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Quantifying Street Tree Regulating Heat Effects Using a Generalized Linear Mixed Model Approach

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Abstract

Climate change has emerged as a significant global environmental concern, prompting increased interest in utilizing trees as an alternative means to enhance human well-being and thermal comfort in urban settings. This study endeavors to assess the influence of street trees on the urban microclimate in tropical cities, employing a Generalized Linear Mixed Model (GLMM) approach. The investigation was conducted in Cotonou, Porto-Novo, and Ouidah within Benin. Data collection was conducted along thoroughfares, where a systematic inventory was performed to measure various characteristics of each street tree. Meteorological data, encompassing air temperature, relative humidity, and wind speed, were recorded at three different heights thrice an hour from 7 a.m. to 7 p.m. Subsequently, these datasets were analyzed using GLMMs. A total of 1127 street trees belonging to 20 species and 13 families were identified. The Shannon Diversity Index and Pielou Equitability values ranged from 2.33 to 2.92 bits and 0.17 to 0.64, respectively. The GLMM analysis revealed that the presence of trees, daytime, and height significantly influenced air temperature, relative humidity, and wind speed. Street trees on both sides of roadways induced an air temperature decrease from -0.6°C to -1.4°C and an increase in relative humidity ranging from +2.5% to +5.2% between 11 am and 5 pm, as compared to other layouts. Furthermore, closed canopy patterns exhibited the most favorable outcomes, resulting in an air temperature decrease from -0.4°C to -1°C and an increase in relative humidity from +2.4% to +5.5% between 11 am and 5 pm.

Keywords: Climate change, Generalized Linear Mixed Model, heat effects mitigation, meteorological parameters, street tree

Introduction

Climate change has emerged as a significant global environmental challenge confronting humanity. Its manifestation in global warming has tangible effects on communities and public policymakers. Extensive scientific evidence from the Intergovernmental Panel on Climate Change (IPCC) indicates that the primary cause of climate change is the release of greenhouse gases into the atmosphere due to human activities. Their projections suggest a temperature increase from 1.8 ºC for scenario Shared Socio-economic Pathway SSP1-2.6 (Representative Concentration Pathway RCP 2.6) to 4.8 degrees Celsius for scenario SSP5-8.5 (RCP 8.5) by 2100 (IPCC, 2023). The Shared Socioeconomic Pathway (SSP) scenarios encompass a more extensive spectrum of potential greenhouse gas (GHG) and air pollutant outcomes in comparison to the Representative Concentration Pathway (RCP) scenarios. While bearing resemblances, they exhibit dissimilarities, manifesting divergent concentration trajectories for distinct GHGs. The implications include heightened frequency and intensity of meteorological phenomena like heavy rainfall, droughts, heatwaves, and threats to biodiversity, ecosystems, and human activities (IPCC, 2023). Such consequences significantly threaten sustainable development (Stern, 2007). In this context, Africa, without expeditious, profound, and consistent mitigation measures alongside intensified adaptation endeavors, losses and damages remains inevitable. This pertains to the projected adverse consequences as well (IPCC, 2023). In this report, the authors projected that with global warming of 1.5°C in African regions, heavy precipitation and flooding will be intensified (high confidence). As a result, urban heat islands, characterized by elevated temperature, reduced humidity, and altered wind and radiation conditions, will potentially be exacerbated. According to Litschke and Kuttler (2008), inadequate infrastructure, building design, limited vegetation cover, and human-induced pressures would further strengthen urban heat island effects. Additional factors contributing to climatic variations in cities include geographical location, scale factors, city size, density and configuration of urban structures, and the thermophysical properties of materials (Georgescu et al., 2015). Consequently, urban planners face the task of devising innovative strategies to adapt to climate change and mitigate the adverse impacts of urban heat islands (Sénécal, 2007).

One promising approach to alleviate this situation in municipalities involves the implementation of amenity gardens and tree-lined avenues, which serve as crucial solutions for climate change adaptation and sustainable urban development (Pamukcu-Albers et al., 2021). Trees provide multiple benefits, including enhancing human well-being, and improving thermal comfort (Meyer et al., 2005; Arnson et al., 2012). The significance of green spaces, tree-lined avenues, lawns, public gardens, parks, and individual trees, in human life, is widely acknowledged. Trees offer soothing qualities, enhance the quality of the living environment, and provide ecological and landscape benefits (Andrade et al., 2020; Teixeira and Fernandes, 2020). They contribute to the aesthetics of the surroundings, offer shade and coolness, renew the oxygen content in the air, and regulate humidity levels (Parker and Zingoni de Baro, 2019; Spano et al., 2020).

Furthermore, trees actively remove CO2, the predominant greenhouse gas, from the atmosphere through photosynthesis (Kenney et al., 2011). Despite these numerous contributions, urban centers continue to experience high temperatures. Increasing urban vegetation density has been shown to have a cooling effect, resulting in an average temperature reduction of approximately 1°C in urban parks across various climates (Bowler et al., 2010; Zhang et al., 2013). Several approaches have been explored to mitigate the potentially detrimental impacts of urban heat. For instance, Shashua-Bar et al. (2010) employed simulations and the analytical Green Cluster Thermal Time Constant (CTTC) model to analyze the influence of individual variables and their interaction with urban characteristics. Revelli and Porporato (2018) utilized a stochastic ecohydrological model to quantify ecosystem services such as tree cooling effects, soil carbon sequestration, and storm-water management at the scale of individual street trees. Segura et al. (2022) successfully implemented an urban canopy model (UCM) known as Building Effect Parameterization with Trees (BEP-Tree), which exhibited good agreement with empirical observations regarding temperature and radiation.

However, to investigate street tree variables in the country of Benin, located in sub-Saharan Africa, meteorological longitudinal data were collected. Despite the substantial efforts made by the country to enhance economic growth and reduce poverty, it remains highly susceptible to the impacts of climate change (Hallegatte, 2016). Urban areas, characterized by high population densities, economic activities, and built environments, face elevated risks associated with climate and weather hazards such as floods, heatwaves, and pollution, which are anticipated to worsen due to climate change (Harlan and Ruddell, 2011). It is crucial to note that many of these urban centers are situated in areas highly prone to adverse climate events

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(Lankao, 2008). Consequently, this study aims to investigate the influence of street trees on the urban microclimate in the tropical municipalities of Cotonou, Porto-Novo, and Ouidah by employing a Mixed Generalized Linear Model Approach. The research seeks to achieve three objectives: (i) evaluate the biodiversity and dendrometric characteristics of street trees, (ii) assess the impact of street trees on microclimate moderation, and (iii) determine the most effective configurations of street tree layouts and canopy patterns to optimize the cooling effect.

Methods

Study area and field sites

The present study directs its attention to three specific cities, namely Ouidah, Cotonou, and Porto-Novo, which are situated in the southern region of Benin, encompassing a geographical area between 1° 50' and 2° 40' East longitude, and between 6° 20' and 6° 40' North latitude (Figure 1). This particular coastal area is characterized by a sub-equatorial climate, manifesting two distinct rainy seasons spanning from April to July and from October to November, accompanied by two dry seasons spanning from August to September and from December to March (Adam and Boko, 1993). The average annual precipitation recorded in this region ranges from 820 to 1300 mm, while the temperature varies between 31.5 to 33°C (Kingbo *et al.*, 2022). The urbanized landscapes of these cities exhibit a variety of vegetation types, including natural areas, roadside trees, residential trees, vegetation on undeveloped land, shrubs, and ground cover (Tohozin and Orekan, 2017, Agoungbome *et al.*, 2020). These ecological systems serve diverse purposes such as shading, air pollutants absorption, aesthetics, recreation and medicinal uses, economic benefit, and are actively utilized by the local communities (Djikpo *et al.*, 2023). As per the 2013 census conducted by INSAE, the population densities in Cotonou, Porto-Novo, and Ouidah were estimated at 8595 inhabitants per square kilometer, 2403 inhabitants per square kilometer, and 252 inhabitants per square kilometer, respectively. Economic activities within these urban centers primarily revolve around trade, urban agriculture, fishing, animal husbandry, and agricultural product processing (INSAE, 2013).

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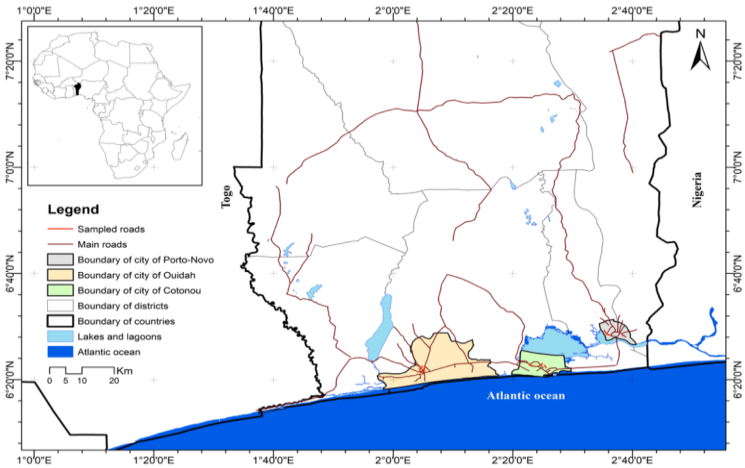

Figure 1. Study area

Data collection

The study collected data from three cities in Benin, namely Cotonou, Porto-Novo, and Ouidah. These cities were selected based on the presence of tree-lined plantations established during reforestation campaigns. These plantations have been in place for over a decade and consist of tree species capable of tolerating the impacts of urbanization. Thoroughfares within each city were chosen based on specific criteria, including the presence of trees, length, configuration, and pattern. In Ouidah, four thoroughfares were selected for sampling: Kpassè, Gbèna, Mairie, and RNIE1. Three thoroughfares were chosen in Porto-Novo: L'entente, Lagunaire, and Hôtel de ville. Similarly, three thoroughfares were sampled in Cotonou: Europe, Saint-Rita, and Ouémé. These thoroughfares represented distinct tree layouts and canopy patterns, as outlined in Table 1.

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Table 1. Tree layouts and canopy patterns variables

Parameters	**Variables**		
Trees layouts (TL)	TL-A	TL-B	TL-C
			
	Street trees at the central median and on both sides of the roadway.	Street trees located on both sides of the roadway.	Street trees at the central median.
Tree canopy pattern (TCP)	TCP-A	TCP-B	TCP-C
TCP is defined throughout inter-canopy distance (ie. the distance between two successive canopies on the same alignment of street trees.			
	Trees are widely spaced out and the inter-canopy distance is either equal to or greater than 5 meters.	The spacing between trees is typically sparse, with inter-canopy distances ranging from 0 to 5 meters.	The canopy of the street trees is completely closed and the inter-canopy distance is equal to 0 meter.

In each street, precise measurements of trees and weather conditions were systematically recorded. A comprehensive inventory was conducted to obtain data on various aspects of each tree, such as the shape of its canopy, the pattern of shadows cast on the ground, the diameter of the canopy, and the diameter of the tree at breast height (dbh), which was measured using a measuring tape. Furthermore, the height of the trees was determined using a SUNNTO clinometer, and the tree species were identified by consulting a botanical identification key (Akoègninou *et al.*, 2006).

Additionally, meteorological data, including temperature, relative humidity, and wind speed, were collected at two specific locations: the roadside and the central median. The measurements were taken at three different heights (1.5m, 2m, and 3m) at one-hour intervals between 7 am and 6 pm every 14 days from November 1st to December 21st according to Teka *et al.* (2017a). Wind speed was measured using an anemometer model

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HoldPeak HP-866B, while air temperature and relative humidity were recorded using a thermo-hygrometer.

Data Analysis

The assessment of street tree planting biodiversity involved the utilization of multiple metrics, namely species richness (S), Shannon's diversity index (H), Simpson's diversity index (D), and Pielou's equitability index (R). Furthermore, various dendrometric parameters were analyzed, including linear density (Ni), tree renewal rate (Tr), linear basal area (Gi), total basal area (Gt), quadratic diameter (Dg), shading index (Io), risk index or real fall index (IRr), and crown shape ratio (Ch).

Species richness (*S*) is the total number of species.

Shannon diversity index (H, in bits) varies between 0 and 5 (normally, the upper limit is $\log_2 S$).

$$H = -\sum p_i \log_2 p_i \tag{1}$$

pi represents the ratio of the number of individuals in a particular species i, to the total number of individuals in all species combined. The value of pi can be calculated by dividing the number of individuals in species i (*ni*) by the total number of individuals in all species (*Σni*).

$$p_i = n_i / \sum n_i \tag{2}$$

Pielou equitability (*R*) indicates the stability of the ecosystem and represents the ratio of the current diversity (*H*) to the theoretical maximum diversity (*Hmax*) to be achieved by the plant community. It varies from 0 to 1. It is close to 0 when almost the entire forest stand is composed of a single species and it tends to 1 when each species is represented by approximately the same number of individuals.

$$R = H / H_{\max} = H / \log_2 S \tag{3}$$

Average height (*Hg*) is the arithmetic average height of all trees dbh ≥10cm. *Hi* is the height in meter of the trees *i*.

$$H_g = \sum H_i / n \tag{4}$$

Linear density (*Ni*, in trees/100m) is the average number of trees dbh ≥ 10cm over distance of 100 m. *nt* is the total number of trees and *dt*, the total distance of the thoroughfare.

$$N_i = n_t \times 100 / \mathrm{d}_t \tag{5}$$

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Quadratic diameter (*Dg*, in cm) is the measure of average trees diameter using the following formula. *n* is the number of dbh ≥ 10 cm trees on the thoroughfare and *di*, the diameter of trees *i*.

$$Dg = \sqrt{\frac{1}{n}\sum_{i=1}^{n} d_i^2} \qquad (6)$$

Shading index (I_0, in %) quantifies the extent of shading provided by street tree planting. This metric is subject to variation based on the angle at which solar rays intersect with the trees and is primarily influenced by the total area covered by the tree canopies at ground level. *Ai* is the shading surface of a tree; *ΣAi* is the total shade area on the thoroughfare and *At*, is the total area of the thoroughfare.

$$I_o = \sum A_i \times 100 / A_t \qquad (7)$$

Risk fall index (*IRp*, in %) expressed as a percentage, quantifies the risk of tree fall by evaluating the ratio of crooked trees or side branches posing a threat to the overall number of trees present on a given thoroughfare. The variables involved in this index are *np*, denoting the count of crooked trees or threatening side branches, and *Σni*, representing the total number of trees found on the thoroughfare. By employing this index, the potential risk associated with tree falls can be assessed.

$$IR_p = n_p \times 100 / \sum n_i \qquad (8)$$

Real fall index (*IRr*, in %) is the ratio of the number of annual falls (by accident or not) recorded by the total number of trees. *nc* the number of annual falls recorded and *Σni*, the total number trees.

$$IR_r = n_c \times 100 / \sum n_i \qquad (9)$$

***Crown shape ratio* (*Ch*, in %)**

It is the ratio of the number of individuals with normal tree branches form, in flag or degraded to the total number of individuals. *Σni* represents the total number of street trees planted on the thoroughfare.

$$C_{h\,normal} = n_{i\,normal} \times 100 / \sum n_i$$
$$C_{h\,flag} = n_{i\,flag} \times 100 / \sum n_i$$
$$C_{h\,degraded} = n_{i\,degraded} \times 100 / \sum n_i \qquad (10)$$

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The meteorological observations were subjected to analysis using a generalized linear mixed model (GLMM) in order to investigate the parameters of temperature, relative humidity, and wind speed. The choice of employing the GLMM approach was driven by the non-normal distribution exhibited by the data. The analysis was carried out using R version 4.0.5 (R Core Team, 2022).

Results

Biodiversity and characterization of street trees

An investigation was conducted to assess the botanical composition of street trees in the primary coastal cities of Benin. The findings revealed a total of 1127 plants belonging to 20 distinct species and 13 families, as presented in Table 2. Quantitative measures such as the Shannon Diversity Index and Pielou Equitability were computed, resulting in values ranging from 2.33 to 2.92 bits and 0.17 to 0.64, respectively. These findings indicate a relatively low diversity of tree species within the surveyed areas. Notably, the street tree populations in Cotonou, Porto-Novo, and Ouidah were predominantly composed of *K. senegalensis*, *T. mantaly*, and *T. catappa* species.

Table 2. Diversity and floristic wealth of street trees in Cotonou, Porto-Novo, and Ouidah

	Cotonou	**Porto-Novo**	**Ouidah**
Number of species	20	17	15
Number of genera	17	16	14
Number of families	11	13	12
Shannon's diversity index (H)	2,33	2,92	2,51
Pielou equitability (R)	0,17	0,21	0,64
Total number	532	377	218

The analysis of tree characteristics reveals varying 100-meter linear densities across different locations in Benin, as shown in Table 3. Porto-Novo exhibits a linear density of 3.33 trees, whereas Cotonou showcases a higher density of 8.75 trees. Furthermore, the average diameter of these trees ranges from 41.1 to 49.24 centimeters. The estimated average height of the trees falls within the range of 10.77 to 15.73 meters. Moreover, the shading index, which represents the degree of shade provided by the trees, ranges from 33.94% to 44.38%. In terms of the potential fall index, which assesses the likelihood of tree fall, estimates range from 13.30% to 28.90%. Regarding crown shape ratios, the normal shape accounts for approximately 71.17% to 90.83% of the trees, while the flag shape ranges from 8.26% to 22.65%. Lastly, the degraded shape represents a smaller portion, varying from 0.92% to 6.18% of the trees.

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Table 3. Dendrometric and structural parameters

Dendrometric characteristics		Cotonou	Porto-Novo	Ouidah
Linear density (Ni in trees /100m)		8.71	3.33	6.75
Trees Recruitment rate (Tr in %)		4.50	11.90	0.00
Height (H in m)		15.73	11.66	10.77
Diameter (Dbh. in cm)		41.1	43.70	49.24 159.24±11.62
Quadratic diameter (Dg in cm)		43.4	50.36	52.34
Shading index (I_o in %)		33.94	-	44.38
Risk fall index (IR_p, in %)		13.30	15.87	28.90
Real fall index (IR_r, en %)				2.29
Crown shape ratio (C_h in %)	C_h normal	85.81	71.17	90.83
	C_h flag	12.46	22.65	8.26
	C_h degraded	1.73	6.18	0.92

Effects of street trees on local climate mitigation

Effect of the street tree on meteorological parameters within urban areas

The weather conditions observed during the designated study period, spanning from January to February 2020, exhibited typical characteristics of the summer season. As illustrated in Figure 2, the daytime air temperature ranged from 24 to 33°C, accompanied by a relative humidity of 62 to 87% and a wind speed of 0.6 to 1.8 $m.s^{-1}$. Notably, it was observed that throughout the daytime hours, the air temperature in Porto-Novo consistently surpassed that of Cotonou and Ouidah, as depicted in Figure 2a. Particularly between 11:00 a.m. and 3:00 p.m., the recorded air temperature in Porto Novo exceeded the values in the other two cities by a margin ranging from +0.7 to +1.8°C. Statistical analyses using the generalized linear mixed model (GLMM) revealed significant variations (p-value <0.0001) in air temperature, relative humidity, and wind speed data across the three specified cities. Additionally, these variations were found to be contingent upon the presence or absence of street trees, as indicated in Table 4.

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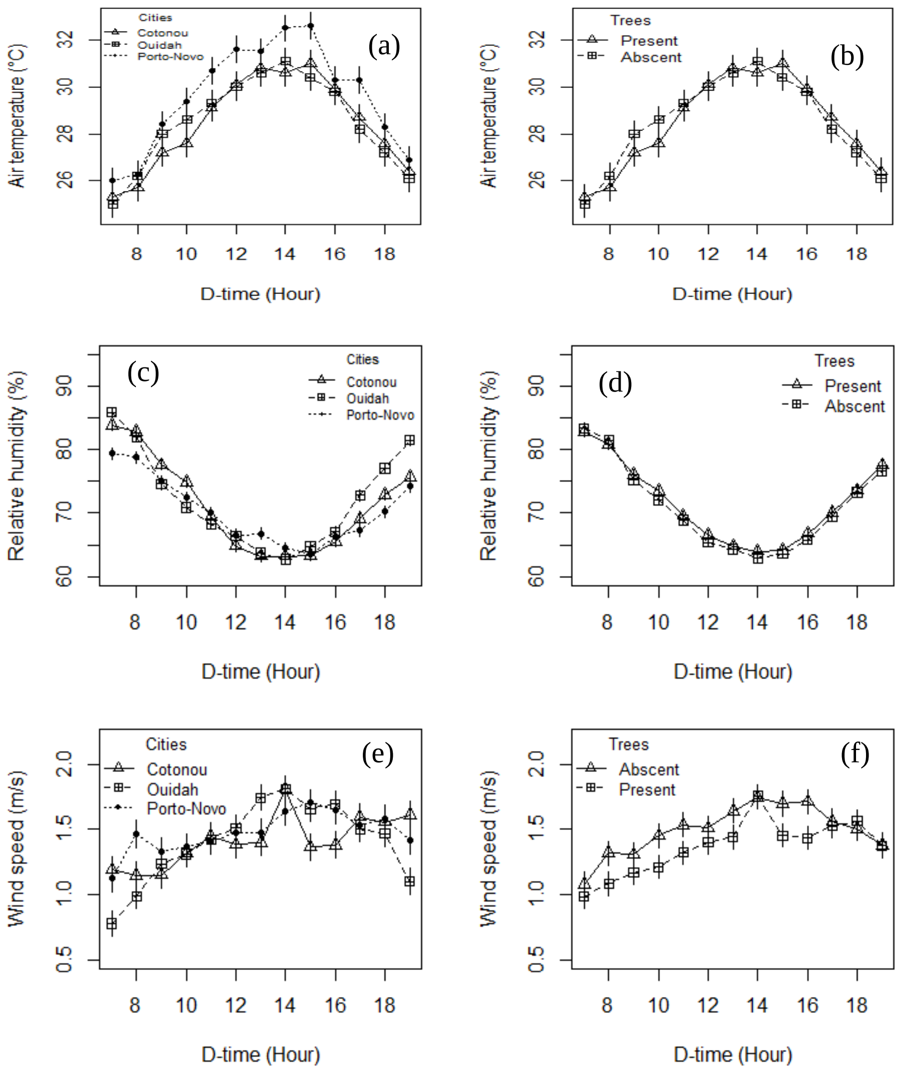

Figure 2. Diurnal Trends in air temperature, relative humidity, and wind speed belong to cities (a, c, e) and tree occurrence (b, d, f)

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Table 4. Generalized linear model with mixed effects on meteorological data in the overall study area

	numDF	denDF	F-value	p-value
A: on temperature				
D-time	12	9397	850.18	<.0001***
Cities	2	9397	437.44	<.0001***
Trees	1	9397	21.35	<.0001***
D-time:Cities	24	9397	11.69	<.0001***
D-time:Trees	12	9397	2.82	0.0007**
Cities:Trees	2	9397	41.83	<.0001***
B: on relative humidity				
D-time	12	9397	806.29	<.0001***
Cities	2	9397	76.61	<.0001***
Trees	1	9397	18.76	<.0001***
D-time:Cities	24	9397	26.42	<.0001***
D-time:Trees	12	9397	1.63	0.0746
Cities:Trees	2	9397	112.69	<.0001***
C: on wind speed				
D-time	12	9397	17.69	<.0001***
Cities	2	9397	1.75	0.1728
Trees	1	9397	27.00	<.0001***
D-time:Cities	24	9397	3.35	<.0001***
D-time:Trees	12	9397	1.55	0.0984
Cities:Trees	2	9397	13.37	<.0001***

Df: Degree of freedom, p-value: Probability test, Significant codes: 0 ‘***’ 0.001 ‘**’ 0.01 ‘*’ 0.05 ‘.’ 0.1

Effect of the street tree on meteorological parameters in Ouidah

In Figure 3a, it can be observed that the temperature trend remains consistent regardless of height. However, the presence of trees in the city of Ouidah leads to a lower air temperature. For instance, at 12 pm, there is a decrease of 0.8°C as depicted in Figure 3b. Hence, street trees play a role in reducing the air temperature. The relative humidity, on the other hand, does not display any variation in trend for the three different heights analyzed in this study, as illustrated in Figure 3c. Nonetheless, the average relative humidity values are higher (+2.5% at 12 pm) in the presence of trees, regardless of the time of day, as shown in Figure 3d. The wind speed reaches its maximum between 1 pm and 2 pm, with the highest values recorded at a height of 3m (Figure 3e). However, when trees are present, the wind speed is lower (-0.3m/s at 1 pm), as illustrated in Figure 3f.

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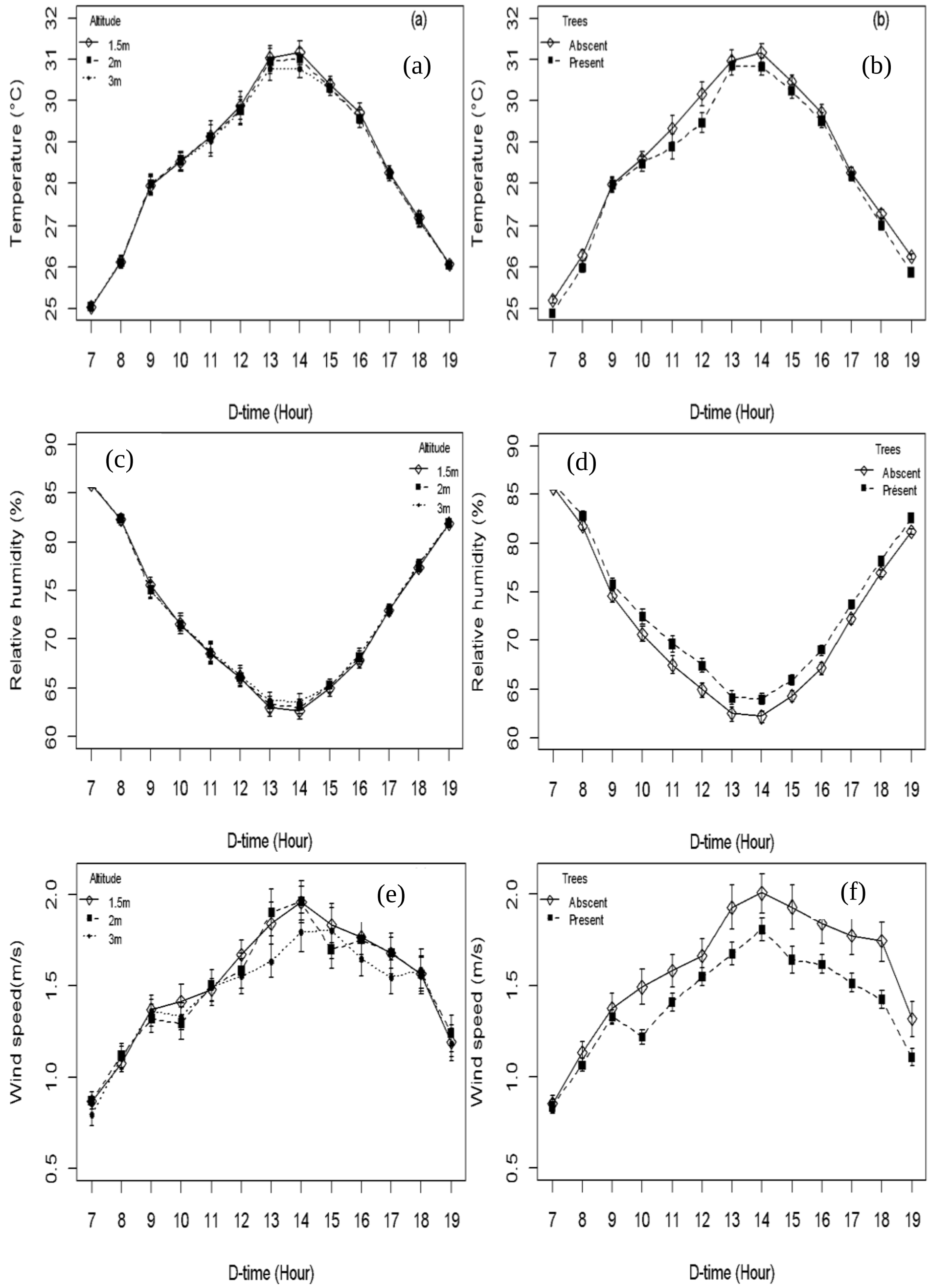

Figure 3. Diurnal Trends in air temperature, relative humidity, and wind speed belong to height (a, c, e) and tree occurrence (b, d, f) at Ouidah

When trees are present, meteorological parameters are noticeably milder. Street trees, therefore, make a significant contribution to mitigating the local urban climate by providing cooling effects. Based on the analysis of

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variance conducted on the best model (Table 5), it has been established that the occurrence of trees, daytime, and height factors have significant effects (p-value <0.0001) on air temperature, relative humidity, and wind speed. The interaction of daytime and height has significant effects on all three meteorological parameters, whereas the interaction of daytime and trees only has an impact on wind speed as indicated by the GLMM outputs. The planting of street trees significantly influences air temperature, resulting in a cooling effect on the climate observed in the thoroughfares of the city of Ouidah.

Table 5. Generalized linear model with mixed effects on meteorological data in Ouidah

	Chisq	**Df**	**Pr (>Chisq)**
A: on temperature			
D-time	41.21	1	0.0002 **
Trees	2.86	1	<0.0001 ***
Height	7.39	2	0.006 **
D-time: Trees	0.74	2	0.390
D-time: Height	350.03	2	0.001 **
B: on relative humidity			
D-time	11.79	1	0.0001 ***
Trees	1.74	1	0.0187 *
Height	6.47	2	0.011 *
D-time: Trees	2.19	2	0.138
D-time: Height	558.33	2	0.001 **
C: on wind speed			
D-time	16.31	1	0.001 **
Trees	14.50	1	0.001 **
Height	13.19	2	0.001 **
D-time: Trees	4.23	2	0.039 *
D-time: Height	26.25	2	0.001 **

Df: Degree of freedom, Pr: Probability test, Significant codes: 0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1

Effect of the street tree on meteorological parameters in Cotonou

A generalized linear mixed-effects model was also utilized to analyze air temperature, relative humidity, and wind speed data at Cotonou. The results showed that air temperature varies significantly ($P < 0.0001$) based on both daytime and the presence of trees (Table 6). Specifically, street trees were found to reduce air temperature by an average of -1.1°C at 2 pm in Cotonou (Figure 4b), indicating that they contribute to mitigating the urban heat island effect. Additionally, relative humidity was found to vary significantly ($P < 0.0001$) based on daytime and the presence of trees. The average relative humidity values were higher (+3.5 to +5% from 9 am to 6 pm) in areas with trees (Figure 4d), further demonstrating the cooling effect of trees in Cotonou. Wind speed was found to be significantly influenced ($P < 0.05$) by only daytime and height. However, despite this, the study highlights street trees' crucial role in cooling and reducing the heat island effect in Cotonou.

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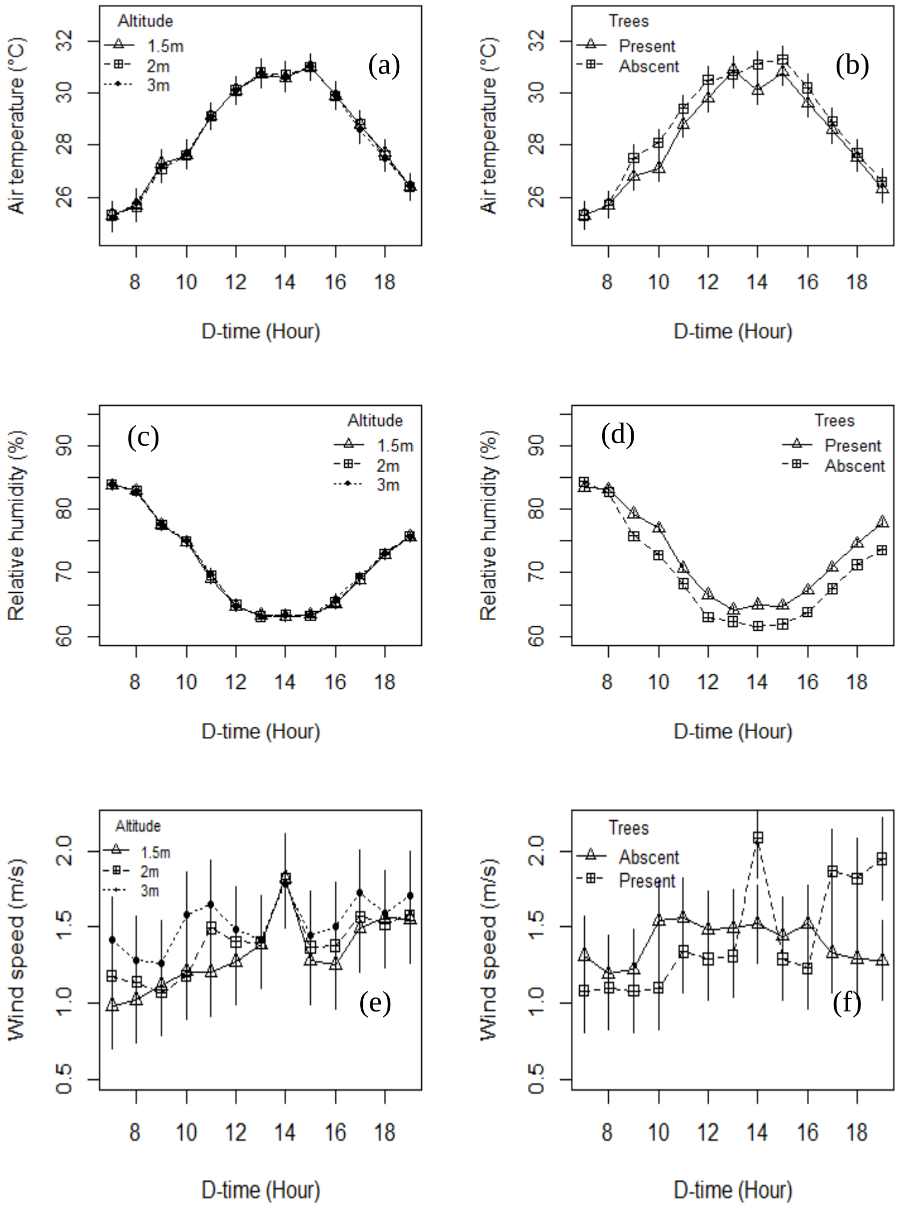

Figure 4. Diurnal Trends in air temperature, relative humidity, and wind speed belong to height (a, c, e) and tree occurrence (b, d, f) at Cotonou

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Table 6. Generalized linear model with mixed effects on meteorological data in Cotonou

	numDF	denDF	F-value	p-value
A: on temperature				
D-time	12	3079	366.46	<.0001***
Height	2	3079	0.10	0.9012
Trees	1	3079	55.30	<.0001***
D-time:Height	24	3079	0.09	1.0000
D-time:Trees	12	3079	3.30	0.0001***
Height:Trees	2	3079	0.12	0.8826
B: on relative humidity				
D-time	12	3079	332.15	<.0001***
Height	2	3079	0.38	0.6857
Trees	1	3079	148.28	<.0001***
D-time:Height	24	3079	0.08	1.0000
D-time:Trees	12	3079	3.48	<.0001***
Height:Trees	2	3079	0.08	0.9266
C: on wind speed				
D-time	12	3079	2.70	0.0012**
Height	2	3079	4.26	0.0141*
Trees	1	3079	0.24	0.6240
D-time:Height	24	3079	0.21	1.0000
D-time:Trees	12	3079	3.23	0.0001***
Height:Trees	2	3079	0.35	0.7005

DF: Degree of freedom, P-value: Probability test, Significant codes: 0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1

Effect of the street tree on meteorological parameters in Porto-Novo

In this scientific study, a Linear mixed-effects model was also utilized to analyze data on air temperature, relative humidity, and wind speed at Porto-Novo. The findings demonstrated that these meteorological parameters exhibited significant variations (P < 0.0001) based on both daytime and the presence of trees (as shown in Table 7). Specifically, the study revealed that street trees had the effect of reducing air temperature and increasing relative humidity by an average of -0.5 to -1.6°C and +2 to +3%, respectively, between 10 am and 5 pm (as depicted in Figure 5b and 5d), thereby contributing to the mitigation of the urban heat island effect. Moreover, the wind speed was also found to be significantly influenced (P < 0.001) by height, with wind moving much faster at a height of 2 meters from the ground.

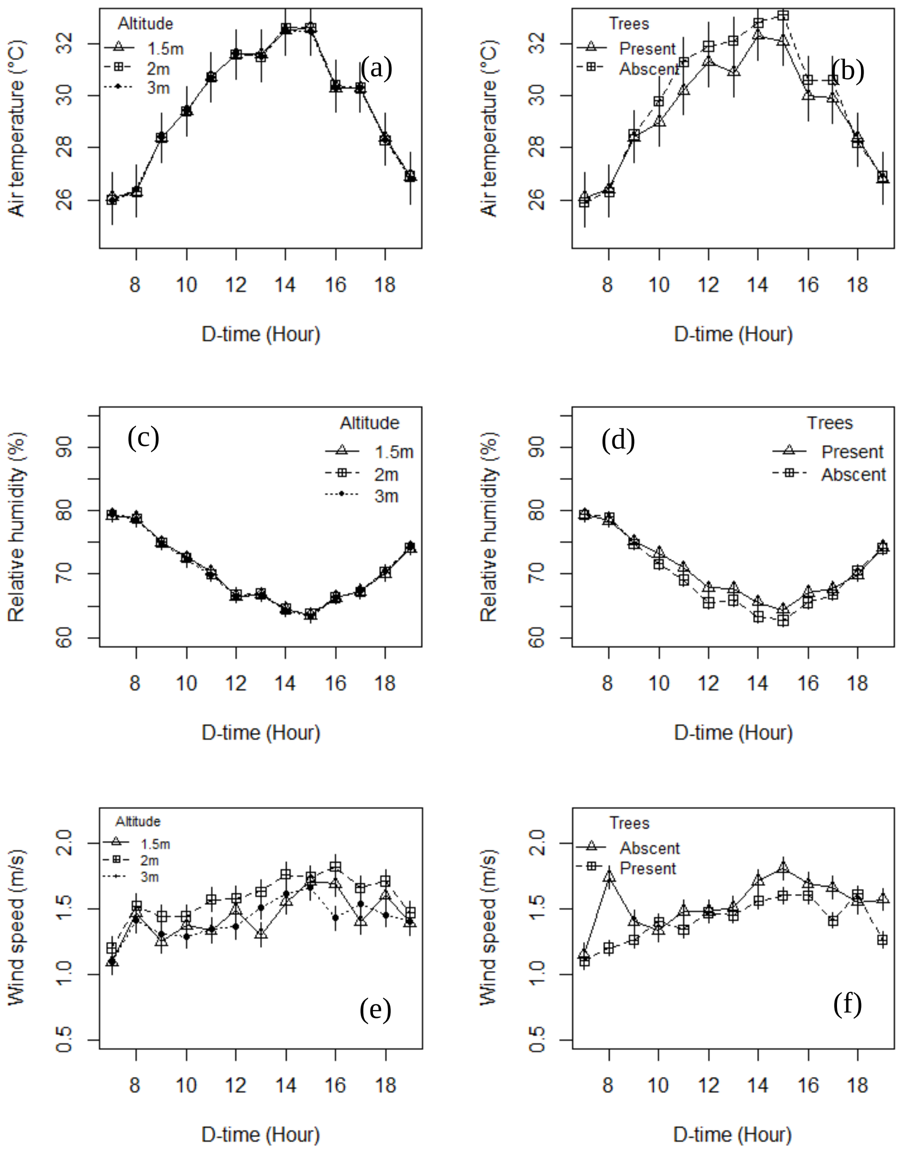

Figure 5. Diurnal Trends in air temperature, relative humidity, and wind speed belong to height (a, c, e) and tree occurrence (b, d, f) at Porto-Novo

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Table 7. Generalized linear model with mixed effects on meteorological data in Porto-Novo

	numDF	denDF	F-value	p-value
A: on temperature				
D-time	12	3079	315.68	<.0001***
Height	2	3079	0.04	0.9555
Trees	1	3079	38.18	<.0001***
D-time:Height	24	3079	0.02	1.0000
D-time:Trees	12	3079	3.16	0.0002**
Height:Trees	2	3079	0.00	0.9927
B: on relative humidity				
D-time	12	3079	183.08	<.0001***
Height	2	3079	0.05	0.9501
Trees	1	3079	20.24	<.0001***
D-time:Height	24	3079	0.03	1.0000
D-time:Trees	12	3079	1.58	0.0883
Height:Trees	2	3079	0.05	0.9423
C: on wind speed				
D-time	12	3079	9.64	<.0001***
Height	2	3079	14.14	<.0001***
Trees	1	3079	22.87	<.0001***
D-time:Height	24	3079	0.73	0.8215
D-time:Trees	12	3079	2.47	0.0032**
Height:Trees	2	3079	0.15	0.8572

DF: Degree of freedom, p-value: Probability test, Significant codes: 0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1

Effects of street tree layouts (TL) and canopy patterns (TCP)

This study uses a linear mixed-effects model to determine the most effective configurations of street trees to maximize the cooling effect. Specifically, the model was applied to air temperature, relative humidity, and wind speed data. Street tree layouts (TL) and canopy patterns (TCP) were manipulated to achieve the desired cooling effect. The results showed that the meteorological parameters examined exhibited significant variations ($P < 0.0001$) due to the interaction between daytime and tree layouts on one side and daytime and tree canopy patterns on the other side, as demonstrated in Table 8.

The thoroughfares, with street trees only on the median strip, recorded the highest air temperatures and lowest relative humidities during the day. Based on the findings, the most effective layout for maximizing the cooling effect of street trees was the placement of trees on both sides of the roadway. This layout resulted in an air temperature difference ranging from -

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0.6°C to -1.4°C and relative humidity ranging from +2.5 to +5.2% from 11 am to 5 pm compared to other layouts (Figure 6a and 6b). Moreover, the best TCP was identified as closed canopies, resulting in an air temperature difference ranging from -0.4°C to -1°C and relative humidity ranging from +2.4 to +5.5% from 11 am to 5 pm compared to the other arrangements (Figure 6c and 6d). In conclusion, street trees should be placed on both sides of the roadway with closed canopies when the trees reach adulthood, to optimize the softening effect in urban centers.

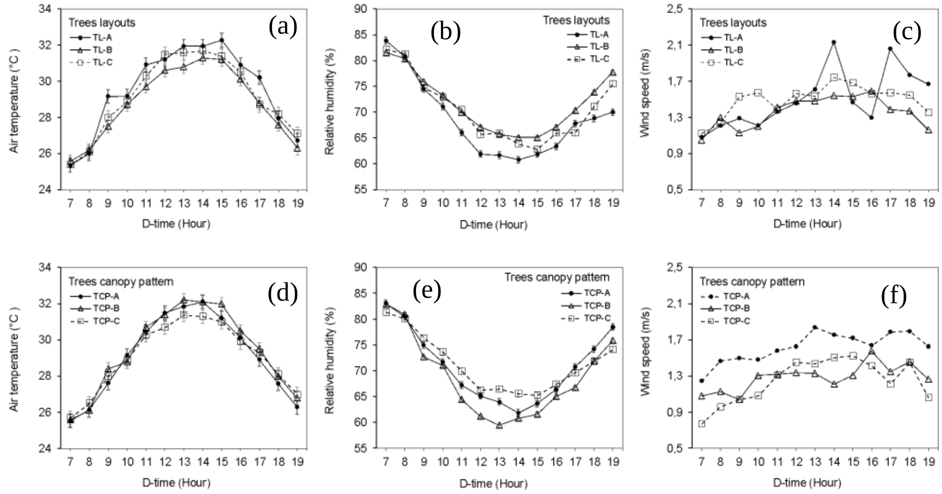

Figure 6. Temperature trends belong to the tree layouts and canopy patterns. (TL-A) trees on the roadside and in the central median, (TL-B) trees only on the roadside, and (TL-C) trees only in the central median, (TCP-A) inter-canopy distance ≥ 5 m, (TCP-B) inter-canopy distance < 5, and (TCP-C) closed canopy

Table 8. Generalized linear model with mixed effects on meteorological data in Porto-Novo

	F	Df	Df.res	Pr(>F)
A: on temperature				
D-time	19.49	12	6095.0	<.0001***
Type	0.57	2	6095.0	0.5622
Cover	0.11	2	6095.0	0.8934
Hour:Type	1.97	24	6095.0	0.0030**
Hour:Cover	1.11	24	6095.0	0.3115
Type:Cover	0.37	3	6095.0	0.7677
Hour:Type:Cover	1.58	36	6095.0	0.0148*
B: on relative humidity				
D-time	25.82	12	6095.0	<.0001***
Type	0.73	2	6095.2	0.4784
Cover	2.61	2	6095.1	0.0730
Hour:Type	3.20	24	6095.0	<.0001***

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Hour:Cover	1.81	24	6095.0	0.0086**
Type:Cover	2.43	3	6095.1	0.0625
Hour:Type:Cover	3.43	36	6095.0	<.0001***
C: on wind speed				
D-time	0.69	12	6095.0	0.7571
Type	0.01	2	6096.2	0.9876
Cover	0.49	2	6095.7	0.6107
Hour:Type	73.01	24	6095.0	<.0001***
Hour:Cover	71.67	24	6095.0	<.0001***
Type:Cover	0.38	3	6095.7	0.7628
Hour:Type:Cover	44.20	36	6095.0	<.0001***

Discussion

Biodiversity and characterization of street trees

Compared to natural ecosystems, the floristic composition of street trees in the three examined cities exhibits reduced diversity. The species richness ranges from 15 to 20 species, and the Shannon diversity index spans 2.33 to 2.92 bits, indicating low diversity along the urban thoroughfares. The Pielou equitability index reveals a strong dominance of a few tree species in Ouidah (0.64) compared to the other two cities (0.17 - 0.21). Osseni *et al.* (2014) reported analogous findings for Porto-Novo's street plantations, suggesting a relatively weak floristic composition. In contrast, Cotonou exhibits monospecific formations of *Khaya senegalensis*, *Terminalia mantaly*, and *Terminalia catappa* along major thoroughfares such as Cica Toyota, Etoile rouge, and Place du Bicentenaire, respectively (Houinsou, 2009), while boulevard de Missebo-Zongo comprises four species dominated by *K. senegalensis* (Teka *et al.*, 2017a). The Sacré Coeur thoroughfare displays greater species diversity, akin to Ouidah, yet with a higher floristic composition (33 species). A 2010 survey identified 31 species in Cotonou, predominantly *T. catappa* (15.87%), *K. senegalensis* (15.64%), and *T. mantaly* (13.17%), similar to Ouidah but with varying proportions (Gnélé, 2010). These findings suggest that southern Benin's reforestation efforts primarily utilize the same tree species. Most of the stand is characterized by *Terminalia mantaly* and *Khaya senegalensis*, considered highly valuable species for urban development in West Africa (Sokpon and Ouinsavi, 2004). This observation suggests a limited effort to diversify species selection in Beninese development policies. The preference for these species may be attributed to their well-understood silviculture, characterized by rapid growth, resilience to human activities, and minimal maintenance requirements. This finding is supported by the actual fall index, which is significantly lower than 50% (IRr = 2.29%). Additionally, these plants' ecological and therapeutic functions may

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contribute to their prevalence. For instance, *Khaya senegalensis* is utilized by local communities to treat 41 diseases, particularly employing its bark for gynecological afflictions (Ouinsavi, 2000; Sokpon and Ouinsavi, 2004), while *Terminalia mantaly* serves as an anti-diarrheal agent. The diametric structure analysis of the trees within these thoroughfares reveals a predominance of young individuals with diameters between 40cm and 50cm, resulting in a mean quadratic diameter (Dg) for the stand of 52.34cm. This structure resembles a natural forest (Guimbo *et al.*, 2010; Abdourhamane *et al.*, 2013), suggesting that thoroughfare-aligned trees receive limited care and are subject to widespread disregard by the population. Despite recognizing the importance of these trees in daily life, inhabitants often repurpose these spaces as marketplaces for various products. The remaining species, not subjected to the same pressures as *T. mantaly* and *K. senegalensis* (such as debarking for therapeutic treatments), remain unmonitored. The potential fall risk index (IRp = 13.30 - 28.90 %) indicates that these plantations have experienced insufficient monitoring, and silvicultural operations were likely influenced by anthropogenic pressures during their development stage.

Influence of street trees on local climate and warming mitigation

Observations indicate diurnal variations in air temperature, relative humidity, and wind speed within tree alignments and roadways. Generally, temperatures are lower in plantation areas compared to roadways. Conversely, relative humidity is higher in tree alignments than on roadways. These average trends persist regardless of height and time of day. These findings corroborate the natural diurnal fluctuations in meteorological parameters, resulting in inverse relationships between temperature and relative humidity. As temperature decreases, relative humidity increases, and vice versa. The observed trends can be attributed to the crown shape (vegetation cover), which inhibits solar radiation penetration and reduces warming in plantation areas (Stewart & Oke, 2009; Lafontaine-Messier *et al.*, 2014; Teka *et al.*, 2017a). The cooling effect of crown shape is likely due to leaf evapotranspiration, which increases relative humidity and generates a microclimate around tree foliage. Tree foliage shields solar radiation and cools the air through evaporation and shading on the ground and walls. Under certain conditions, trees have been shown to reduce radiation and attenuate wind speed (Feyisa *et al.*, 2014; Gromke *et al.*, 2015; Teka *et al.*, 2017a). Factors such as tree spacing, linear density, and foliage density (dependent on species) influence sunlight penetration, temperature, and relative humidity. Tree linear density may also decrease wind speed (windbreak effect) and enhance relative humidity. Potes *et al.* (2012) suggest that orientation, planting distance from buildings, and vegetation cover also impact thermal levels.

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In a recent study, Vailshery *et al.* (2013) observed that the absence of trees increases roadway surface temperatures, contributing to a significant rise in discomfort levels for pedestrians and cyclists. This phenomenon may promote the use of vehicle air conditioning and discourage energy-efficient transportation modes, such as walking and cycling. Albedo, a measure of a material's reflectivity, is crucial in heat accumulation. Urban surfaces, particularly roadways, typically comprise low-albedo materials with darker colors, resulting in heat storage and increased temperatures (Teka *et al.*, 2017a). In contrast, alignment plantations exhibit lower albedo rates and do not contribute to air warming. This is due to the immediate release of absorbed heat through plant evapotranspiration, providing localized cooling compared to heat-retaining roadways (Fischer, 2005). Factors such as site location, measurement heights, and time of day significantly influence temperature variations, relative humidity, and wind speed in different thoroughfares. These variations may be attributed to differences in vegetation density and tree height. Notably, the Kpassè and Gbèna thoroughfares exhibit lower temperatures due to their high shading indexes (60.8 and 50.8), indicating reduced light and solar radiation permeability. The dominance of *K. senegalensis* and *T. mentaly* species in these areas may further contribute to the overall coolness.

Additionally, architectural and housing orientation factors should be considered for optimal results. A collaborative effort among researchers and authorities is necessary to ensure the sustainability of urban forestry programs. The critical role of urban green spaces in carbon sequestration and climate change mitigation (Teka *et al.*, 2017b) highlights the need for immediate action, such as community sensitization, to preserve and enhance alignment plantations.

The results also suggest that street trees significantly reduce heat stress in urban areas, particularly in warmer regions such as Porto-Novo. The study found that street trees had a notable effect on reducing air temperature and increasing relative humidity during the daytime, specifically between 10 am and 5 pm. The average reduction in air temperature was -0.5 to -1.6°C, while relative humidity increased by +2 to +3%. It is important to note that the impact of street trees was more pronounced in Porto-Novo compared to the neighboring cities of Cotonou and Ouidah. The air temperature in Porto-Novo was consistently higher than that of the other two cities, with a difference of 0.7 to 1.8°C between 11:00 a.m. to 3:00 p.m. This suggests that street trees have a more significant potential to mitigate heat stress in areas with higher temperatures. Otherwise, Teichmann *et al.* (2022) conducted in Vienna an investigation for evaluating the influence of small-scale vegetation on the local microclimate within two school buildings. During a hot summer day, specifically at 3 p.m., the study revealed a maximum temperature reduction of

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0.3 °C within a proximity of 0.1 m from the facade greening, as well as within the confines of the vegetated pergola. Furthermore, with respect to the perceived temperature, a discernible decrease of up to 4 °C was observed beneath the green pergola in comparison to the unshaded rooftop terrace. Overall, the results of this study demonstrate the importance of street trees in reducing heat stress in urban areas. As cities continue to experience the effects of climate change, implementing urban forestry programs may be an effective strategy to mitigate the impacts of extreme heat.

Influence of street tree layouts (TL) and canopy patterns (TCP) on heat mitigation

The finding that street trees located on both sides of the roadway resulted in a significant difference in air temperature and relative humidity compared to other street layouts is an essential contribution to our understanding of the cooling effect of street trees in urban environments. The observed decrease in air temperature and increase in relative humidity can be attributed to the shading provided by the street trees, which reduces the amount of solar radiation reaching the ground, and the transpiration of water from the leaves of the trees, which increases the moisture content of the surrounding air. These factors create a cooler and more humid microclimate than the surrounding areas. The magnitude of the difference in air temperature and relative humidity observed in this study is noteworthy (-0.6°C to -1.4°C and +2.4% to +5.5%). A decrease in air temperature of 1°C can translate to a 10% reduction in energy consumption for air conditioning (IEA, 2022), which has significant implications for reducing greenhouse gas emissions and mitigating the impact of climate change.

Similarly, an increase in relative humidity can help alleviate the adverse health effects of dry air, such as respiratory irritation, dry skin, and dehydration. The findings of this study have practical implications for urban planners and policymakers seeking to mitigate the impact of climate change on urban areas. Planting street trees on both sides of the roadway can effectively reduce urban heat island effects and improve the microclimate in urban environments. Furthermore, identifying closed canopies as the best tree canopy pattern for cooling suggests that planting dense, closely spaced street trees may be the most effective approach. However, careful consideration must be given to species selection and maintenance to ensure the long-term viability and sustainability of the street tree ecosystems.

Conclusion

It has been observed that the street trees in Cotonou, Porto-Novo, and Ouidah exhibit low plant diversity, with only three dominant species, namely *Terminalia mantaly*, *Terminalia catappa*, and *Khaya senegalensis*.

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Unfortunately, these species are being over-exploited by the neighboring communities, destroying them through burning, slaughtering, debarking, or pruning. Additionally, the study has revealed that street trees, height, and daytime significantly affect air temperature, relative humidity, and wind speed. It was found that street trees located on both sides of the roadway resulted in a considerable difference in air temperature ranging from -0.6°C to -1.4°C and relative humidity ranging from +2.5% to +5.2% from 11 am to 5 pm, as compared to other street layouts. Furthermore, the study has identified that closed canopies of street trees result in the best tree canopy patterns, leading to an air temperature difference ranging from -0.4°C to -1°C and relative humidity ranging from +2.4% to +5.5% from 11 am to 5 pm. The research concludes that street trees play a crucial role in cooling and reducing the heat island effects in coastal cities of Benin. It is, therefore, essential to preserve and maintain these ecosystems. The findings can inform urban planners and policymakers in designing and implementing effective street tree planting strategies to optimize their cooling effect and mitigate the impact of climate change on urban areas.

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