally fulfil the assumptions to estimate it. However, Ballinas and Barradas [37] found that r_A was from three to five times lower than r_C in some urban trees in Mexico City; therefore, this error was considered not significant.

2.4. The Thermal UrbaN Environment Energy Balance Model

The Thermal UrbaN Environment Energy (TUNEE) balance model is a physics-mathematical-biological-ecological-environmental-urban phenomenological model used to determine strategies to mitigate UHI. The model is based on the first law of thermodynamics and determinates energy distribution while incorporating plant physiological traits (i.e., transpiration and/or stomata conductance) [19]. TUNEE model shows the effect of urban vegetation on air temperature (T_A) after increasing latent heat flux. Previous research determined the diagnosis equation for Mexico City as $T_A = 0.03892[Q_N - (Q_E + Q_{ETRP})] + 15.3$, where basal temperature is ~15 °C during the day, when $Q_N > 0$ (this relationship can change in function of basal temperature) and Q_E and Q_{ETRP} are the actual latent heat flux and the necessary latent heat flux, respectively, provided by evaporating surfaces by vegetation [19].

2.5. (Re)Designing Urban Parks

We developed a theoretical proposal based on a 50 × 50 m urban park design in which the planting technique was used as a module. We generated a tree community using urban tree species with aesthetic value and high transpiration and combined from a landscape point of view. Here, we defined a 'tree community' as a set of tree species that grow in the same place and present an association or affinity with one another. Therefore, these tree species can be used in urban forests to promote an adequate establishment and development of individuals, to ensure their performance and survival. Although aesthetics is subjective, the construction of the tree community was based on three principles of aesthetics: beauty, balance, and harmony [40,41]. The final set presented a structured that was considered beautiful (the result of the sum of the flowering, fall color, showy fruit, and pleasing bark [42]), which had balance and harmony and where the structural characteristics of each species predominate, articulating them to shape the space from an architectural and artistic point of view.

2.6. Statistical Analysis

We assessed differences in E, g_S, T_A, and T_L and VPD among species using analysis of variance and Fisher's test and a Student's t-test to identify differences between T_L and T_A in the same species. We assessed relationship between species climate of origin and E and g_S using linear regression models. Model performance was evaluated through the calculation of an R^2 value and the F-statistic at a significance level of $p < 0.05$. Statistical analyses were conducted using R version 4.0.5 (R Core Team, 2021).

3. Results

The highest midday E was registered for *L. styraciflua* (0.0357 g m^{-2} s^{-1}) and the lowest for *B. cordata* (0.0089 g m^{-2} s^{-1}) ($F_{(14,465)} = 1196.8$, $p < 0.001$). Transpiration rates represented an energy consumption or cooling potential from 87.13 (*L. styraciflua*) to 21.69 J m^{-2} s^{-1} (*B. cordata*). We identified three homogenous groups based on their transpiration rates: High E (*L. styraciflua*, *A. acuminata*, *Q. rugosa*, *L. lucidum*, and *F. benjamina*), moderate E (*P. deltoides*, *F. uhdei*, *P. alba*, *C. occidentalis*, and *A. negundo*), and low E (*A. longifolia*, *U. parvifolia*, *R. pseudoacacia*, *L. indica*, and *B. cordata*) (Table 2).

Table 2. Averages of stomatal conductance (g_S, cm s^{-1}) transpiration (E, g m^{-2} s^{-1}), cooling potential (CP, J m^{-2} s^{-1}), net radiation (Q_N, W m^{-2}), vapor pressure deficit (VPD, kPa), leaf temperature (T_L, °C), and air temperature (T_A, °C) of 15 dominant urban tree species from eight urban green areas of Mexico City. Species are ordered (Nr) accordingly to their transpiration (E) from high to low.

Nr	Species	g_S	E	CP	Q_N	VPD	T_L	T_A
1	*Liquidambar styraciflua*	3.81	0.0357	87.2	365.5	2.79	28.2	28.2
2	*Alnus acuminata*	3.52	0.0352	86.0	119.7	2.93	29.6	29.6
3	*Quercus rugosa*	3.65	0.0348	84.9	345.0	3.38	32.5	32.4
4	*Ligustrum lucidum*	2.89	0.0324	79.2	475.0	2.73	27.8	27.7
5	*Ficus benjamina*	3.01	0.0307	74.9	112.2	2.69	27.8	27.5
6	*Populus deltoides*	2.17	0.0215	52.5	162.2	3.01	29.6	29.2
7	*Fraxinus udhei*	2.6	0.0194	47.5	355.3	2.90	29.5	28.9
8	*Populus alba*	2.57	0.0187	45.5	410.48	2.80	28.5	28.3
9	*Celtis occidentalis*	2.85	0.0166	40.5	295.13	2.81	29.0	28.2
10	*Acer negundo*	2.10	0.0130	31.8	37.83	2.51	26.9	25.9
11	*Acacia longifolia*	1.82	0.0117	28.6	299.83	2.56	26.8	26.7
12	*Ulmus parvifolia*	1.6	0.0108	26.4	384.15	3.01	30.1	30.1
13	*Robinia pseudoacacia*	1.62	0.0107	26.2	462.17	3.21	31.5	31.4
14	*Lagerstroemia indica*	1.26	0.0102	25.1	346.5	2.01	24.1	23.8
15	*Buddleja cordata*	1.08	0.0089	21.7	482.98	2.14	24.6	24.1

In concordance, g_S was higher for *L. styraciflua* and lower for *B. cordata* ($F_{(14,465)} = 1180.9$, $p < 0.001$). Concerning Q_N, *B. cordata* had the highest values and *A. negundo* had the lowest ($F_{(14,465)} = 925.3$, $p < 0.001$). Although we found no statistical differences among tree species in differences between T_A and T_L ($F_{(14,465)} = 1.45$, $p = 0.10$) and among individuals of the same species ($p > 0.05$), we observed that leaf temperature was higher than air temperature in species with low E. VPD values were the highest for *Q. rugosa* and lowest for *L. indica* ($F_{(14,465)} = 79.174$, $p < 0.001$). We found a relationship among E, VPD, and T_A. Species that had low E, such as *B. cordata*, *L. indica*, and *A. negundo*, recorded low VPD, where the air was more saturated with water vapor and relatively lower leaf temperature were recorded compared to the other species. We considered four groups accordingly to the relationship among E, VPD, and T_A and species responses (Table 3). Species that recorded high E (Group 2 from Table 3) differed with respect to species that showed a moderate E, increased T_L, and higher humidity (Group 3 from Table 3), although differences between ranges of temperature and humidity were not negligible for these two groups. High E for species within group 2 was likely caused by greater irrigation; however, irrigation data were not available.

Regarding microclimate, *B. cordata* had the highest values of PAR, whereas *A. negundo* had the lowest. *Quercus rugosa* presented the highest values of T_A and VPD and *L. indica* the lowest. The highest T_A and T_L were associated with *Q. rugosa*, whereas *L. indica* had the lowest temperature values. *Acer negundo* had the greatest difference between T_A and T_L (1 °C), while *L. styraciflua*, *A. acuminata*, and *U. parvifolia* had no difference between air and leaf temperatures.

Table 3. Relationships among air temperature (T_A), vapor pressure deficit (*VPD*) and transpiration (*E*) for 15 dominant urban tree species from eight urban green areas of Mexico City.

Group	Species	T_A	*VPD*	*E*
1	*Lagerstroemia indica* *Buddleia cordata*	Low	Low	Low. Air is nearly saturated with water vapor; therefore, the leaf cannot release water through stomata
2	*Alnus acuminata* *Ulmus parvifolia* *Quercus rugosa* *Robinia pseudoacacia*	High	Moderate	High. VPD is favorable and leaf temperature is high
3	*Populus deltoides* *Liquidambar styraciflua* *Ficus benjamina* *Fraxinus uhdei* *Celtis occidentalis* *Ligustrum lucidum* *Populus alba* *Acacia longifolia*	High	Moderate	Moderate. VPD is favorable and leaf temperature is high
4	*Acer negundo*	Low	High	Low. Stomatal closure could avoid water loss and desiccation of leaves

We found no significant correlations between the species' climate of origin (i.e., MAT, MTWM, AP, and PDQ) and *E* and g_S ($p > 0.05$), although we found a trend that species with a wet and warm origin (i.e., high MAT and AP) have higher *E* (Supplemental Table S2).

The proposal and outline for an urban park design was developed for a space of 2500 m^2 (50 m × 50 m), considered functional and physiological parameters—mainly based on transpiration and aesthetic perspective—and consisted of six species with 19 individuals, including three individuals of *P. deltoides*, two individuals of *A. acuminata*, two individuals of *C. occidentalis*, four individuals of *L. styraciflua*, three individuals of *Q. rugosa*, and five individuals of *F. benjamina* (Figure 2).

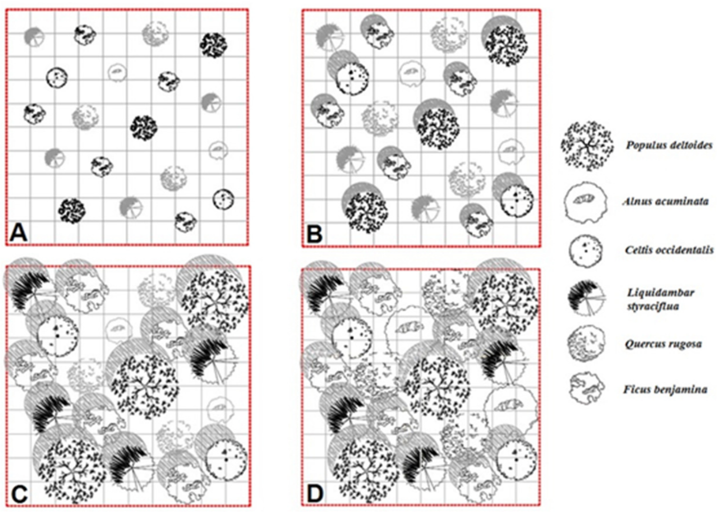

Figure 2. Proposed urban park design conformed by a tree community module and its enlargement over time, from the initial planting ((**A**), 2 years) to full growth ((**D**), ≥20 years), growing differentially due to different species growth rates. Fast-growing trees exceed the other trees in size generating shade zones ((**B**), 15 years), while moderate-growth trees surpass slow-growing trees in size in the medium-term, ameliorating the environment by producing more shade zones whereas fast-growing trees have full growth ((**C**), ≥15 years).

The planting technique used to generate a tree community module with different perspectives is presented in Figures 2–4. Figures 2 and 3 show an example of how trees can be associated and grow together, not only depending on their growth rate, leaf characteristics, and aesthetic perspective but also on their transpiration rates, showing the highest potential to mitigate UHI with aesthetic and landscape potential. This urban park design includes four fast-growth (*P. deltoides*, *A. acuminata*, *C. occidentalis* and *F. benjamina*), one medium-growth (*L. styraciflua*), and one slow-growth (*Q. rugosa*) species. Fast-growth species consist of those trees that reach their maximum development between five and 15 years, medium-growth are trees that reach their full development between 15 and 20 years, and slow-growth species reach their full development >20 years. Figure 4 shows a realistic ambience profile of the proposed tree community during the growth stage and at full growth.

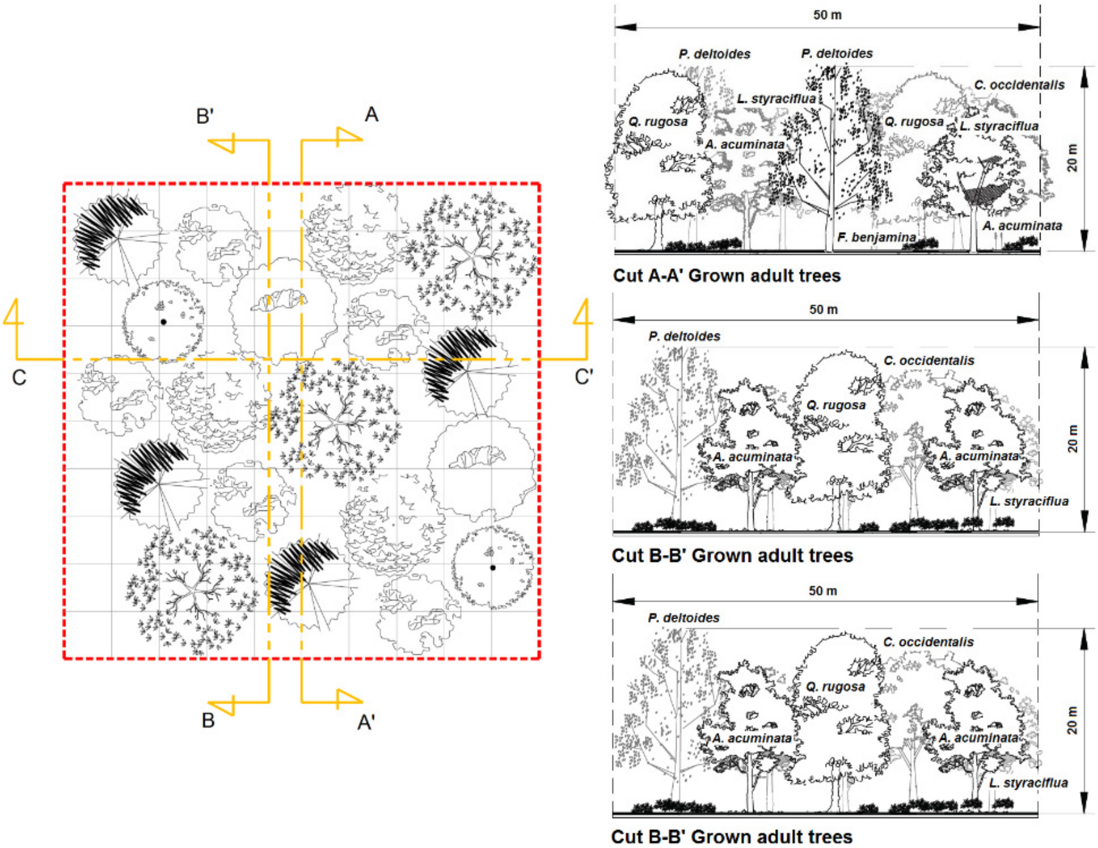

Figure 3. Final outlook of a proposed urban park design of a tree community module showing three different internal profiles as A-A′, B-B′ and C-C′ cuts.

According to the results given by the TUNEE model, the proposed urban park design of a tree community can reduce air temperature up to 5.3 °C without considering the effect of shade, with a cooling potential of 142.7 W m^{-2} when trees are fully developed (i.e., mature trees). The cooling benefit varied among each set of trees and species, so the set with the highest cooling potential is given by *F. benjamina* (187.7 W m^{-2}), while the set of *C. occidentalis* had the lowest cooling potential with 86.4 W m^{-2} (Table 4).

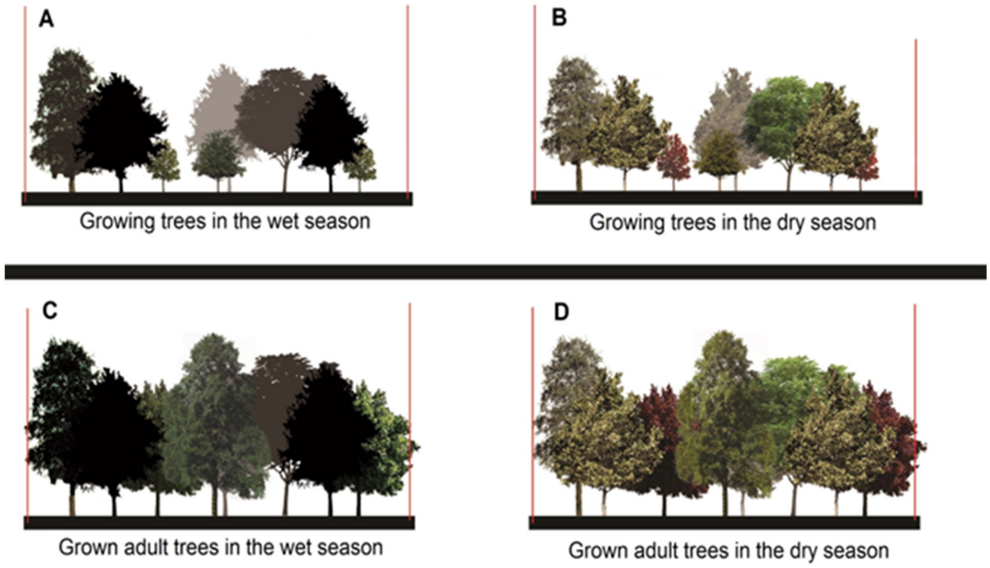

Figure 4. Realistic ambience of the B-B′ profile on Figure 3 of the proposed urban park design of a tree community during the growth stage (**A**,**B**) and at full growth (**C**,**D**) in the wet (**A**,**C**) and dry (**B**,**D**) seasons.

Table 4. Cooling potential of a proposed urban park design of a tree community of six tree species in a space of 2500 m^2 (50 m × 50 m) in one day and one hour. Values were calculated using the TUNEE model with an urban air temperature of 28 °C (T_{AU}), net radiation of 680 W m^{-2}, energy storage (urban fabric) of 252 W m^{-2}, and latent and sensible heat of 94.0 and 392 W m^{-2}, respectively. The values of the latent heat flux (Q_{EP}, W m^{-2}) and the air temperature (T_{AP}, °C) generated by each of the species, as well as the difference between the urban temperature and that of the park species ($\Delta T = T_{AP} - T_{AU}$, °C) are shown.

Species	Q_{EP}	T_{AP}	ΔT
Populus deltoides	96.8	24.5	3.4
Alnus acuminata	99.6	24.4	3.6
Celtis occidentalis	86.4	24.9	3.1
Liquidambar styraciflua	185.9	21.1	6.9
Quercus rugosa	122.1	23.5	4.4
Ficus benjamina	187.7	21.0	7.0
Weighted average	142.7	22.7	5.3

4. Discussion

Here, we used a bioclimatic approach for (re)designing urban parks to demonstrate that species selection considering *E* can significantly decrease local air temperature and mitigate UHI. Our research can contribute to landscape design by providing recommendations for the selection and management of urban trees with high *E* and proper species establishment. We propose an approach for comprehensive vegetation management with tree communities to mitigate urban heat by promoting high *E*. Our work also raises the following question: Is it possible to obtain moderate *VPD* and high *E* (i.e., comfort zones) for urban trees through landscape design? One approach to this concept could be (re)designing urban parks emulating natural communities (or park communities) because nature uses certain principles of order to control the conditions where vegetation grows.

4.1. Transpiration and Stomatal Conductance

In general, high E and g_S are related to sufficient irradiance ($PAR \geq 300$ µmol m^{-2} s^{-1}) on leaves to stimulate stomatal opening by raising leaf temperature [43,44], while a moderate VPD prevents stomatal closure produced by the influence of dry air and high pressure of humid air [45,46]. However, for these conditions to occur, plants must have water available in the soil. Indeed, high E requires that most of the water of the substrate is absorbed by the roots, which depends on the permeability and type of soil [47]. The absorbed water must be efficiently conducted through the vascular system to all tissues and organs to perform vital functions. Finally, leaf characteristics and stomatal sensitivity facilitate water loss [48]. Therefore, species used in landscape and urban planning should have positive or desirable physiological and morphological traits (Table 1) to promote high E and g_S.

To maintain high E, it also should be considered that when T_L is higher than T_A, stomata close (i.e., no E occurs) because water is limited to increase E and decrease T_L [45,46]. Therefore, we recommend the establishment of trees under conditions of adequate irrigation (or during the rainy season) and light shade (with enough light infiltration to decrease T_L). Shadows cast by taller trees help to reduce excessive sunlight on leaves, preventing stomatal closure when trees are in conditions of low water availability in the soil [49–51]. Additionally, shade decreases the surface temperature of the soil and thus reduces water loss by evaporation of the substrate [50].

4.2. (Re)Designing Urban Parks

Urban parks are conformed by groups of trees of different species where E differs among species and individuals depending on their characteristics and spatial location within the park and relative to other individuals, and on local environmental conditions [52]. Trees have mechanisms to adapt to different environmental conditions and stomatal behavior has different responses depending on these conditions [50,53]. Furthermore, urban trees can adapt and change their morphological and physiological traits as an adaptive response to the environment [54]. Thus, urban park communities can provide suitable environments that promote high E. However, an urban park community that promotes high E must consider species selection, density per unit area, park area, frond size of the selected individual trees, distance between individuals, number of individuals, diversity, and climate of origin. Indeed, although we did not find a significant correlation between E and climate of origin, we found evidence that species with warmer and wetter origin have high E; thus, climate of origin can be used as a tool to inform species selection [55].

Urban park communities can allow strategic tree location; fast-growing species can play the role of "nurse species" to create favorable conditions for the development of other species [56]. These communities within the urban context can promote the proper establishment and development of individuals to ensure plant performance [57]. However, care must be taken because cities are artificial entities that require management and practices different from natural environments, such as the case of species introduced due to their high E, such as *F. benjamina*, a tree native to Asia.

4.3. Additional Management Considerations

Our results suggest that to be able to compare E among species, it is important that all individuals are under similar or controlled conditions, considering irrigation, drafts, and type of substrate, among other factors. Moreover, it must be considered that E is not only determined by external conditions but also depends on internal conditions, especially water supply, which in turn depends on the roots, driving resistance, and soil conditions [58].

Transpiration is also reduced by decreasing the ratio of root/leaf area [59]. Hence, care must be taken to avoid improper pruning that removes most of the foliage. A large leaf surface increases E due to the presence of a greater number of leaves [60]. However, if a tree structure does not allow enough light infiltration to stimulate E, this will decrease [61]. To avoid this problem, we recommend performing pruning shaping and thinning to form open spaces within the canopy and allow air circulation and light infiltration to stimulate

E. It is also important to avoid the excessive cutting of roots that is performed when maintenance work is running on sidewalks or underground infrastructures, such as power grids or drainage.

As for irrigation, we did not find recommendations based on morpho-physiological characteristics of our species, but rather on experience (empirical knowledge). Harris [62] proposed a formula based on estimated coefficients to calculate irrigation of trees, shrubs, ground cover, mixed-grass coverage, and transpiration. However, Harris [62] did not consider soil characteristics or specific species. Because irrigation in urban parks is limited, it is necessary to know the real water demand of individual tree species, which to date is vastly unavailable. In places such as Mexico City where water for irrigation is limited, urban park communities can achieve more efficient use of water using our approach to estimating more accurately the amount of water needed for irrigation, especially during periods of increased scarcity, depending on the size of the urban park and the number of species and individual trees. Indeed, according to the conditions of the eight green areas used in this work, it seems that irrigation is inadequate in all green areas, causing water wastage, tree damage, and poor landscape, with additional socioeconomic losses.

Knowing more accurately the water requirements of urban trees can help to form tree communities with high, moderate, or low water requirements, depending on the water availability of the space to (re)design, and even zoning the park regarding the irrigation system and type of activities to provide water more efficiently and potentially at low cost. Nevertheless, despite lack of irrigation data, the proposed urban park design of a tree community presented in Figures 2 and 3 shows a similar cooling potential (Table 4) than that of the LGUP park (measured as 5.6 °C [63]), which is a park almost 39 times larger (9.9 ha) than the module proposed here.

Another approach is replacing tree species currently planted in parks with low *E* with tree species with medium or high *E*, considering the characteristics highlighted in this study and redesigning them to include in the palette species with high *E* and other physiological variables as a criterion for species selection aside from aesthetic and landscape features. This is especially important when species richness and diversity is encouraged while (re)designing urban parks [64]. This inclusion not only would reduce heat loads but could also improve human thermal comfort indices with a direct effect on human health [65].

While we have presented a novel method for (re)designing urban parks to maximize urban heat mitigation, there are some limitations to our study. First, we considered only a small number of species (i.e., 15 dominant urban tree species) that may not enhance urban tree diversity or account for the role of rare or endangered species [66,67]. Second, physiological data on *E* and g_S might not be readily available for a great number of species, limiting decision making about species selection. Third, other physiological traits, such as leaf area or leaf water potential at turgor point can also be used to guide species selection [68]. Finally, additional factors that can mitigate (e.g., presence of blue infrastructure) or exacerbate (e.g., air pollution) urban heat are not considered in our approach.

5. Conclusions

This work allowed us to understand how some plant traits of urban trees can be considered tools of landscape and urban design to reduce air temperature and mitigate UHI. Moreover, applying a bioclimatic approach, as proposed here for (re)designing urban parks, can help to improve local environmental conditions through proper management of vegetation, and make more efficient use of irrigation. Furthermore, our approach can be used to enhance urban greening strategies aiming to increase canopy cover while mitigating urban heat.

Our study offers a comparison of physiological responses among species facilitating the identification of the most efficient species to reduce urban heat via transpiration. A simultaneous evaluation of several urban tree species is useful for prioritizing tree options for urban greening in policies and plans. For example, we considered that species with high *E* and g_S, such as *L. styraciflua* and *Q. rugosa*, can help to mitigate the effects of the UHI.

Therefore, these species can be considered good plant choices when landscape design and urban planning aim to reduce local air temperature. We recommend increasing the number of urban tree species with different attributes to promote species and trait diversity in cities while (re)designing urban parks. We also highlight the need for research on physiological data for urban tree species to fill gaps in knowledge to assist species selection. Although our approach is based in Mexico City, other cities can replicate our method and use *E* or other plant traits to identify which species are more efficient to mitigate heat and achieve more effective irrigation conditions.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/f13071143/s1, Table S1: Mean values of mean annual temperature (MAT, °C), annual precipitation (AP, mm), maximum temperature of the warmest month (MTWM, °C) and precipitation of the driest quarter (PDQ, mm) for 15 dominant urban tree species based on their realized climatic niches; Table S2: Results of linear regression models used to assess relationships between two physiological traits (transpiration = *E*; stomatal conductance = g_S) and four climate variables (mean annual temperature = MAT; annual precipitation = AP; maximum temperature of the warmest month = MTWM; precipitation of the driest quarter = PDQ) of 15 dominant tree species.

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