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Urban forests mitigate extreme heat exposure in a vulnerable tropical city

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ABSTRACT

Urban forests (UF) have been documented as a strategy for mitigating urban heat in population centers of the Global North that are affected by extreme temperatures. However, few have studied this ecosystem service in such climate-vulnerable, humid, tropical cities with less than 50,000 inhabitants, limited resources, and weak adaptive capacity to heatwaves. Accordingly, we studied the tropical city of Puerto Carreño, Colombia, to explore the links between tree heat regulation, human thermal comfort, and the subsequent effects on human well-being during the extremely hot season of 2021. Using a mixed methods approach, we measured hourly temperature and humidity for six months with sensors in paired exposed and tree-shaded sites in eight locations across the city, while also surveying residents' thermal perception during the heat event. We found thermal regulation provided by UF was non-linear and increased exponentially with ambient temperature, for example reaching 8.7 °C at 44 °C, but only 2 °C at 34.9 °C. UF shading mitigated extremely high discomfort indices by a factor of 10 during the hottest hours and substantially reduced the potential heat lethality associated with such events. Survey respondents also noted the positive co-benefits of trees for human health, provision of climate-regulating ecosystem services, fruit production, and tree shade, while the discomfort index is likely underestimating reported felt comfort in such extremely hot tropical places. Measuring the link between urban forest structure, ecosystem services, and human well-being provides evidence for the use of trees as a sustainable Nature-Based climate adaptation strategy for vulnerable, resource-poor, tropical cities in the Global South.

1. Introduction

Urban forests (UFs), regardless of climatic and geographical settings, can offer multiple ecosystem services and numerous co-benefits to people including climate regulation (Reynolds et al., 2017; Pataki et al., 2011), removal of air pollutants (Vieira et al., 2018), storm protection (Farrugia et al., 2013), numerous other socio-cultural benefits such as improved wellbeing and social cohesion (Kabisch et al., 2021) and also human health benefits (Villadiego and Velay-Dabat, 2014; Tavárez and Elbakidze, 2021). However,

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most of the literature on UFs comes primarily from temperate United States, Canada, Europe, and now China, thus little is known about how the provision of ecosystem services by UFs varies across different types of biomes and cities (i.e., large versus small cities, tropical versus temperate, or in low-income versus high-income countries; Escobedo et al., 2019). Hence, there is limited information that characterizes UF ecosystem services from tropical regions of the world, and that accounts for differences in their socio-ecological and environmental contexts.

Indeed, global warming scenarios have predicted that changes in climate will particularly affect tropical, low-elevation low-income countries and cities (IPCC, 2021). Therefore, assessing climate-regulating ecosystem services in less populated and tropical cities of the Global South is critical due to the climate vulnerability of the tropics (Mora et al., 2013). However, addressing these climate mitigation and adaptation challenges requires quantifying both the structural and functional traits and indicators of urban trees such as photosynthesis, shade, and evapotranspiration as well as carbon sequestration and temperature regulation (Dobbs et al., 2011; Pataki et al., 2011).

This influence of vegetation on urban heat (Lai et al., 2020) is recognized as a regulating ecosystem service and as such is a function of not only UF structure, but also latitude and season (Quesada et al., 2017). While a change from forest cover to non-forest cover (bare land, croplands, grasslands) in temperate zones results in a decrease in temperature due to the increase in surface albedo (Lee et al., 2011), in the tropics these changes lead to biophysical warming (Quesada et al., 2017). For example, deforestation-related warming in the tropics is mainly driven by the decrease in evapotranspiration because of the reduction in vegetation and foliar density (Perugini et al., 2017). Tropical trees can regulate local heat through multiple mechanisms (biophysical effects): they increase evapotranspiration, reducing ambient air temperature; their shading effect limits solar radiation penetration to surfaces; and their higher albedo compared to impervious surfaces like asphalt or roads increases solar heat reflection. Spatially, these effects are more pronounced in areas with dense tree cover and during high radiation periods, such as midday in urban environments (Seneviratne et al., 2010; Rahman et al., 2020). Studies have found that differences between areas with and without trees, in cities, can be up to 8 °C during the midday and 2 °C during low radiation hours (Coronel et al., 2015; Di Leo et al., 2016; Mallen et al., 2020). At global level, tropical trees also reduce atmospheric carbon dioxide by absorbing it through photosynthetic processes (biochemical effects), which in turn reduces global temperatures.

Plant traits (e.g., leaf area index, leaf density), urban forest structure (e.g., height, leaf dimension, canopy height), albedo, water interception, and eco-physiological processes (vapor pressure deficit, stomatal conductance, maximum rubisco capacity; Meili et al., 2021b; Xiao et al., 2024) all determine the potential temperature reduction of trees in cities. Weather also affects plant stomatal activity and transpiration leading to cooling effects (Gillner et al., 2015). Other factors like wind and tree location as well as size, planting density, management (i.e., soil irrigation), and species are important determinants of local cooling effects (Pataki et al., 2011). By quantifying these cooling effects, we can better guide urban planners and landscape architects in designing cities that mitigate heat islands and improve thermal comfort for inhabitants.

However, actual climate regulation benefits of UFs can also be measured by accounting for human perceived temperatures, and the mitigating effect of wind speeds, relative humidity, and shade (da Hirashima et al., 2016; Rodríguez et al., 2016). Improved human temperature perception, or thermal comfort (i.e., human wellbeing), is affected by human perception and physiology, therefore people who have lived in places with high temperatures and humidity, perceive less negative effects on their activities by heat due to their adaptive processes (Villadiego and Velay-Dabat, 2014).

Most of the above research (Lee et al., 2011; Pataki et al., 2011; Farrugia et al., 2013; Gillner et al., 2015; Quesada et al., 2017; Lai et al., 2020; Mallen et al., 2020; Rahman et al., 2020; Xiao et al., 2024) has been conducted in higher-income, temperate countries; however, there is less information on lethal heat conditions, that are now increasingly more common, in low- and middle-income tropical countries (Gamero-Salinas et al., 2020; Geirinhas et al., 2020; Mora et al., 2017). Such information is direly needed since, e.g. a recent multi-country heat vulnerability study by Guo et al. (2018) found that countries such as Colombia are highly vulnerable to heat waves under several climate change scenarios. They found that heat wave-related excess mortality increased 20-fold for Colombia during 2031–2080 as compared to 1971–2020 under a climate change no-adaptation scenario, potentially making Colombia the most severely affected tropical country among the 20 countries and regions studied. This, combined with the country's poverty, might exacerbate the impact of climate change and severe heat on vulnerable urban communities (Campbell-Lendrum and Corvalán, 2007; Mazzone, 2020).

To better inform climate change mitigation goals in tropical cities of the Global South and the climate regulating effect of trees on residents, this study aims to determine the potential of urban trees to provide regulating ecosystem services in a less populated, vulnerable tropical city in Colombia. Specifically, it studied: 1) the role of urban trees in temperature regulation in a tropical context and 2) subsequent effects on human thermal comfort and wellbeing. We first outline the methodological approach for studying such tropical ecosystems and function in resource scarce, less accessible communities. Findings are then used to discuss the role of urban trees as a Nature-Based Solution to mitigate local climate change impacts in lowland tropical cities of the Global South.

2. Data and methods

2.1. Study area

Puerto Carreño is the capital city of the Department of Vichada in the eastern plateau of the Colombian Orinoquia ecoregion and is located at 6°11′16" N and 67°28′ 57" W, at an elevation of 51 m above sea level. The municipality is 12,409 km^2, with an urban area of 6 km^2 (Fig. 1). Mean annual rainfall is 2233 mm and the humid season is May to August, while the drier season is December to March (Supplementary Material Fig. S1). Two months, on average, are characterized by less than 60 mm of rainfall per year. Puerto Carreño has semi-humid hot weather and a daily maximum average temperature of 36.3 °C; the hottest period is between December and March and maximum temperatures are in February, while the lowest temperatures occur from April to November (IDEAM, 2018).

Puerto Carreño's urban forests are distributed throughout the city in both public (e.g., parks, streets) and private spaces (e.g., yards, gardens) as well as in peri-urban areas in dense forests along the Meta and Bita Rivers. In 2018, the urban zone had 27 neighborhoods and 14,974 inhabitants, of which almost 10 % belong to Indigenous communities (or are recognized as Indigenous); the proportions for females and males are 52.7 % and 47.3 % respectively, with an overall occupancy rate (activities that generated some income) of 32 %. By 2015, the percentage that met "Unsatisfied Basic Needs" was 41.98 %, due to incomplete coverage of basic services such as running water, septic systems, refuse management, electricity, housing, school truancy, and economic dependency. Currently, the multidimensional poverty index is approximately 50–70 % (Esteban Cantillo and Quesada, 2022; Rozo et al., 2021).

Puerto Carreño has one of the highest vulnerability indices to extreme flooding due to its location at the confluence of the Meta, Orinoco and Bita rivers. Fires in the area are also a concern for its inhabitants, as they are common in rural and peri-urban areas during the dry season (December to March). These processes are linked to the climate during the annual hydrological cycle and to climate variability phenomena such as La Niña and El Niño (IDEAM, PNUD, MADS, DN, and CANCILLERÍA, 2015). Thus, in addition to social vulnerability, Puerto Carreño is highly exposed to extreme weather events with limited response capacity. This combination of environmental and social risks makes Puerto Carreño a case study where the generation of knowledge on urban forests could play a role in mitigating some of the impacts faced not only by this city, but also by others with similar conditions.

2.2. Methods

2.2.1. Thermal climate and meteorological context

We characterized Puerto Carreño's meteorology using available data such as temperature, precipitation, humidity, sun hours per day, and cloudiness for recent decades from Puerto Carreño's Institute of Hydrology, Meteorology and Environmental Studies (IDEAM) airport weather station located inside the study area (IDEAM, 2021). Data were then used to obtain the diurnal cycles to better identify maximum and minimum values, as well as to develop annual histograms using a range of 10 days to explore the relationships between variables. Daily climatic variation information was used to determine the appropriate season and time period for data collection from December 2020 to May 2021 due to the frequent occurrence of extreme heat events.

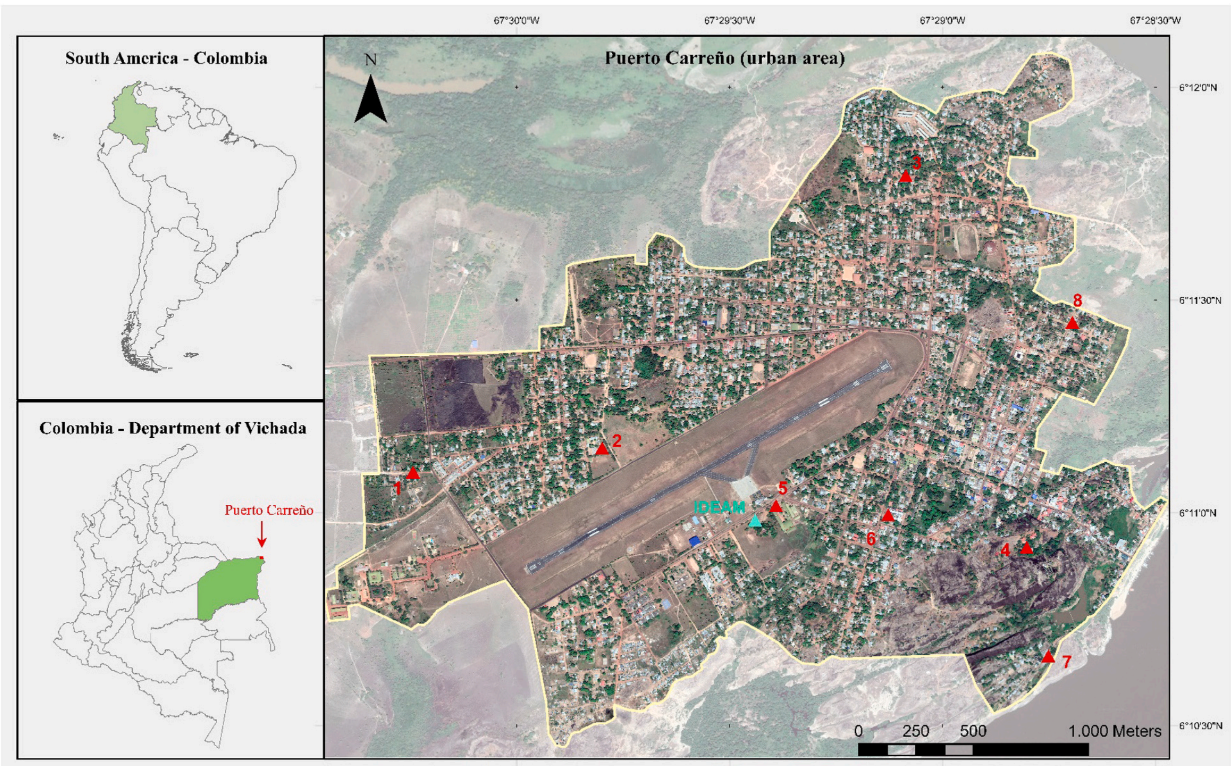

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Fig. 1. Location of the study site and the sensors. Upper left is Colombia, lower left is the Department of Vichada and Puerto Carreño (red rectangle). Right image is the study area. Red triangles indicate i-button sensors (See Table 1 for the site numbers) and cyan triangle shows the IDEAM meteorological station. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

2.2.2. In situ sampling of air temperature and humidity

From December 2020 to May 2021, sixteen iButton® DS1923 humidity and temperature sensors were installed across eight representative sites in the study area to assess local-scale climate conditions (Mallen et al., 2020; Kabisch et al., 2021; Meili et al., 2021a). These sites were established in seven urban locations and one peri-urban site based on homeowner permission, accessibility, crew safety, and reduced chances of vandalism (Fig. 1 and Table 1). All sensors were arranged in pairs within a maximum distance of 100 m from each other, with one set of sensors exposed to direct sunlight and the other sensors were positioned under tree canopies. Each sensor, powered by an internal battery with a one-year battery life, was programmed to record air temperature at one-hour intervals. The accuracy of temperature and relative humidity measurements was set to ±0.0625 °C and ± 0.04 %, respectively (Analog Devices, 2019). Each sensor was mounted on a 2-in. diameter PVC pole placed vertically 1.5 m above the ground, and covered with a plastic roof lined with aluminium insulating tape of 25 × 25 cm. The sensor was placed between two plastic covers (15 × 15 cm) lined with aluminium insulating tape to protect from rain and direct sunlight, with a space of 5 cm between the sensor and the covers to allow adequate air exchange (Fig. 2). This setting is similar to other studies (Hellström and Mark, 2006; Scott et al., 2017). Sensor data were collected hourly for five months and downloaded five times during this period. The eight sampling sites represented different land cover types (Table 1). We demonstrate that the density of sensors per km^2 can be considered high density and higher than most of similar studies (see "Justification of sensor's density" section in Supplementary Material; Supplementary Tables S2 and S3).

2.2.3. Data pre-treatment and analyses

During the December 2020 to March 2021 sampling period, two sensors (4 and 8) located under tree crowns were vandalized, thus data from December and March were not collected nor analysed. Also, in March 2021, the sensor located under sun exposure was used as a bird nest, so these data were filtered to detect outlier temperatures. Accordingly, these atypical measurements were adjusted resulting in the 'complete dataset' that was used in subsequent analyses (Supplementary Table S1 and Supplementary Fig. S2).

Using the complete dataset described above, significant differences in monthly temperature and humidity in each sensor pair (i.e., shaded and sun exposed conditions) were tested using the Welch *t*-test ($\alpha = 0.05$). Data normality was assumed because of the high number of monthly data (>100 records) and correction for unequal variances was done when necessary, using Fisher's test ($p > 0.05$).

Diurnal temperature and relative humidity cycles were obtained using average hours for all sensors for each month. The data set was also used to characterize daily temperature and relative humidity changes, as well as the difference between each shaded and exposed sensor pair. We calculated the effect of temperature and relative humidity of exposed sensors on the temperature difference using a polynomial order 2 nonlinear model using the ***nlstools*** library in R language v.4.0.1 (Eq. (1)):

$$T_{diff} = a \bullet \beta_{exp}^2 + b \bullet \beta_{exp} + c \quad (1)$$

where, Tdiff = temperature difference between sun exposure and shade for the same hour for each sensor, β_{exp} = Temperature or relative humidity of the exposed sensors (sun exposure), a and b = slopes, and c = intercept. Standard error, determination coefficients (R^2), Akaike Information Criterion and *p*-values were used to determine the model fitness.

To determine the risk of increased lethality due to temperature and humidity conditions in Puerto Carreño between December 2020 and May 2021, we utilized Mora et al.'s (2017) 95 % Support Vector Machine deadly threshold with the daily average of both shaded and exposed sensors. This threshold was established using a global analysis of documented lethal heat events that differentiated lethal from nonlethal heat events across different cities. It also plotted specific climatic thresholds for temperature and humidity at which an event could lead to significant increases in human mortality risk.

We then used Thom's discomfort index DI (Thom, 1959) to relate temperature and humidity data to a human discomfort category. Specifically, we calculated DI for each sensor, using both hourly temperature and relative humidity in both sun-exposed sensors and tree-shaded sensors. The DI was used since most rational and direct indices need variables that are difficult and expensive to collect in these types of contexts (vapor pressure, wet-bulb temperature, globe temperature, wind speed, mean radiant temperature). We

Table 1
Location of temperature and humidity sensors in Puerto Carreño, Colombia.

Site	Coordinates	Site description
1	67°30′15.1"W 6°11′6.2"N	House in a peri-urban neighborhood with unpaved roads, pastures and houses with large wooded yards.
2	67°29′49.5"W 6°11′10.3"N	Urban school with an area of 2 ha with small 1-floor buildings (15 % of the area) and an area of 2 ha on a matrix of bare earth pastures and trees.
3	67°29′5.2"W 6°11′47.7"N	House in an urban neighborhood with paved streets.
4	67°28′52.2"W 6°10′53.6"N	House in an urban neighborhood with paved streets and surrounded by bare rock.
5	67°29′22.9"W 6°10′58.9"N	Urban school of 2 ha with small 1-floor buildings (50 % of the area) and close to a paved main road.
6	67°29′7.4"W 6°10′59.7"N	College in an urban neighborhood with medium-sized 4-floor buildings surrounded by paved roads
7	67°28′45.3"W 6°10′39.5"N	House in an urban neighborhood with paved roads, surrounded by bare rock and few trees.
8	67°28′41.7"W 6°11′26.7"N	House in an urban neighborhood with paved roads and bare ground, close to the bare rock.

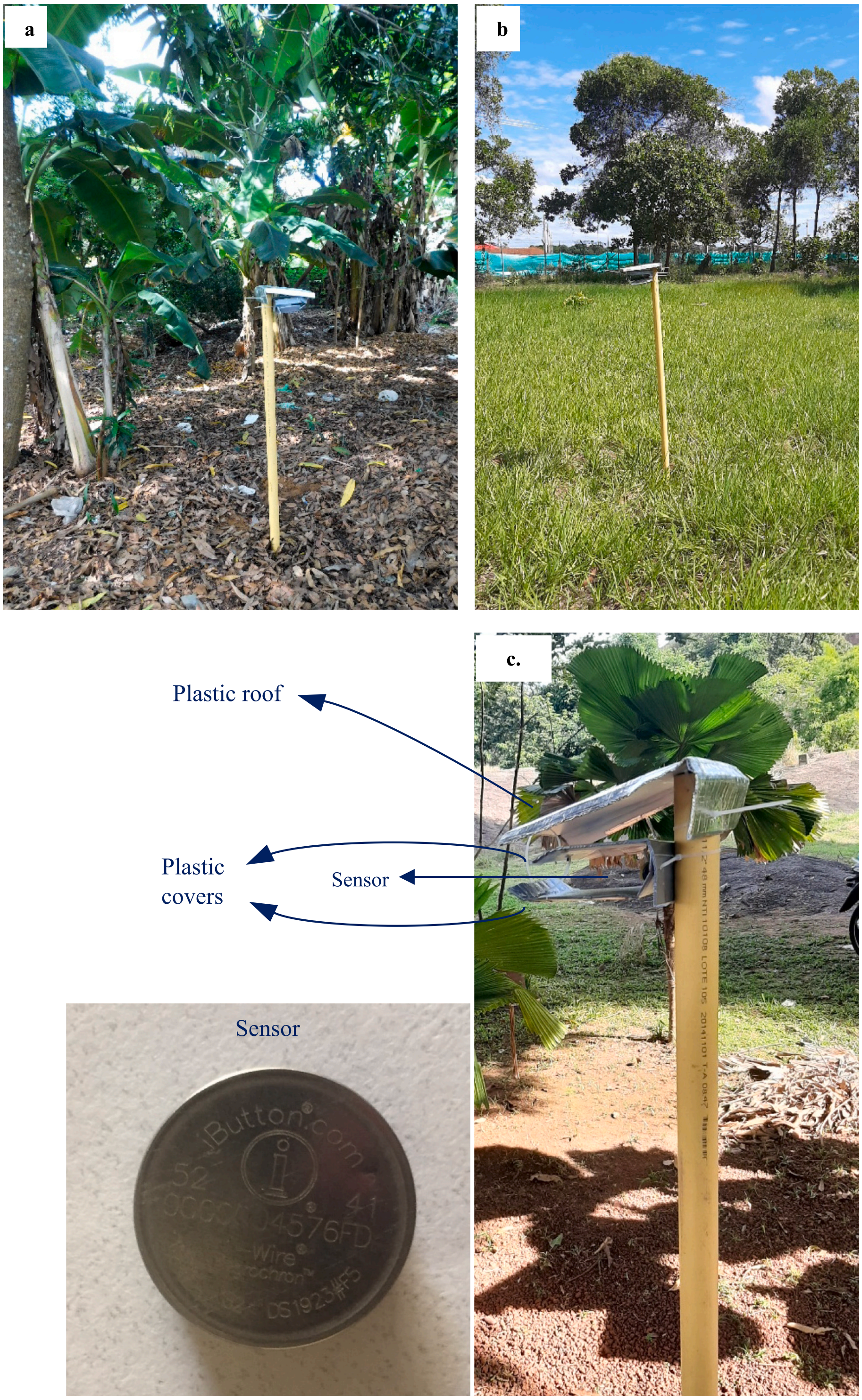

Fig. 2. iButton DS1923 assembly. a. Shaded sensor under tree cover. b. Exposed sensor on grass cover. c. Shield structure of the sensors. d. Sensor.

calculated DI using Eqs. (2) and (3).

$$DI_{exp} = T_{exp} - 0,55 \bullet (1 - 0.01 \bullet RH_{exp}) \bullet (T_{exp} - 14,5) \quad (2)$$

$$DI_{shd} = T_{shd} - 0,55 \bullet (1 - 0.01 \bullet RH_{shd}) \bullet (T_{shd} - 14,5) \quad (3)$$

where:DI_{exp}: discomfort index for exposed sensors, DI_{shd}: discomfort index for sensors under tree's shadow, $T_{exp/shd}$: ambient temperature in °C (*exp*: exposed, *shd*: under tree shade), and $RH_{exp/shd}$: was the relative humidity expressed as a percentage.

Thom's (1959) DI index originally uses four different classes, however, given Puerto Carreño's more narrow tropical climate ranges, we applied the adapted classification proposed by de Souza e Silva et al. (2022) for a similar tropical city in Brazil where: 1. No discomfort: DI ≤ 22; 2. Somewhat comfortable: 22 < DI ≤ 25 (Less than 50 % of the population feels discomfort); 3. Uncomfortable: 25 ≤ DI ≤ 28; and 4. Discomfort is very strong: 28 < DI ≤ 31, and 5. State of medical emergency: DI > 31. We then used these 5 classes/ranges to characterize DI between sensors in exposed versus shaded sites to characterize the effect of the urban trees on human thermal comfort potentially perceived by people in the study area.

3. Results

3.1. Thermal climate and meteorology

We found a monomodal precipitation pattern marked by a single wet season from April to October and a dry season between November and March (see Supplementary Fig. S1b). During the dry season, temperature and solar brightness values were the highest and most extreme values (Supplementary Fig. S1a-d). Based on data from previous decades (IDEAM, 2021), we found that days with extreme temperatures greater than 37–38 °C were more frequent in the recent 2010–2019 decade than the previously in 2000–2009 (Supplementary Fig. S1a). Likewise, we found that wet days (days with precipitation >1 mm) increased by 9 days between 2000 and 2018, while the precipitation amount during the consecutive rainiest days of the year increased by 40–60 mm between 2000 and 2018 (see Supplementary Fig. S1b). 2020 was a notably hot year as indicated during October 2020 when 75 % of the days had temperatures above 30 °C and 16 % of days with temperatures above 33 °C, which is very close to the 90th percentile.

3.2. In situ sampling of air temperature and humidity

3.2.1. Monthly patterns and temperature regulation

During the hottest period, December 2020 to March 2021, average air temperatures were 29.5 °C and 28.9 °C in exposed and shaded sensor sites, respectively. During the April to May 2021 rainy period, average air temperatures were 28.4 °C and 27,7 °C in exposed and shaded sensors, respectively. Overall, the months with a higher frequency of hot days (i.e., "hot" is used for temperature higher than the 90th percentile: 34.5 °C) were February (16 %) followed by March (14 %), with extreme temperatures up to 44 °C. The hottest period during the day was between 12:00–3:00 p.m. (12:00 and 15:00). when almost 71 % of the temperatures were hot, notably higher than the time periods before and after 12:00 p.m. (15 %) and 3:00 p.m. (14 %) respectively. There were no hot

Table 2

Monthly average temperature and relative humidity for each sensor in Puerto Carreño, Colombia. ND: No Data due to vandalization of the sensor. Underlined values belong to the "nested" sensor. The difference values refer to the corresponding (Sun sensor MINUS Shade sensor) calculation. * indicate significant difference *t*-test, $p < 0.05$. DEC20: December 2020, JAN21: January 2021, FEB21: February 2021, MAR21: March 2021, APR21: April 2021 and MAY21: May 2021.

Site	Sun/shade	Temperature °C						Relative humidity %					
		Dec 20	Jan 21	Feb 21	Mar 21	Apr 21	May 21	Dec 20	Jan 21	Feb 21	Mar 21	Apr 21	May 21
	Sun	28.6	28.2	29.5	29.5	28.6	27.7	73.9	71.1	62.4	65.6	78.9	86.7
1	*Shade*	27.7	27.6	29.1	28.9	27.8	27.0	75.2	72.4	62.9	66.3	80.6	88.7
	Difference	***0.91****	***0.63****	***0.47****	***0.59****	***0.74****	***0.71****	***−1.33***	***−1.29***	***−0.54***	***−0.67***	***−1.74***	***−2.04****
	Sun	28.4	28.1	29.6	29.4	28.3	27.5	75.9	73.8	63.8	67.0	80.4	88.2
2	*Shade*	28.3	28.0	29.4	29.2	28.1	27.3	72.3	70.0	61.2	64.7	77.9	85.9
	Difference	***0.12***	***0.18***	***0.22***	***0.19***	***0.18***	***0.25***	***3.64****	***3.78****	***2.65****	***2.30****	***2.44****	***2.27****
	Sun	28.8	28.5	30.1	29.8	28.6	27.8	72.5	70.2	60.9	64.3	77.8	85.2
3	*Shade*	28.0	27.8	29.3	29.0	27.7	26.8	73.6	70.6	61.7	65.5	79.9	87.7
	Difference	***0.72****	***0.67****	***0.80****	***0.87****	***0.95****	***0.99****	***−1.05***	***−0.41***	***−0.79***	***−1.22***	***−2.06****	***−2.52****
	Sun	29.0	28.6	30.0	29.8	28.7	27.8	71.0	68.7	60.3	63.9	76.3	84.3
4	*Shade*	28.5	28.3	29.7	29.4	ND	ND	71.5	68.6	60.0	61.8	ND	ND
	Difference	***0.51****	***0.30***	***0.34***	***0.30***	ND	ND	***−0.29***	***0.16***	***0.30***	***0.11***	ND	ND
	Sun	29.1	28.9	30.4	30.1	28.9	27.9	68.5	66.3	58.0	62.1	75.5	83.5
5	*Shade*	28.7	28.3	29.8	29.5	28.4	27.4	69.4	67.4	59.1	62.8	75.9	83.9
	Difference	***0.43****	***0.58****	***0.62****	***0.59****	***0.52****	***0.48****	***−0.88***	***−1.19***	***−1.10***	***−0.72***	***−0.44***	***−0.43***
	Sun	29.3	28.9	30.3	30.0	28.9	28.1	67.5	66.1	58.0	62.2	75.1	82.0
6	*Shade*	29.0	28.5	29.8	29.5	28.4	27.6	69.0	67.0	59.1	63.0	76.4	84.0
	Difference	***0.35***	***0.46****	***0.54****	***0.43****	***0.50****	***0.48****	***−1.48***	***−0.92***	***−1.04***	***−0.84***	***−1.29***	***−2.05****
	Sun	29.9	29.4	31.1	31.2	29.6	28.6	67.7	66.3	58.1	60.4	75.5	84.3
7	*Shade*	29.0	28.5	30.0	29.7	28.6	27.5	67.5	66.5	58.5	62.2	75.1	84.0
	Difference	***0.90****	***0.85****	***1.19****	***1.46****	***0.99****	***1.11****	***−0.69***	***−0.24***	***−0.47***	***−1.87****	***0.35***	***0.29***
	Sun	29.6	29.2	30.7	30.5	29.3	28.2	68.9	66.7	58.3	61.8	75.4	83.8
8	*Shade*	28.2	ND	ND	ND	ND	ND	72.6	ND	ND	ND	ND	ND
	Difference	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND

temperatures before 7:00 a.m. and after 5:00 p.m. (7:00 and 17:00). The lowest temperature, 21.5 °C, was measured in both shaded and exposed sensors between 4:00 a.m. and 6:00 a.m., in site 2 (periurban neighborhood).

Relative humidity averaged 65 % to 81 % over the study period for both shaded and exposed sensors. From February–March 2021, the relative humidity was at its lowest (less than 67 %) compared with the rest of the analysis period but was more noticeable in exposed sensors (Table 2). Once the rains started in April 2021 the relative humidity increased rapidly to greater than 75 %. Overall, temperature and relative humidity showed a contrasting pattern, where the hottest months were those with lower relative humidity. With few exceptions, relative humidity was higher in shaded relative to exposed sites (Table 2).

3.2.2. Hourly patterns and temperature regulation

During the daytime, there was a difference in both temperature and humidity in exposed sites. In measured sites with fewer trees, the greater the effect of trees in terms of temperature regulation (Fig. 3, sites 7 and 8), likewise where there were fewer trees and green covers, a greater difference in the relative humidity was observed compared to those areas where vegetation cover was greater (Fig. 4, sites 7 and 8). The highest difference for both temperature and relative humidity was found during the 12:00–3:00 p.m. (12:00 and 15:00) critical period of the day (Fig. 5). During this time, the maximum temperature differences between exposed and shaded sensors range from 4 °C in environments with more green covers and trees (site 2, periurban neighborhood), up to 11 °C in sites with more impervious covers and less vegetation around (site 7), showing the influence of trees in highly urbanized spaces, especially during February and March 2021. During this time, humidity decreased by 10 % in both exposed and shaded sensors in sites surrounded by hard covers (Fig. 4, sites: 3 and 7).

During night-time, microclimates were homogeneous across the different sites with a small range of amplitudes (closer to zero) compared to daytime. However, shaded sensors located under trees maintained greater temperatures (up to 40 °C) than did exposed sensors, while humidity decreased in shaded sites (i.e., under trees) but only during the hottest months (February and March, (up to 10 %) but increased during the beginning of the rainy season, due to an excessive humidity in the environment between tree crowns and ground surfaces (Figs. 3 and 4).

Temperature regulation as measured by the temperature difference between exposed and shaded sensors, was related to air temperature and relative humidity. Fig. 6(left) shows that when the ambient temperature was higher, heat mitigation by trees was exponentially greater. When conditions reached a daily temperature of 44.0 °C (maximum daily exposure temperature registered), the average mitigation due to trees was 7.5 °C while at 34.9 °C (mean daily exposure temperature registered), the thermal regulation was 2 °C. Findings related to humidity (Fig. 6- right) displayed two conditions, one where high relative humidity resulted in lower heat mitigation (i.e., heat or suffocation), and another in which higher relative humidity generated temperature decreases during rain events or increased cloudiness (Fig. 6 and Supplementary Fig. S1). There was however a pattern when temperatures were under 28 °C and relative humidity was greater than 60 % when thermal regulation by trees was not as effective as in the extreme conditions described above (Fig. 6).

Using Mora et al. (2017) lethal heat risk threshold, we found that in exposed sensors approximately 82 % of the days between December 2020 and May 2021 were considered lethal heat events or conditions in which there could be significantly more human mortality due to increased heat. However, this percentage dropped to 63 % of lethal days in sensors located under tree shade (Fig. 7).

3.2.3. Discomfort index

The number of daily records with DI >28 (i.e., discomfort is very strong and dangerous) was twice as high for the sun-exposed sensors than for the tree-shaded sensors (26 % vs. 13 %, respectively). Most of these days occurred from March to May 2021 in the sun-exposed sensors, especially in environments with fewer trees (sites 7 and 8). Conversely, for tree-shaded sensors, the highest DI values (greater than 28) were more likely to occur in March and April at the peak of the dry season and the beginning of the rainy season. Comfortable records (DI <25) were more common for both exposed and shaded sensors in December 2020 and January 2021 (Fig. 8).

During the day, the hours of discomfort began at 7:00 a.m. (7:00) for sun-exposed locations and at 9:00 am for sensors in the shade (Fig. 8). However, between 9:00 a.m. and 4:00 p.m. (9:00 and 16:00), the number of records that had a DI value where the weather was considered strong and dangerous to humans (DI >28) was 29 % of the records (2541 out of 8824) for shaded sensors, while it was 74 % of the records (7848 out of 10,573) for exposed sensors. That is, between 9:00 a.m. and 4:00 p.m. (16:00), DI > 28 was 2.5 times more frequent at the exposed sites than at the shaded ones, while between 12:00 pm and 2:00 pm (12:00 and 14:00), it was 4 times more frequent, at the exposed sensors than at the shaded ones.

Table 3
Parameters of the equations (based on Eq. (1)) for tree regulation of air temperature and relative humidity of exposed sensors. a and b slopes, c intercept. Determination coefficient (R^2), Akaike criterion (AIC), significance of predictors indicated by ($p < 0.1$), * ($p < 0.05$), ** ($p < 0.01$), *** ($p < 0.001$).

Predictor: β	Parameter	Estimate	Standard error	Confidence interval 2.5 % / 97.5 %	Determination coefficient (R^2)	AIC
	a	0.019***	0.0003	0.019 / 0.02		
Air temperature	*b*	−0.931***	0.0183	−0.966 / -0.895	0.992	63,221.49
	c	11.057***	0.2743	10.520/ 11.595		
	a	0.001***	1.942e-05	0.00098 / 0.0010		
Relative humidity	*b*	−0.179***	2.685e-03	−0.184 / -0.174	0.997	76,326.6
	c	7.840***	8.826e-02	7.667 / 8.013		

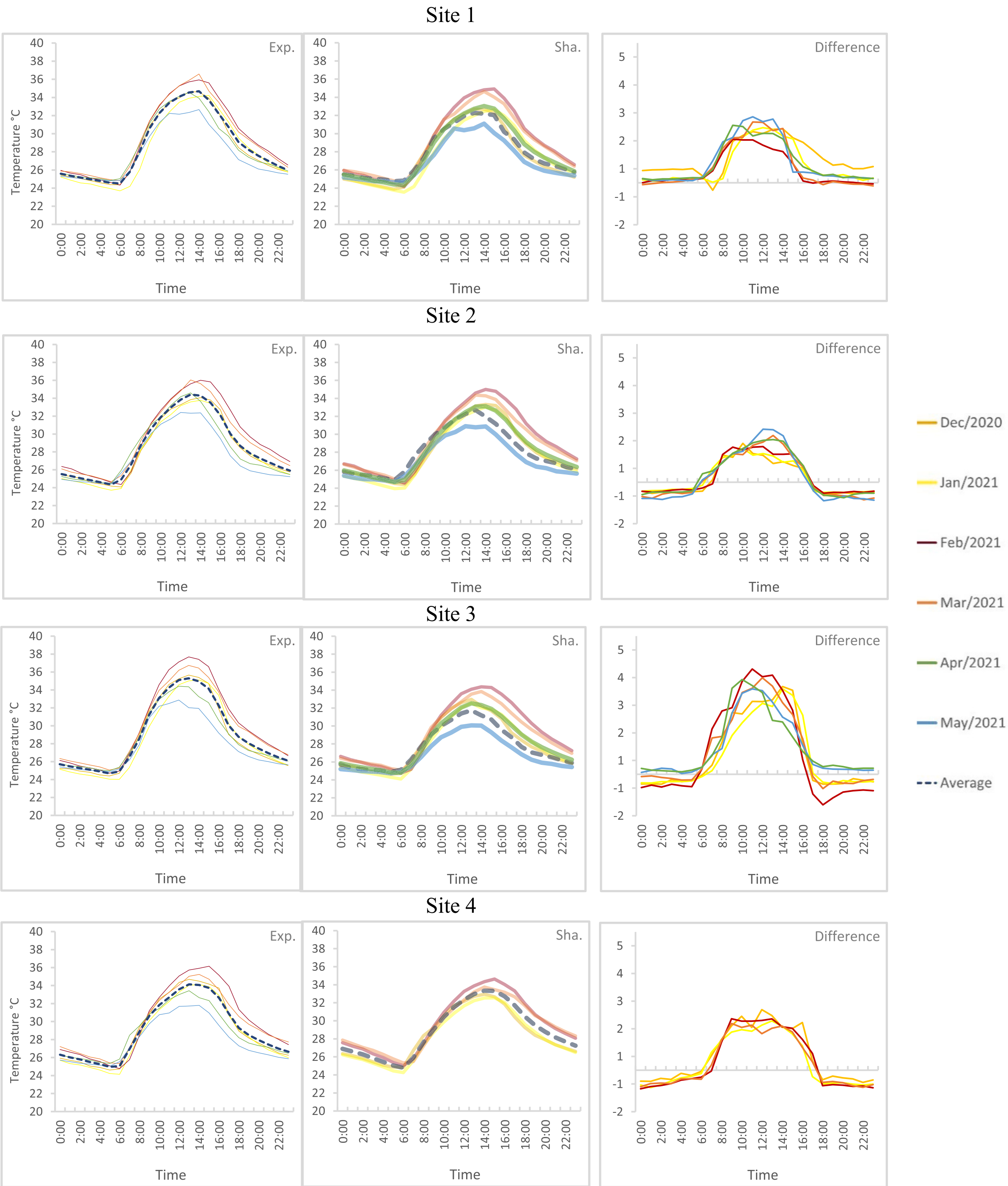

Fig. 3. Hourly temperature cycle for each month (solid lines, from December 2020 to May 2021) by location. Left column: Exposed sensors, middle column: shaded sensors, right column: difference between exposed and shaded sensors. Average values are indicated by dotted lines.

Values above the state of medical emergency (DI >31) were found in the exposed sensors (0.25 % of the hourly records) and were more common between 1:00 p.m. and 6:00 p.m. during the month of April, and the number of records with high DI values decreased even during the critical hours (9:00–16:00) for sensors under tree cover (Fig. 8). However, DI values <22 (comfortable) were similar for both shaded (0.24 %) and exposed (0.30 %) sensors. Sites with trees that provided better thermal comfort were those surrounded by more grass or unpaved roads (Sites 1 and 2). The most comfortable hours were between 12 a.m. and 7 a.m., either at shaded or exposed

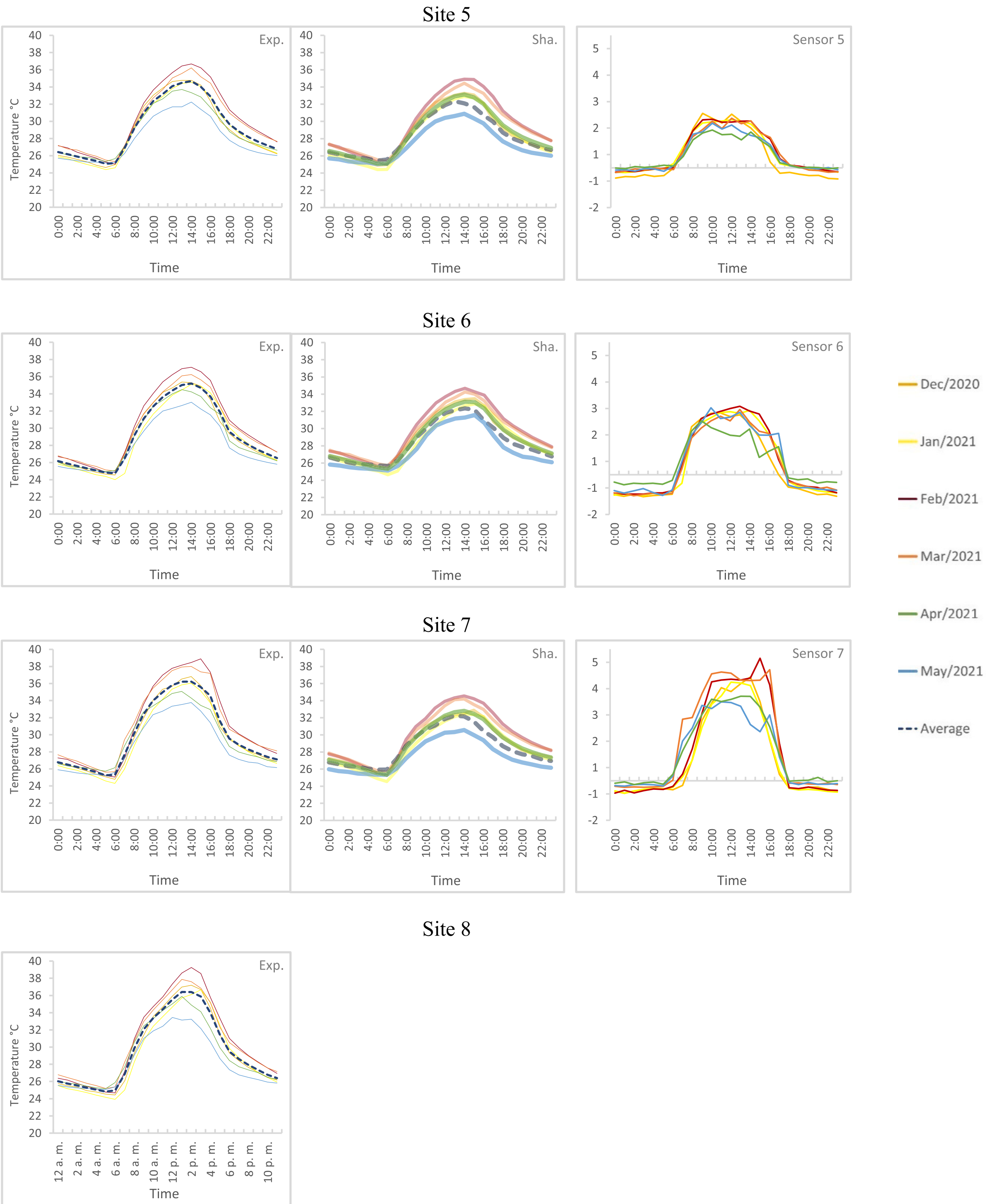

Fig. 3. (*continued*).

sensors.

4. Discussion

Very few studies in humid tropical lowland cities particularly in Latin America, have analysed the effect of urban trees on

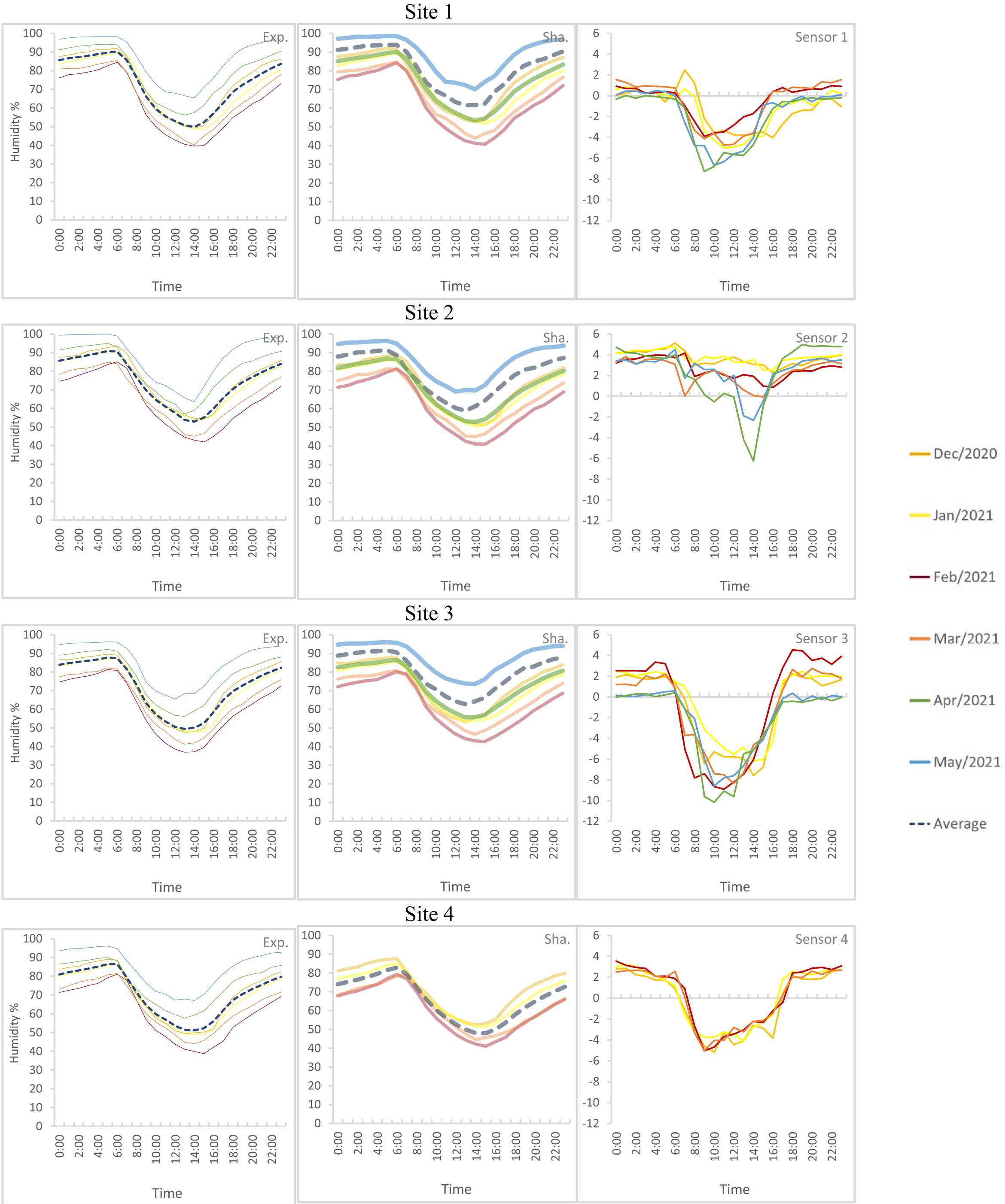

Fig. 4. Hourly humidity cycle for each month (continuous lines, December 2020 to May 2021) by location. Left column: Exposed sensors, middle column: shaded sensors, right column: difference between exposed and shaded sensors. Average values are indicated by dotted lines.

temperature and subsequent human well-being (Meili et al., 2021b; Rubiano Calderón, 2019). Accordingly, our methods and study measured the urban forest function of providing climate regulating ecosystem services and then linked it to human well-being in a less populated and vulnerable tropical city. Specifically, it quantified the potential temperature regulation, human perception, and also lethal heat risk during an extreme heat event in 2021. The approach and findings provide a sampling and measurement approach to better understand temperature regulation in little-studied climate change vulnerable tropical cities with limited resources (Ordóñez

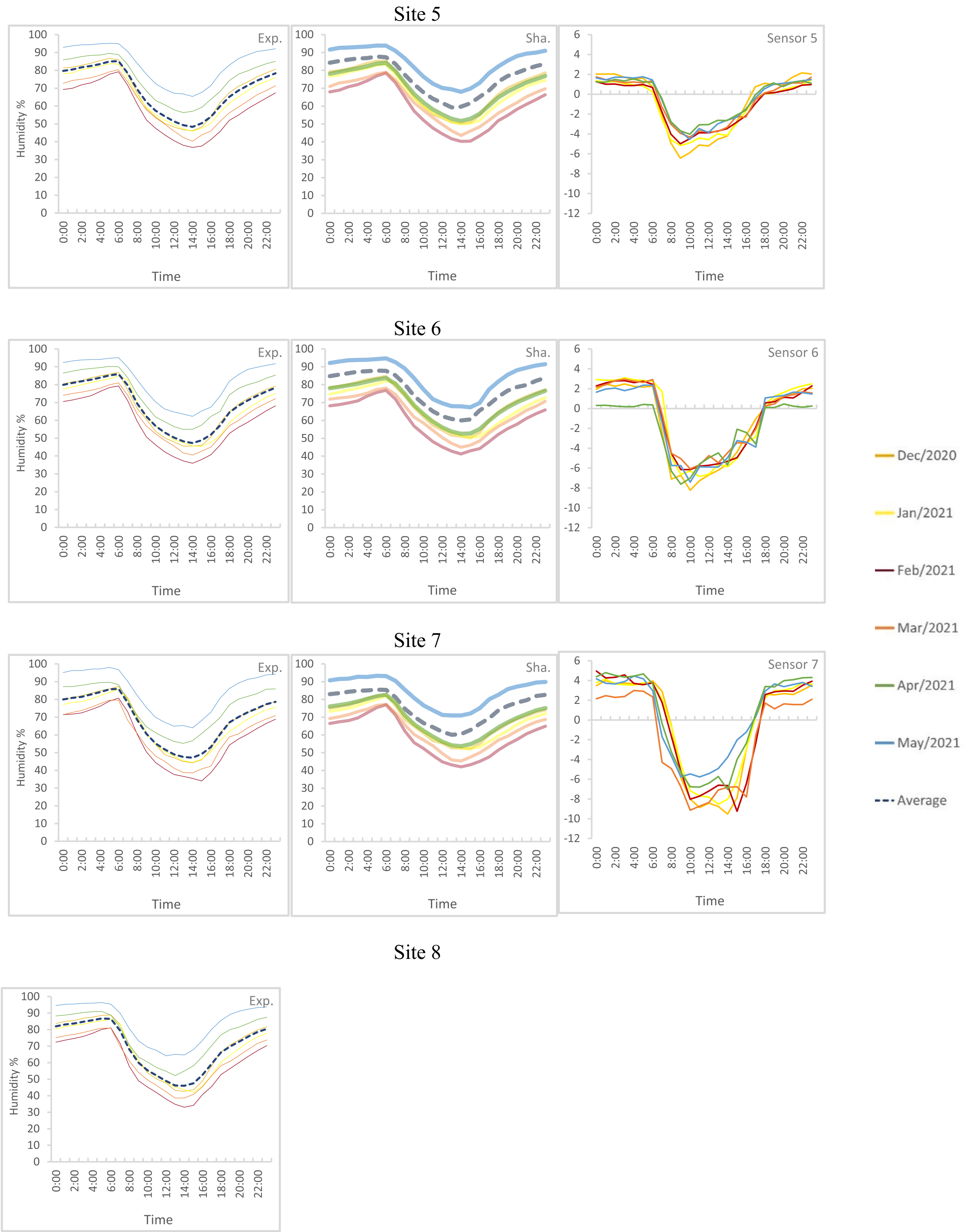

Fig. 4. (*continued*).

et al., 2020).

The analysis of temperature regulation by trees during the hottest season of 2021 shows how UFs mitigate heat in the city generating better microclimate and human well-being conditions (Gillner et al., 2015). However, this effect depends on site-specific weather (hot days, cool and cloudy days, rainy days) and actual tree cover surrounding the sensor (Mallen et al., 2020; Xiao et al.,

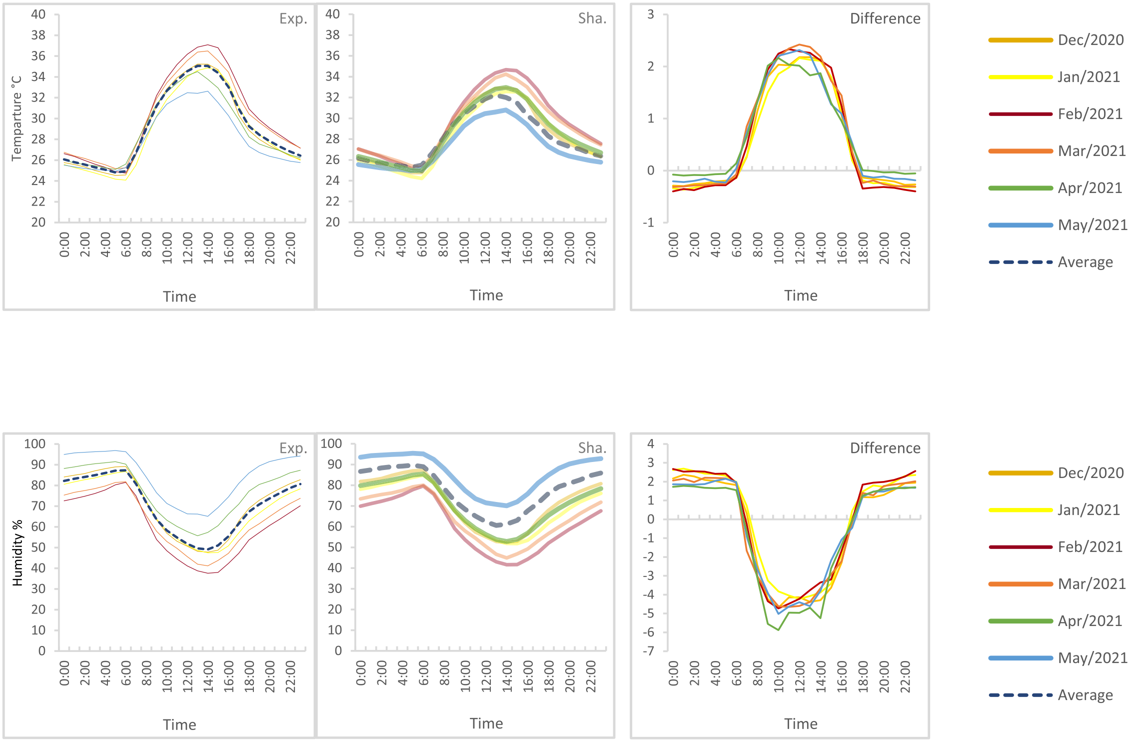

Fig. 5. Upper panel: multisite average temperature cycle for each month (solid lines, from December 2020 to May 2021). Bottom panel: Multisite average temperature cycle for each month (solid lines, from December 2020 to May 2021). Left column: Exposed sensors, middle column: shaded sensors, right column: difference between exposed and shaded sensors. Average values are indicated by dotted lines.

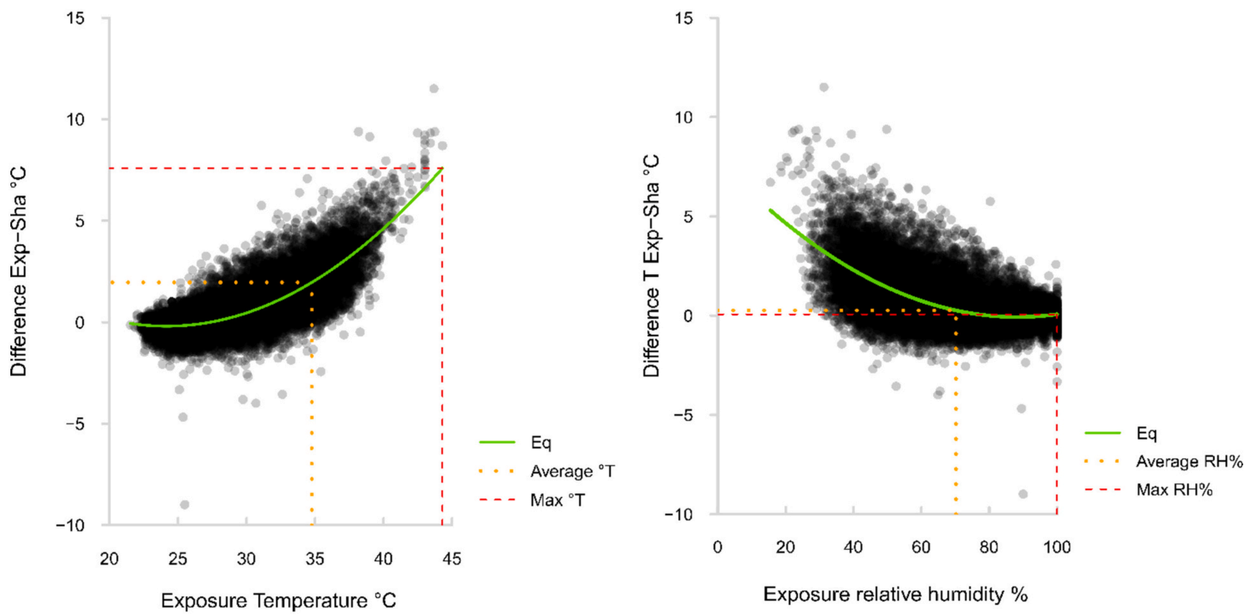

Fig. 6. Relations between hourly air temperature (left x-axis) and relative humidity (right x-axis) of exposed sensors and the hourly thermal regulation (measured through the difference of temperature between exposed and shaded sensors pair, y-axis) for each sensor. Parametric fit is indicated with green solid line (parameters of the equations are in Table 3). Average and maximum values (for both temperature and humidity) are indicated with orange and red vertical dotted lines, respectively. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

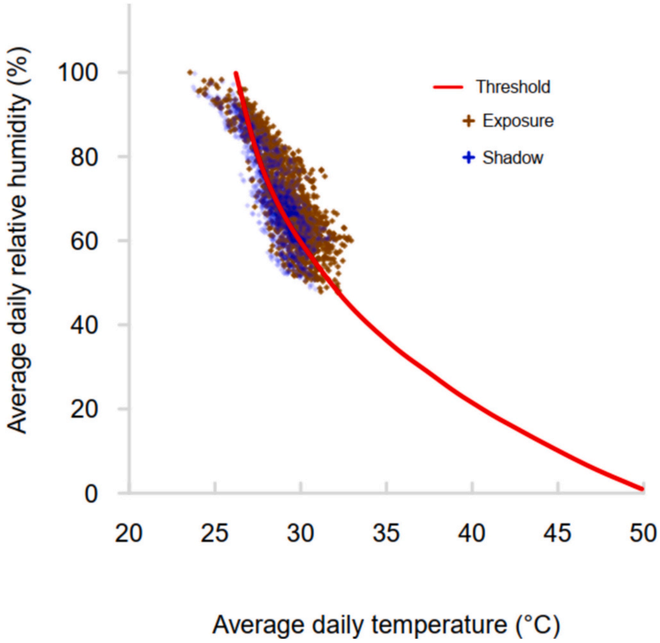

Fig. 7. Average daily temperature and relative humidity for exposed (brown, $n = 1324$ measurements) and tree shaded sensors (blue, $n = 1107$). Red line represents Mora et al.'s (2017) lethal threshold for the location of Puerto Carreño and depicts the climatic thresholds of temperature and humidity above which heat events can cause a significant increase in mortality risk. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

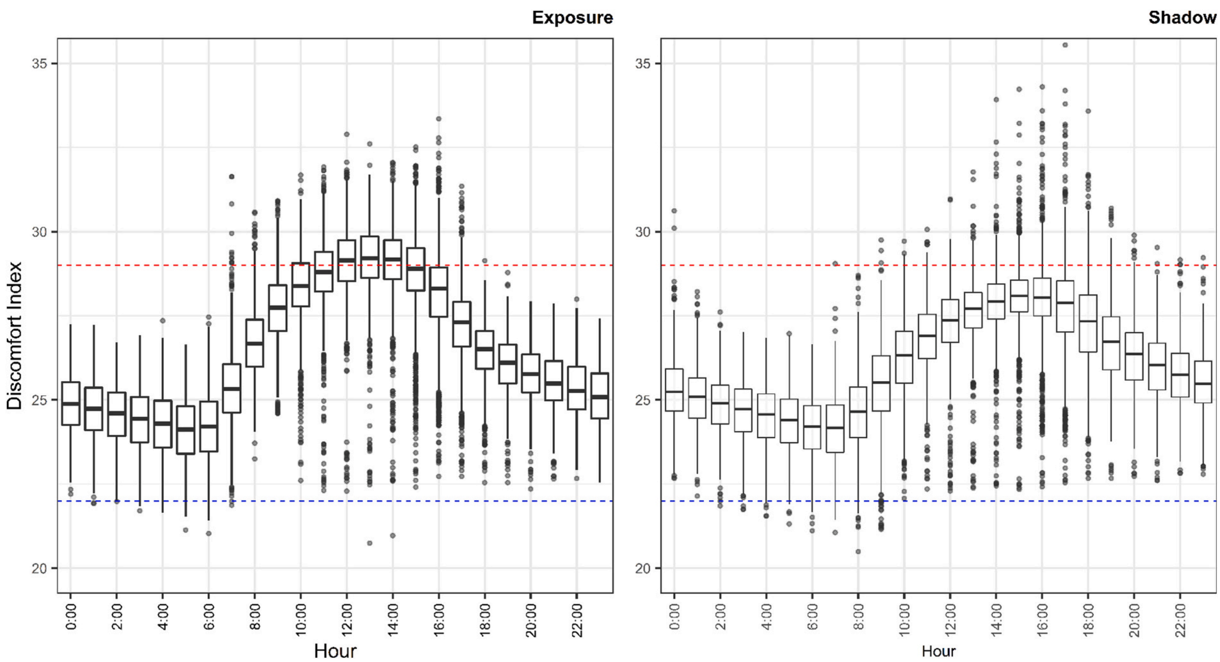

Fig. 8. DI records per hour. Left panel: sensors under sun exposure (exposed). Right panel: sensors shaded (shadow). Dotted red and blue line correspond to DI >28 (discomfort is very strong and dangerous) and DI <22 (no discomfort) respectively. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

2024). The largest differences for both temperature and humidity were found in the hottest months, February and March when fewer trees were present in both exposed and shaded sensors. Indeed, the presence of even a few trees helped to mitigate the temperature up to 7 °C during the hottest periods from 12:00 p.m. until 3:00 p.m. (12:00 until 15:00), while maintaining higher humidity relative to areas with sun exposure. But, during cloudy days (more common in April and May), temperature and relative humidity tended to be homogeneous even if the environment had few or many trees (Figs. 2 and 3); highlighting the important effect of thermal regulation during heatwaves.

Elsewhere, vegetation cover and tree patches have been documented to regulate temperature in cities (Coronel et al., 2015; Di Leo et al., 2016; Grilo et al., 2020; Rubiano Calderón, 2019) In general, the greater the amount of vegetation; the cooler the area due to an increase in evapotranspiration and shade (Cavan et al., 2014; Bowler et al., 2010; Ossola et al., 2020). Our results confirm this since our lowest temperature (21.5 °C) was recorded in sensors with higher grass cover (site 2, periurban neighborhood) compared to those with low tree cover (site 7). The opposite situation occurred during night-time non-radiation hours from 5:00 p.m. to 6:00 a.m. (17:00 to 6:00) when stored heat was released allowing for temperature regulation at night. This is especially the case under scattered tree cover, when dense tree canopy could not retain as much heat at night as shown in Fig. 2 (Bowler et al., 2010).

Findings suggest that thermal regulation and heat intensity are non-linear: at higher daily heat extremes, tropical urban forest cooling effects are maximized. This specific result is novel when compared to other studies which generally assume a linear relationship (De Frenne et al., 2019; Ossola et al., 2020; Gohr et al., 2021). This might be due to the non-linear behaviour of surface temperature in exposed conditions when soil moisture is limited (Seneviratne et al., 2010). In shaded conditions, under higher ambient temperatures, the evapotranspiration flux is maintained and continues to cool the surface, while in exposed conditions, when moisture is critically decreased, the evapotranspiration flux can abruptly decrease and incoming solar radiation begins to increasingly heat the surface (Quesada et al., 2012; Miralles et al., 2019).

In terms of tropical urban forests improving thermal comfort and mitigating lethal heat risk, our results show that thermal regulation was higher during high discomfort indices. In particular, extremely high discomfort days (DI >28) are more noticeably mitigated (factor 2.3) than high discomfort days (DI >25, factor 1.2) under shaded conditions when compared to exposed conditions. Our findings show that thermal regulation in a tropical urban forest is more effective at extreme temperatures (8.7 °C at 44 °C, but only 2 °C at 34.9 °C in an environment with less trees). This is confirmed by the lower number of days during the dry season that could become lethal in shaded conditions (63 %) compared to those without shade (82 %) based on the global threshold proposed by Mora et al. (2017). This indicates that urban forests can decrease the potential lethality of hot days by 23 % in similar vulnerable cities. Findings highlight the need for this type of climate change adaptation measure that as shown in this study, can lead to improved human wellbeing and reduced extreme heat mortality, particularly in vulnerable cities of the Global South.

For example, an average climate change ensemble scenario for Puerto Carreño by year 2100 estimates an increase in average temperature from 28 °C to 31 °C (IDEAM, PNUD, MADS, DN, and CANCILLERÍA, 2015) and an increased number of dry days and drought frequency (IPCC, 2021). During the dry season of 2021, the results obtained for daily temperature and humidity were comparable to findings by Mora et al. (2017) and Guo et al. (2018) under their worst climate change scenario (RCP8.5) at the end of the 21st century. This shows that there is an increase in heatwave-related excess mortality and in the number of days per year with climatic conditions that can become deadly (Fig. 7), likely implying new hospital emergencies for which the city is currently unprepared. Thus, nature-based solutions, such as urban greenery, can be a complementary strategy when access to health care and higher quality of services are not available to mitigate heat-related mortality (Sarmiento, 2023).

The high climate adaptive capacity of the people of Puerto Carreño (Supplementary material, survey tool) is contradictory to Mora et al. (2017) information in that their model does not account for local-scale human physiological adaptation in their deadly heat thresholds. As such, we recommend that the use of such models in the tropics, where very few studies exist on epidemiology-heat relationships, should account for site-specific human condition adaptation in their heat-related morbidity or mortality thresholds (Sarmiento, 2023). Doing so will allow for more precise projections of heat-related hospital burden under global warming scenarios. That said, our study did show a substantial cooling effect by urban forests under extreme conditions, thus very likely mitigating heat-related morbidity and mortality.

In terms of practical, cost-effective, policy-relevant solutions for using urban forests to mitigate heat in resource-constrained contexts, our finding could be used to design such strategies. For example, we found that tropical urban forest structure and species composition was highly diverse in our study area; as is common in tropical forests (Reynolds et al., 2017; Acuña-Simbaqueva et al., 2021; Wang et al., 2023). Accordingly diverse tree, shrub and palm structure and functional traits, such as those found in the study area, can be used to promote the mitigating effect of both urban and conserved forests on temperature and humidity in different ways as reported by Helletsgruber et al. (2020), Rahman et al. (2020), and Vieira et al. (2018); while providing a suite of other ecosystem services (Dobbs et al., 2011). Specifically, vertical urban forest structure was more complex, thereby providing a greater capacity to reduce air temperature relative shrub and pasture-dominated areas (Richards et al., 2020; Ordóñez et al., 2020). Thus, the availability of diverse tree species and high precipitation, could provide a suite of different low-cost planting practices and strategies (i.e., Nature-based Solutions) that inclusively and sustainably: maximize shade and wind circulation, create employment and food security, while minimizing maintenance costs, ecosystem disservices and irrigation needs in less populated, vulnerable tropical cities (Escobedo et al., 2019; Seddon et al., 2021).

Our study offers valuable insights into the thermal regulation benefits of urban forests in tropical, resource-constrained cities, yet several limitations must be acknowledged. First, the six-month timeframe, focused solely on the hottest season of 2021, provided critical data on extreme heat events but did not capture the full seasonal variability that could influence the performance of urban forests in regulating temperature. Second, while we demonstrated the link between tree shading and improved human thermal comfort, the direct and long-term impacts on health and well-being were not extensively explored, leaving room for more future research on physiological and psychological outcomes (Taylor et al., 2024) in tropical contexts. Third, the study also did not account for the adaptive behaviours residents may employ to mitigate heat exposure, such as modifying activity schedules or clothing, which could influence thermal perceptions and well-being (Navas-Martín et al., 2024). Fourth, the thermal comfort indices used, although informative, are not sufficiently well-validated for the unique conditions of extremely hot, humid tropical climates, potentially underestimating actual thermal discomfort. Fifth, another critical limitation lies in the scale dependency of heat regulation benefits, as our localized analysis may not fully represent variations caused by differing spatial distributions of tree cover or urban morphology. As shown by Ziter et al. (2019), the magnitude of daytime cooling of urban forests can increased with spatial scale but we only studied the specific local impact (not a tens or hundreds meters away). Addressing these limitations in future research will enhance our understanding of the role of urban forests as a Nature-Based climate adaptation strategy for tropical cities like Puerto Carreño.

5. Conclusions

Our findings indicate that tropical urban forests can help protect people from extremely high temperatures reducing them by up to almost 9 °C. Although people in Puerto Carreño were acclimated to warm environments, they are aware of how trees can regulate temperature and create microclimates, which will be more important in the future as climate change impacts increase. As such, our results provide useful information on the mitigation and adaptation potential that trees in cities can have in adapting cities to adapting to climate change, not only at the national level, but also at the local level, where such Nature-Based Solutions can have a measurable impact extreme temperature events. This study is one of the first to address these issues in the tropical regions of Latin America.

Our mixed methods-based results indicate that temperature mitigation by tropical UFs was exponential with ambient temperature and that respondents generally recognize the regulating ecosystem service and benefits of trees. However, the importance of developing discomfort and well-being indices that can more accurately account for tropical contexts and provide more relevant information about people's thermal sensations, preferences, and physiological thresholds are needed. Especially under projected future extremely high temperatures that are not adequate for human health.

Future research could study the role of epidemiologic awareness of how existing thermal conditions during extremely hot temperatures indirectly affect human well-being via the incidence of diseases and how human acclimatization can be used to adapt models to site-specific conditions. Studies analyzing how forest structural attributes (e.g., tree density, vertical structure) and functional traits influence temperature regulation could be used to design specific nature-based solutions and strategies to reduce heat impacts. As part of this strategy, informing residents and policymakers of the many co-benefits of urban forests (e.g., stormwater mitigation, food provision, biodiversity conservation) could also be used to address many of Puerto Carreño's vulnerabilities and extreme events related to climate change. We hope this study, one of the first efforts to provide information for small, tropical cities, provides information to mitigate extreme events in such contexts in the global south; home to a growing proportion of the world's vulnerable population.

Ethical declaration

The non-interventional and anonymous survey involved adult human subjects. This study was granted an exemption by the ethics committee of our University (Comité de Ética en Investigación de la Universidad del Rosario, under ID: 36861451). All the subjects provided appropriate informed oral consent before answering the survey, and after receiving a disclaimer explaining the purpose of the study, how the data would be used (only research purposes), and stating that the data are anonymous.

Author statement

B.Q. and F.J.E conceived and planned the analyzes. D.L.G.C. carried out the measurements, calculations and surveys. All the authors contributed to the interpretation of the results. D.L.G.C., F.E.B. and B.Q took the lead in writing the manuscript. B.Q. secured funding for this work, F.E.B. and B.Q supervised the in-field work. All authors provided critical feedback and helped shape the research, analysis and manuscript.

CRediT authorship contribution statement

Diana Lucia Giraldo-Charria: Writing – review & editing, Writing – original draft, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Francisco J. Escobedo:** Writing – review & editing, Writing – original draft, Validation, Supervision, Methodology, Investigation, Conceptualization. **Nicola Clerici:** Writing – review & editing, Validation. **Benjamin Quesada:** Writing – review & editing, Writing – original draft, Validation, Supervision, Resources, Project administration, Methodology, Investigation, Funding acquisition, Conceptualization.

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests:

Diana Lucia Giraldo Charria reports financial support and administrative support were provided by the Colombian-French Association of Researchers COLIFRI. If there are other authors, they declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.uclim.2025.102311.

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