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Addressing Increased Temperatures in Cities: Determination of Pedestrian Routes with Thermal Comfort in Barranquilla, Colombia

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Abstract: Thermal stress due to high temperatures has different negative effects on citizens as it generates a decrease in physical capacity and causes cardiovascular and respiratory alterations, which is especially true for pedestrians. In this paper, using a drone, routes for pedestrians with the best thermal comfort were traced between the different headquarters of the Simón Bolívar University (Barranquilla, Colombia). Maps were created for three time intervals, from 10 a.m. to 1 p.m., from 1 to 2 p.m. and from 2 to 3 p.m., and variations in temperature and relative humidity of both natural and artificial shadow areas were identified. The routes with the best thermal comfort were those with natural shade that presented ca. 3 °C less than the unshaded areas. The predominant trees' genera in most of the traced pedestrian routes were *Arecaceae* (palm), *Tabebuia* (purple oak), *Mangifera* (mango), and *Delonix* (red acacia). Some of them lose their leaves between March and June, which gives rise to an increase in the temperature along those routes. The developed cell phone application allows for the selection of walking environments with the best thermal comfort, favoring the mobility of the pedestrians along the considered area.

Keywords: drones; shadeways; thermal stress; vegetation cover; mobile phone application

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Received: 17 March 2025
Revised: 12 May 2025
Accepted: 2 June 2025
Published: 5 June 2025

Citation: Bolívar-Anillo, H.J.; Vega Benites, S.; Reyes Almeida, G.; Ortega Llanos, S.d.J.; Taba-Charris, V.; Acuña-Ruiz, K.A.; Reales Vargas, B.S.; Chapuel Aguillón, P.F.; Sánchez Moreno, H.; Iglesias-Navas, M.A.; et al. Addressing Increased Temperatures in Cities: Determination of Pedestrian Routes with Thermal Comfort in Barranquilla, Colombia. *Sustainability* **2025**, *17*, 5211. https://doi.org/10.3390/su17115211

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1. Introduction

One of the most relevant aspects all over the world of the impacts related to the Climate Change process is the rise in the mean global temperature that increased by 1.0 °C compared to the 1950s [1]; a further increase of 2.5–4 °C is estimated by the end of the 21st century under a high CO_2 emission scenario [1]. Although changes in global climate were common at geological time scales, the present global increase in temperatures is an order of magnitude faster than in the past [2] and is referred to as "Global warming" [3].

Historically, species have adapted to the effects of Climate Change through different strategies such as acclimatization, evolutionary adaptation, migration, or the use of refuges that provide safe microhabitats [2]. However, given the pace of change and its magnitude,

those compensatory mechanisms may be inadequate if sound adaptation and mitigation measures are not applied in the short term to slow down Climate Change [2,4]. Warming trends in cities are influenced by both large- and local-scale climate processes [5]. It is estimated that the magnitude of urban overheating may exceed 4–5 °C on average with peaks exceeding 10 °C [6,7].

Citizens in urban areas of low- and middle-income countries are the most vulnerable due to their high exposure to changing conditions and their limited capacity to manage and adapt to changes [8]: exposure to extreme heat in cities is very unequal and affects poor areas more severely [9]. It is therefore an urgent priority for many cities to actively respond to the challenges of urban heat [10]. The frequency, intensity, and duration of hot days in cities have increased since the mid-twentieth century [3,11]. The increase in temperature in cities generates a rise in energy demand for buildings cooling and an associated electricity consumption, an increment in the concentration of air pollutants, a reduction in workers' productivity, an increase in the number of hospital emergency room visits, and an increase in the rate of hospitalization and associated cost for healthcare systems [7,12,13].

In human beings, high heat stress reduces physical work capacity (especially for people working in occupations that cannot use air conditioning or other technical cooling methods), produces disturbance in cardiovascular (e.g., cardiac ischemia, infarction, and cardiovascular collapse) and respiratory systems (e.g., hyperventilation, pulmonary edema, and acute respiratory distress syndrome), and affects mental health (e.g., mood disorders, organic mental disorders, schizophrenia, and neurotic, depression and anxiety disorders) [6,14,15]. Finally, under conditions of extreme heat stress, the body's thermoregulatory capacity may be exceeded leading to heat stroke, which can be fatal [14,16,17] and especially affects pedestrians and cyclists [18].

Modern cities must be inclusive, safe, resilient, and sustainable to meet Goal 11 of the UN Sustainable Development Goals [10]. Many cities are currently implementing smart mobility solutions [19] that promote the use of technology and data to improve the efficiency, sustainability, and accessibility of transportation systems, which results in an improved quality of life for people [19,20]. In this regard, walking is considered one of the most advantageous ways to travel short distances in cities. Therefore, the creation of a sustainable walking environment is considered a challenging factor [21,22]. The possibility of citizens walking safely and comfortably is considered central to a socially and spatially just city [23]. Furthermore, walking is the most primitive and basic way of urban mobility, accounting for approximately 12–26% of total trips in developed countries and even more in developing countries [23–25]. Walking rates depend on pedestrian comfort facilities, e.g., landscape characteristics, presence of trees, signage, and seating areas [26,27] and, therefore, city landscaping and trees are considered an essential component for increasing attractiveness, safety, and usability at street level [28,29]. Improving pedestrian mobility in a city requires a clear knowledge of the urban microclimate and its impact on pedestrian behavior [30,31].

In the last decade, different adaptive strategies against extreme heat waves in cities have been implemented to enhance walking infrastructures [12], the implementation of which is therefore of paramount relevance for the adequate and sustainable economic development of cities [13]. There are different cooling strategies to mitigate heat in cities, including the use in houses/buildings of cool/reflective and permeable materials, permeable pavements, cool and/or green roofs, green walls, and the application of an innovative urban design and vegetation, e.g., by enhancing the smart configuration and distribution of green spaces [12,28,32–34]. Although all these strategies contribute to thermal comfort in cities, street-level heat mitigation strategies are considered the most effective in improving pedestrian thermal comfort through shading, evaporation, and evapotranspiration [34].

The increase in tree cover in cities improves urban resilience to extreme heat [7] and a 30% enhancement would reduce the temperature by up to 4 °C [35]. Trees in cities provide several ecosystem services such as air and water filtration, temperature regulation, noise reduction, carbon sequestration, retention and detention of stormwater runoff, increased biodiversity, and esthetic landscape enhancements; all factors contribute to enhance residents' health [7,36]. Shadeways are sidewalks or pathways that have a relatively high amount of natural (i.e., linked to vegetation) and artificial (i.e., linked to buildings) shading that provides thermal comfort for active travelers [37]. The existence of shadeways and bike paths is also effective in reducing the use of private vehicles and, therefore, costs and traffic congestion [12,38,39].

Actually, drones or unmanned air vehicles are among the most beneficial and emerging technologies to improve citizens' quality of life [40]. Drones can be used in a variety of applications such as disaster management, air pollution monitoring, fire detection, building inspection, search operations, wind estimation, civil security, traffic monitoring and safety, and the detection/characterization of urban trees [40,41]. Despite the advantages of drones for data collection in cities, the establishment of shadeway routes and urban tree detection is usually made with satellite imagery [42–45].

The aim of this paper is to create a map of routes for pedestrians' thermal comfort using images captured by a drone in order to facilitate the pedestrian mobility of students, professors, and administrative staff of the Simón Bolivar University to allow them to walk under the best thermal comfort conditions among the different headquarters of the mentioned university. Drone surveys were complemented by detailed visual field observations (e.g., on the number and species of trees) along each of the proposed routes and temperatures and relative humidity values were also measured at sun exposed areas and in areas with natural and artificial shade. Finally, a mobile application was developed to allow all members of the Simón Bolívar University to know in real time, when moving between the different headquarters during high temperature hours, the routes with the best thermal comfort.

2. Materials and Methods

2.1. Study Area

Barranquilla is located in the north of Colombia, at the mouth of the Magdalena River in the Caribbean coast (Figure 1) [46]. It is a medium-sized city with approximately 1,200,000 inhabitants and covers an area of 166 km^2 [47]. The city presents an elevation from 4 to 120 m above sea level and has a tropical savanna climate (Aw) according to the Köppen climate classification [48]: its mean annual temperature is 28 °C, the thermal oscillation does not exceed 10 °C, and the mean annual relative humidity is 80% [46]. Barranquilla is organized into 5 sectors: Southwest, Southeast, North-Historic Center, Metropolitan, and Riomar. The North-Historic Center of Barranquilla is full of history and culture [49] since this is the area where the city originated. This sector is composed of 41 neighborhoods, including El Prado, which is the heart of Barranquilla and covers approximately 113 hectares [50]. All Colombian cities are crossed by a system of avenues (carreras) and streets (calles) which are broadly normal. El Prado is located between Carreras 50th and 60th and Calles 53rd and 75th and is classified as "national monument" for its historical, architectural, and urbanistic value [51].

One of the main characteristics of El Prado is the presence of different universities, health centers, gastronomic areas, hotels, shopping malls, banks, schools, and companies, which make it a neighborhood with a high pedestrian presence. Among the universities, the Simón Bolívar University has 16,066 bachelor's degree students, 1337 postgraduate students, 1290 professors, and 567 administrative staff, distributed in seven headquarters,

some of them quite distant from each other (Figure 2). Each of those headquarters, except for site 5 and the White House, has classrooms equipped for teaching activities, recreational spaces for students, administrative buildings that host different faculties and academic programs, soccer fields, volleyball and basketball courts, and auditoriums. Site 5 has the university museum, an auditorium, and a space for cultural practices and exhibitions. The White House is a space for administrative use only, i.e., admissions and enrollment of new students [52].



Figure 1. Location map showing the city of Barranquilla (10°59′ N and 74°47′ W), with the North-Historic Center (in gray) and El Prado neighborhood (in red). The satellite image was obtained from Google Earth.

2.2. Determination of Pedestrian Routes

The aim of this paper is to establish the best routes in terms of thermal comfort to enhance the quality of the mobility of the members of the Simón Bolívar University between its different headquarters during high temperature hours. For the determination of the most thermally comfortable routes, the degree of tree vegetation cover present along the routes was established by the use of a DJI Mavic 3 Multi Spectral Drone (DJI, Shenzhen, China) [53]. The drone has an integrated 20 MPX RGB camera with the capacity of obtaining high precision aerial photographs of up to 200 ha and images up to 15 km away from the take-off point. In order to cover different shadows conditions, six flights were scheduled in May 2024, at one-hour intervals, departing from 10 a.m. to 3 p.m. (i.e., the hours of maximum daily temperature). An area of 48 ha covering all the headquarters of the Simón Bolívar University was surveyed by taking photos every 2 s with a focal distance of 12.29 mm between them, with a resolution of 5280 × 3957 and a pixel size of 3.36 × 3.36 microns. At the end of each flight, a total of 338 photos aligned at an average flight height of 129 m with a ground resolution of 3.37 cm/pix were obtained.

2.3. Elaboration of High Resolution Orthophotos

To obtain the orthophotos, the images were processed by implementing a motion structure workflow with Agisoft Metashape v2.1.2 software [54]. By means of the automatic georeferencing process, the software is able to convert the raster coordinates (set of pixels of the flight photos) into a known coordinate system that allows for locating them on the Earth's surface. The orthophotos were exported in TIF format and inserted into the QGIS Desktop v3.28.0 program [55] to establish the different potential routes among the different

headquarters of the Simón Bolivar University, their length, the areas covered by trees, and the extensions of shadow areas linked to both natural (trees) and artificial (i.e., due to buildings) factors.

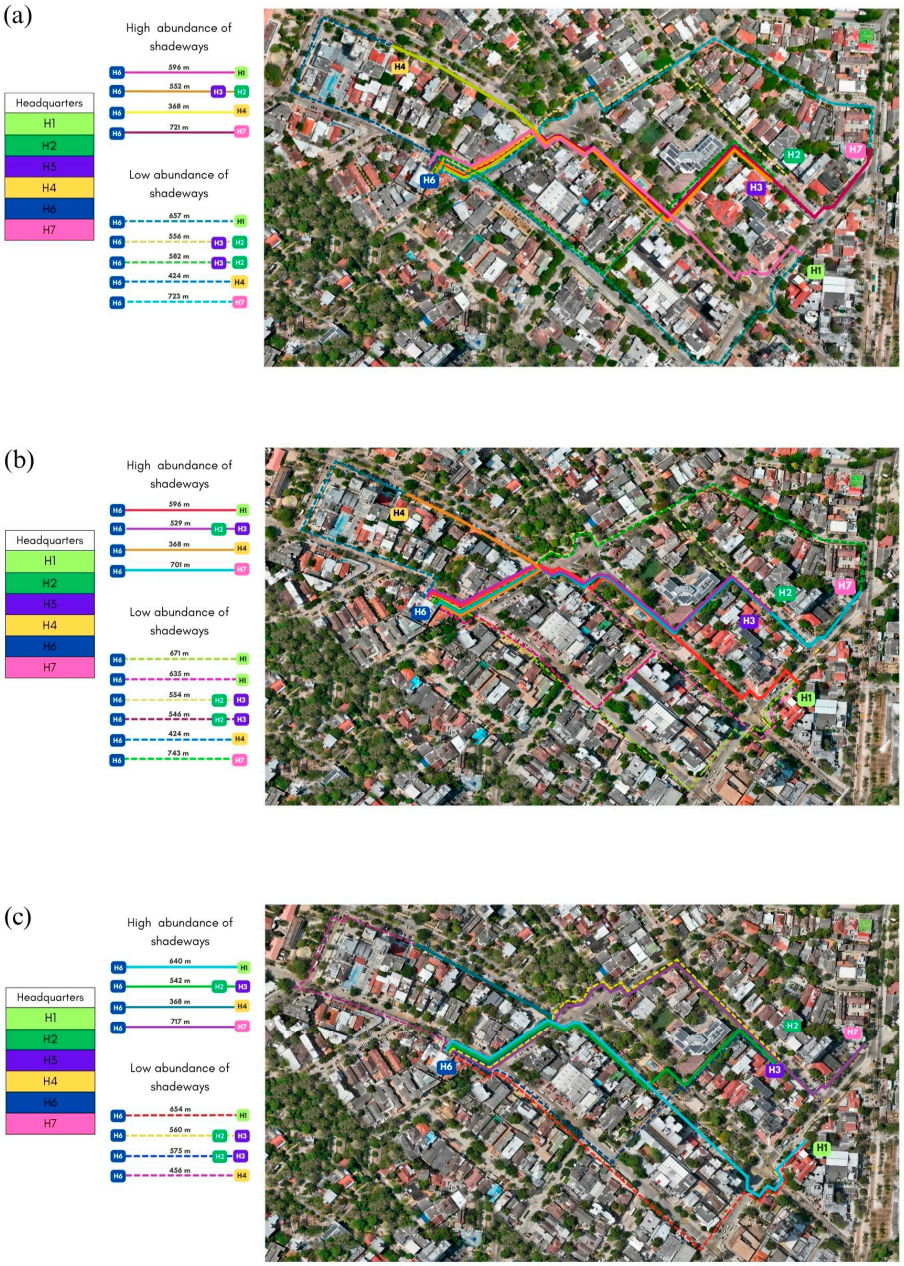


Figure 2. Pedestrian routes between headquarters for the following time intervals: (**a**) 10 a.m.–1 p.m.; (**b**) 1–2 p.m.; and (**c**) 2–3 p.m. Source: Authors' own work.

2.4. Measurement of Humidity and Temperature on Routes

Temperature and relative humidity were measured several times at various points along the routes each hour from 10 a.m. to 3 p.m. and hourly average values were then calculated. Measurements were taken in natural and artificial shaded areas, as well as in unshaded areas along the selected routes using a digital thermohygrometer with a humidity–temperature probe (KTJ Thermo). The thermohygrometer had the following features: temperature range from 0 °C to 50 °C; temperature accuracy ±1 °C; relative humidity range from 20% to 98%; and humidity accuracy of ±5%.

2.5. Determination of Plant Species

The identification of the different species of trees present along the pedestrian routes was carried out by observing their morphological characteristics, i.e., leaves, stems, height, and flowers. In addition, the application PictureThis—Plant Identifier (https://www.picturethisai.com/es/, accessed on 30 July 2024) [56] was used since it provided information on the scientific name and botanical description of each tree identified.

2.6. Design and Implementation of Mobile Phone Application

The mobile application was built using interactive mapping and its essential features were defined to fulfill users' requirements. A conceptual sketch was developed using Figma (https://www.figma.com/), which enabled the visualization and usability refinement of the interface before its implementation. Upon completion of the prototype, a Minimum Viable Product (MVP) was implemented to validate core functionalities before optimization and scalability. Due to its flexibility and cross-platform compatibility, React Native, with its use of TypeScript and TSX, was selected for mobile application development. The MVP's validation, optimization, and scaling phase began, incorporating improvements such as time-of-day routing and a refined, structured interface optimized for usability. To restrict application access to Simón Bolívar University students and staff, the app backend was developed using Firebase and Django. Firebase, a Backend-as-a-Service (BaaS) platform, handled efficient information management and user authentication and Django, a high-level Python v3.10.12 web framework, ensured scalability and security.

3. Results

3.1. Pedestrian Route Determination

Maps were created for three different time intervals considering pedestrian movement necessities and the location/variability during the daylight of shadow areas. The first one covered from 10 a.m. to 1 p.m., as no significant differences in the location of shadow areas were observed within this time range. During the time intervals from 1 to 2 p.m. and from 2 to 3 p.m., variations in the distribution of both natural and artificial shadow areas were identified and, therefore, different maps for each interval were created (Figure 2). In Figure 2a, the results of the different routes that pedestrians can choose depending on the intervals considered, i.e., from 10 a.m. to 1 p.m., 1 to 2 p.m., and 2 to 3 p.m., are shown. Pedestrian routes were drawn up to joint headquarter 6 to the others because it houses research laboratories and classrooms that everybody uses and is the furthest from the other headquarters so university members have to travel long distances to get there.

In the time intervals from 10 a.m. to 1 p.m., shadeways were essentially related to the presence of trees (natural shade) since areas shaded by buildings (artificial shade) were not significant; therefore, the identified pedestrian routes essentially run through wooded areas (Figure 2a). During the 1 to 3 p.m. interval, a greater number of routes was available due to the presence of areas shaded both by buildings and urban woodlands (Figure 2b). Such routes were generally longer than the ones observed for the 2 to 3 p.m. time interval during which shorter routes are available due to the presence of large and numerous shadow areas linked to both buildings and urban woodlands (Figure 2c).

Finally, an overlapping was observed between several of the pedestrian routes available for the three time intervals presented, as was the case for some routes heading to headquarters nos. 1, 2, and 3. These sectors common to diverse mobility routes are linked to the great abundance of trees and, for this reason, they will probably record a large number of pedestrians (Figure 3a).



Figure 3. Pedestrian routes: (**a**) route with natural shade (Los Fundadores Park); (**b**) pedestrians protecting themselves from the sun with hats and laboratory coat; (**c**) *Tabebuia rosea* without leaves; (**d**) *Arecaceae* sp. on the route between headquarters nos. 6 and 7. Source: Authors' own work.

3.2. Humidity and Temperature Along Routes

The results of field work highlighted that, despite the considered time intervals, the average measured temperature was always higher in sunny areas compared to areas shaded both by buildings and urban woodlands (Table S1 of Supplementary Materials). During the period of investigation, the recorded temperatures in sunny areas presented small variations among the considered time intervals, i.e., average values were 40 °C from 10 a.m. to 1 p.m., 39.1 °C from 1 to 2 p.m., and 41 °C from 2 to 3 p.m. In contrast, shaded areas generally recorded lower temperatures, with average values of 36.4 °C from 10 a.m. to 1 p.m., 36.3 °C from 1 to 2 p.m., and 36.7 °C from 2 to 3 p.m. in areas shaded by urban woodlands, and average values of 37.7 °C from 10 a.m. to 1 p.m., 37.5 °C from 1 to 2 p.m., and 38.5 °C from 2 to 3 p.m. for areas shaded by buildings. Regarding the average values of relative humidity recorded in sunny areas during the investigated days, they were in the ranges of 45% from 10 a.m. to 1 p.m. and from 2 to 3 p.m. to 48% from 1 to 2 p.m. In contrast, the shaded areas generally recorded higher relative humidity, with average values of 53% from 10 a.m. to 1 p.m. and from 1 to 2 p.m. and 54% from 2 to 3 p.m. in areas shaded by urban woodlands, and average values of 50% from 10 a.m. to 1 p.m., 49% from 1 to 2 p.m., and 48% from 2 to 3 p.m. in areas shaded by buildings.

3.3. Tree Inventory

The number of trees and predominant genus varied along the different pedestrian routes. Several routes were observed with urban woodland cover > 90% and other routes had urban woodland cover of only 6.6%. The predominant trees' genera in most of the traced pedestrian routes were *Arecaceae* (palm), *Tabebuia* (purple oak), *Mangifera* (mango), and *Delonix* (red acacia) with 68, 60, 18, and 13 individuals, respectively. The average height of all observed trees (but palm) was ca. 20 m and palms presented an average height of 5 m. Tabebuia rosea is a leafy but deciduous tree and its leaves fall off between March and June (Figure 3a). In turn, *Arecaceae* is not a very leafy tree and generates little shade (Figure 3d). The largest number of trees was observed in Los Fundadores Park with a total of 75 trees and the predominant genus was *Arecaceae*. It should be noted that some routes were characterized by the presence of trees of the *Ceiba* genus that shows large size and leafiness. However, they are deciduous trees and, therefore, their leaves fall off between January and March. Because of this, the routes with abundant *Ceiba* genus lose part of their effectiveness during the above-mentioned months.

3.4. Mobile Phone Application

The app's wireframe, with its two-dimensional layout, was designed to incorporate map visualizations that included shadow maps generated from the defined routes. It also facilitated navigation between locations and allowed users to activate a guide for directions. Mock-ups allowed for the precise definition of the application's esthetics (Figure 4a) and also facilitated the integration of secondary functionalities such as travel distance, estimated arrival time, real-time temperature, and the determination of their visual hierarchy. React Native, a cross-platform JavaScript framework, allowed us to develop the prototype (Figure 4b–d) and establish a base interface. From the different prototypes created, the version with the lower container was selected (Figure 4d).

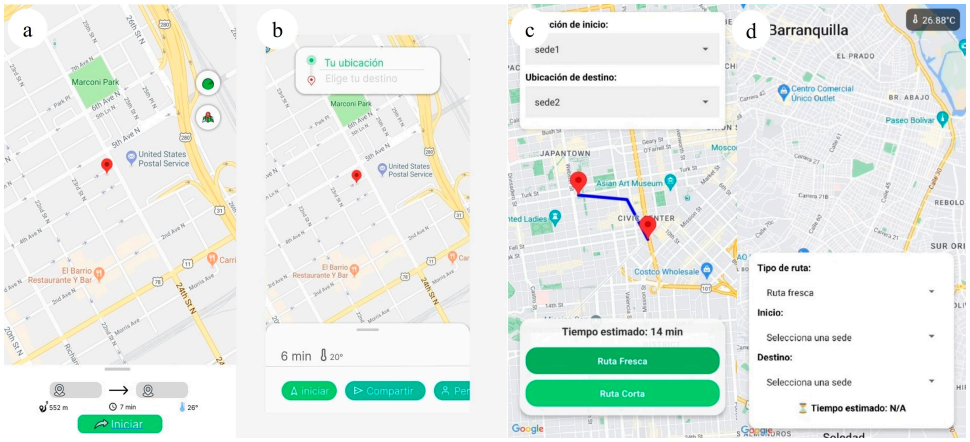


Figure 4. (**a**) Mockup with only one lower container; (**b**) mockup has an upper container for the route and a lower one for the other interactions; (**c**) prototype with two containers (upper and lower); (**d**) prototype with one container (lower). The maps images were obtained from Figma and Google Maps.

During the optimization phase, functional and esthetic features were refined. Key functionalities, such as real-time temperature display, personalized route representation, and Google Maps integration for automatic path generation, were incorporated. Additionally, a route adaptation system based on three time ranges was implemented this way, ensuring optimized navigation based on time-specific conditions. The optimized mobile application features a minimalist and user-friendly design (Figure 5). Upon launching the application,

users select their starting and destination headquarters. The application (Android Application Package: https://drive.google.com/file/d/1EODo9GPtARg9be9gwfB2Q4wdk3YspRBU/view?usp=sharing, accessed on 20 May 2025) then generates a route based on the created maps. Integrated with Google Maps, the application provides real-time navigation guidance and automatically sends key waypoints to Google Maps (Figure 5f).

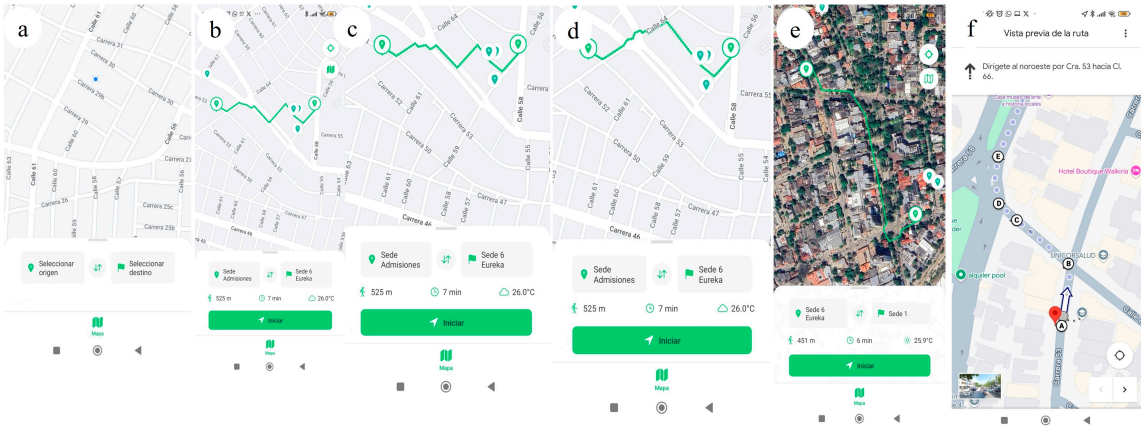


Figure 5. Application design: (**a**) first image is when opening the application; (**b**) route traced at 10 a.m.; (**c**) route traced at 1 p.m.; (**d**) route traced at 3 p.m.; (**e**) satellite view of the map; (**f**) application integration with Google Maps. The map images were obtained from Figma.

4. Discussion

Earth surface temperature was approximately 1.09 °C higher in the 2011–2020 period with respect to the 1850–1900 period [57] and it is projected to rise between 3.3 and 5.7 °C by 2100 under the very high greenhouse gas emission scenario [12,57]. In Colombia, during the 1971–2000 period, an increase in the average temperature of 0.13 °C per decade was observed and Climate Change scenarios predict an increase of 1.4 °C by 2040 and 2.14 °C by 2100 [58]. The increase in global temperature is one of the main factors responsible for ecosystems' degradation and extreme heat waves threaten the sustainability of urban settlements worldwide. Exposure to high temperatures endangers the health of citizens, the development of cities, and their overall environmental quality [6,9]. High temperatures adversely and especially affect developing nations due to the lack of adaptive capacity as well as different cultural constraints [11]. Furthermore, global urban population has now reached 3.9 billion, i.e., almost 54% of the total world population and, by 2050, it is expected that around 66% of the world's population will live in urban areas [32]. Despite the fact that Latin American and Caribbean regions are among the most biodiverse and urbanized regions of the world [59,60], vegetation in Latin American and Caribbean cities is fragmented, unconnected, and inequitably distributed [59]. Therefore, maintaining adequate urban vegetation is key to producing more livable and resilient cities, improving health and well-being, and promoting Climate Change adaptation and mitigation strategies [59].

Barranquilla is the capital of the department of Atlántico in Colombia and the most populated city along the Colombian Caribbean coast with ca. 1.2 million inhabitants [61]. Since 2011, the mayor's office has been implementing a program called "Everyone to the Park" in Barranquilla, which has resulted in 91% of the city blocks having a park or green area less than 800 m away. A total amount of 185,155 trees was planted and this has allowed Barranquilla to be recognized as the "Tree City" in 2023 by the FAO and the Arbor Day Foundation [62,63]. Actually, Barranquilla is considered a BiodiverCity where green corridors are prioritized for sustainable and safe mobility for citizens [64]. However, Arellana et al. (2021) [65] established that, in Barranquilla, the poor planning of some neighborhoods, mainly the ones with low incomes, prevents their inhabitants from

taking advantage of the potential of walking and cycling in these green areas. The highest potential pedestrian accessibilities are located in high- and medium-income zones where people rely more on private transport modes. In this paper, which deals with a high-income zone, it was observed that pedestrians have no indications on adequate walking routes and often increase their exposure to the sun as they walk in sunny areas parallel to existing shaded areas. This behavior was observed at other areas too, e.g., Deilami et al. (2020) [37] established that in the city of Greater Bendigo (Australia), approximately 52% of the routes traveled by pedestrians lacked shade or had very low levels of shade. This is in accordance with Tong and Bode (2022), who established that the choice of a route frequently traveled by a pedestrian may sometimes not be a conscious decision and may essentially be determined by the inertia of the choice [66]. However, Lee (2020) [31] observed that in New York, pedestrians tend to seek shade and avoid strong solar radiation. Although in Barranquilla, the presence of trees is considered an important component of comfort by pedestrians, the main factor taken into account is security [67]. Therefore, the pedestrian's selection of a route is more associated with security.

Despite that shadeway route maps and urban tree detection are usually carried out by means of satellite images [42–45], in this paper, drone images were used, which actually constitutes an effective and alternative tool [68,69]. Therefore, several studies have used drone-obtained images to evaluate and improve the thermal environment of pedestrian spaces. Zhao et al. (2020) [70] using thermal images collected by an infrared camera, developed a method based on 3D thermography to analyze and evaluate the spatial distribution of thermal comfort. They determined that the difference in mean radiant temperatures in the pedestrian space between sunlit and shaded areas was >3 °C. Videras et al. (2022) [71] developed a new method to evaluate the measurement of radiant heat transfer in an urban pedestrian space using aerial thermography taken by drones. Based on the surface temperatures of the infrared images collected by a drone, previous authors estimated the mean radiant temperature at multiple points in a pedestrian area of the city of Huelva (Spain) during a typical summer day. The mean radiant temperature was influenced by several aspects related to the architectural design of the public spaces, from the materials that cover a street/square to the existence of vegetation to urban geometry issues. The vegetation proved to be one of the determinants in the distribution of mean radiant temperature, with the lowest temperatures located next to trees. Alkaabi et al. (2023) [72] explored the feasibility of using drones in conjunction with specific software to analyze various thermal images to perform thermogrammetric mapping to monitor and classify heat indices as a function of building components and pedestrian spaces at the United Arab Emirates University in Al Ain. They observed that a shaded natural grass surface represents the most tolerable thermal environment while an unshaded sand surface represents the most unfriendly thermal environment.

In this paper, routes were traced between the different headquarters of the Simón Bolívar University in Barranquilla using images captured by a drone and which routes presented the best thermal comfort for pedestrians due to the presence of natural and artificial shade were established. The obtained results coincided with those recorded by previously mentioned authors in other areas around the world. Shaded areas linked to trees were the most thermally comfortable for pedestrians with a difference of approximately 3 °C less than unshaded areas, which is consistent with the studies carried out by Sanusi et al. (2017) [73] who observed that shaded areas with trees can decrease the temperature between 0.1 and 5.6 °C, depending on specific environmental factors and tree species. Through reflection and absorption, trees eliminate a large amount of short-wave solar radiation in public spaces [71]. Jia and Wang (2021) [34] determined that the universal thermal climate index reductions are the most significant where trees are planted. In this

regard, Detommaso et al. (2021) [28] established that a high level of urban greening (e.g., green roofs and urban forestation) guarantees the well-being of pedestrians. The effects of vegetation are not limited to the area where it is located but extend to the surrounding areas too. They also established that the areas where vegetation is present are characterized by the highest relative humidity, which is consistent with the results of this study [28].

In this paper, it was also observed that pedestrians in Barranquilla use different means of protection (e.g., umbrellas, clothes, and caps) to avoid the effects of the sun (Figure 3b), e.g., the use of umbrellas has become very popular on very sunny and hot days. However, umbrellas provide shade from direct UV but do not protect against diffuse UV, as established by McMichael et al. (2013) [74]. The best route established according to the drone images was through Los Fundadores Park, which has 75 trees (Figure 3a). This emblematic park of the city is used by many pedestrians due to the large amount of natural shade offered and is a common route between different headquarters of the Simón Bolivar University. The predominant tree genera in most of the traced pedestrian routes were *Tabebuia* (purple oak) and *Arecaceae* (palm). The purple oak is a light-demanding species that forms sparse canopies with minimal self-shading and is a deciduous tree [75,76]. Tabebuia trees exhibit considerable shoot growth and leaf flushing during the rainy season, while leaf fall is pronounced during the dry season in response to increasing air temperature [76]. Therefore, shadow areas linked to Tabebuia trees are lost between the months of March and June, decreasing the utility of the shadeways for pedestrians. Palm trees (*Arecaceae*) (Figure 3c) are usually planted in very warm climatic zones mainly for their esthetical value [77], such as in the El Prado neighborhood where trees with a larger canopy could be planted. Small canopy palms, such as those observed in this paper, can be useful to provide thermal comfort to pedestrians only when space for planting large trees is limited [78]. For the successful planning and management of tree planting in cities, it is necessary to take into account factors such as the dynamics of urban forests, species composition, soil composition and dynamics, root damage to infrastructure, tree falls, pollen allergies, changing climatic conditions, and the costs of planting and management of the designed spaces [79]. In Barranquilla, as mentioned above, green spaces have only been improved in recent years and, therefore, it is necessary to continue working to develop strategies for adaptation to Climate Change and improve the quality of life of citizens. Finally, different technological applications have been developed worldwide to improve pedestrians' mobility in cities. These applications have been developed for cities as Vienna, Austria [80]; Tokio, Japan [81]; Boston, USA [82]; Heidelberg, Germany [83]; and Victoria, Australia [37]. Furthermore, de Oliveira et al. (2019) [84] developed a mobile phone application to create global maps of the spatial variability of thermal comfort indexes and meteorological parameters. In this paper, for the first time, a user-friendly mobile phone application for the citizens of Barranquilla, Colombia was developed. This application identified routes based on images captured by a drone during time intervals with highest daily temperatures and allows the members of the Simón Bolívar University to choose the routes with the best thermal comfort when they move among the different headquarters. The use of this technological tool will be fundamental to promote intelligent mobility in the investigated area of Barranquilla, which is indeed a first step to enhance its future transformation into a sustainable smart city.

5. Conclusions

Nowadays, it is necessary for cities to rapidly adopt measures to ensure the mobility of citizens in a comfortable and safe way. However, due to the lack of knowledge, research, application design and development, and user-friendly technological tools, pedestrians often unconsciously choose their mobility routes in cities transiting through thermally uncomfortable areas (e.g., sunny areas), exposing themselves to the negative effects of high

temperatures. The use of drones to identify the most thermally comfortable routes for pedestrian mobility can become a fundamental tool for urban and landscape planning in cities where high temperatures are recorded. Further, the use of drone images and tree inventories may improve planting programs and the urban planning of eco-friendly and people-centered walking environments, greatly improving urban mobility.

Access to cutting-edge technology (e.g., thermal imaging cameras, sensors networks, and computer vision technology) in developing countries is still a relevant limitation to evaluate sound walking environments. However, results obtained in this paper demonstrate that the simple use of drone images together with the measurement of air temperature and humidity and a tree inventory allowed to develop an easy to apply and replicable methodology to identify routes with the best thermal comfort for pedestrians during intense heat hours. Furthermore, this methodology is very useful for designing sustainable tree planting activities to improve thermal comfort, e.g., to identify local trees' genera best adapted to adverse climatic conditions such as high temperatures, droughts, poor soil conditions, and strong winds. Indeed, increase in vegetation cover is essential for improving the comfort of sidewalks and the associated thermal comfort of pedestrians and therefore inclusive, safe, resilient, and sustainable cities and communities in accordance with SDG 11.

Last but not least, it is necessary for pedestrians to have technological tools that allow them to improve their conditions of mobility and know at any moment the best available potential routes. The mobility maps designed here serve as input to develop a mobile phone application that can be used by all members of the Simón Bolívar University to improve their thermal comfort during their daily mobility between headquarters. This type of study could be easily replicated in other areas of the city where there is significant pedestrian traffic, e.g., areas close to hospitals, schools, shopping malls, businesses centers, etc. Further research is needed to adapt citizens to the high temperatures recorded in cities, e.g., by integrating drone-borne thermal imaging and automated pedestrian count with artificial intelligence. This will allow for establishing, in real time, the pedestrian routes with the greatest thermal comfort and to design future sound tree planting programs on the routes with the highest temperatures.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/su17115211/su17115211/s1, Table S1. Temperature and humidity redorded in the different time intervals considered.

Author Contributions: Conceptualization, G.A., H.J.B.-A. and H.S.M.; methodology, G.A., H.J.B.-A., S.V.B., G.R.A., V.T.-C., B.S.R.V. and S.d.J.O.L.; formal analysis, G.A., H.J.B.-A., S.V.B., G.R.A. and V.T.-C.; investigation, G.A., H.J.B.-A., H.S.M. and M.A.I.-N.; resources, G.A. and H.J.B.-A.; data curation, H.J.B.-A., S.V.B., G.R.A., V.T.-C., P.F.C.A. and K.A.A.-R.; writing—original draft preparation, G.A. and H.J.B.-A.; writing—review and editing, G.A. and H.J.B.-A.; funding acquisition, H.J.B.-A., H.S.M. and M.A.I.-N. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by the Sistema General de Regalias (SGR) de Colombia under grant number BPIN 2022000100074 and the Simón Bolívar University.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: Data are contained within the article.

Acknowledgments: This work is a contribution to the Andalusia (Spain) Research Group RNM-373 and Center for Research on Biodiversity and Climate Change-ADAPTIA.

Conflicts of Interest: The authors declare no conflicts of interest. The funders had no role in the design of the study; in the collection, analyses, or interpretation of the data; in the writing of the manuscript; or in the decision to publish the results.

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