

Article

Microclimatic Landscape Architecture: From Theory to Application

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Abstract: Global climate change and urban heat island intensification are making many cities dangerously hot during heat waves. There is a need for a clear process for applying microclimate information in urban design to create cooler cities. A recent paper points out the gaps in research methodology and suggests the need for implementation-oriented research. It suggests action steps to take research from theory to practice. The framework has five steps, and in our paper, we have addressed four of those steps: (1) understanding the needs of designers; (2) integrated research on urban microclimate factors; (3) development of guidance methods for better design; and (4) developing user-friendly tools. To address the first step, a group of Chinese landscape architects was given a questionnaire and it was found that they perceived principles and guidelines as being the most useful microclimatic design methods. The second step was addressed through a case study with on-site measurements and modeling. In step 3, microclimate information was used to redesign the site. The process that followed addressed the fourth step by illustrating user-friendly tools.

Keywords: microclimate; landscape architecture; urban design; urban heat island; urbanism; urban ecology; global climate change; thermal comfort



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1. Introduction

Over the last few decades, measurements have revealed a warming trend in the earth's climate [1–3]. Furthermore, there is compelling evidence that the expansion of urban heat islands exacerbates this effect in urban settings [4,5]. The combination of these two processes raises the temperature of the outdoor environment, having far-reaching influences on human thermal comfort and public health [6,7]. This phenomenon will cause a wide range of diseases and lower the quality of life in cities [8]. Living in a hotter urban area will increase the risk of heatstroke and other heat-related illnesses during heat waves, as well as the risk of developing chronic health problems because hot weather discourages people from going outside and walking [6,9].

According to studies, these effects can be mitigated through proper site planning and design, but only if the designer understands how microclimates are created in an urban environment and how to manage microclimates [2,10]. For example, Declet-Barreto's study discovered that a net cooling of air underneath or around canopied vegetation ranged from 0.9 °C to 1.9 °C during the hottest time of day in an urban core neighborhood park in Phoenix, Arizona [11]. According to Lai's research, on summer days, changing the urban geometry, planting vegetation, using cool surfaces, and incorporating bodies of water, resulted in a median reduction in air temperature of 2.1 K, 2.0 K, 1.9 K, and 1.8 K, respectively [12]. Furthermore, according to Zhang's research, the integrated microclimatic design method produced a high-performance design that reduced outdoor discomfort time by 25% in the summer [13].

Recently, there has been a growing call in academia for applying microclimate knowledge into landscape architecture [2,14]. Brown [15] proposed that microclimatic design can

mitigate the adverse effects of global climate change. Landscape planners and designers have the potential to minimize the effects of extreme climatic conditions and should concentrate their efforts on climate adaptation [15]. Brown et al. [16] proposed that heat waves in many climates will create outdoor environments in which people are at high risk of heat stress, but that appropriately designed parks can mitigate the risk. Yang et al. [17] reported that a climate-responsive landscape design could create a more livable urban microclimate that is comfortable for humans. Furthermore, some studies have pointed out the urgent goals for modern urban planners and landscape architects: improving and optimizing the urban thermal comfort environment through effective microclimatic modification strategies, as well as fully utilizing a city's existing natural resources and climatic conditions, for achieving sustainable urban development [18–20].

In recent years, an increasing number of landscape architects have been paying attention to microclimate issues and correspondingly have developed a lot of outstanding projects that address specific microclimatic issues. For example, in Paris, France, for mitigating the heat island effect, the project Redevelopment Place de la Republique used reflective ground surfaces to minimize solar absorption and used multi-row tree planting patterns of trees to provide shade in the summer and support the cooling effect [21]; in Mandai Zoo in Singapore, an innovative technology called Dry Mist was used to create a cooling effect for visitors [22]. Despite the fact that many projects involve microclimate modification, it is difficult to find examples of projects that have integrated microclimates into landscape architecture throughout the design process using research findings as a guide.

The approaches about applying microclimates into landscape architecture have been widely reported in the literature. A review of the related literature from 1995 to 2020 was conducted to categorize these methods into four categories [23]. The keywords in the reviewed article, as well as the understanding of the article, aided in the identification of these four types, as shown below:

1. Investigating and developing principles and guidelines. It discusses the broad and fundamental laws of microclimatic design, as well as provides a broad indication and outline of conduct. It is divided into two sections, the first of which contains principles and guidelines for achieving a specific goal, such as tree species selection guidelines [24]. The other provides principles and guidelines for a broad goal, such as creating thermally comfort outdoor space [25,26].
2. Discussing and recommending strategies. It was primarily concerned with making specific suggestions and recommendations to improve thermal comfort or energy efficiency. There are two types of strategies: object-oriented strategies and goal-oriented strategies. Object-oriented strategies focused on landscape elements (e.g., vegetation, water, etc.) and microclimate parameters (e.g., wind), whereas goal-oriented strategies concentrate on one or more specific goals, such as passive cooling strategies and thermal comfort mitigating strategies [27–29]. Changes in urban geometry, planting vegetation, using cool surfaces, and incorporating bodies of water are all common object-oriented strategies [12].
3. Mapping, the process of creating a map. This method effectively connects necessary microclimate information with spatial information and clearly represents the resulting information. It can be divided into three approaches: directly creating maps using microclimatic software (such as ENVI-met software, Rayman software, etc.), mapping using non-software methods (such as photographic and video techniques), and combining maps obtained in various ways to create new maps using ArcGIS software [23].
4. Applying various evaluation methods. Evaluation is an important part of using microclimates in landscape architecture because it provides a systematic way to examine an intervention or a practice to see how well it accomplishes its objectives. It can be divided into three parts: (1) examine the effect of constructed environments, (2) evaluate simulation outcomes, and (3) evaluate a specific type of landscape. These methods all play their respective roles at various stages of design. Mapping dominates

the process of site inventory and analysis, principles and guidelines are primarily used in design development, strategies are primarily used in detail design, and evaluation is focused on design assessment [23].

Although many approaches have been proposed, it is unclear whether landscape architects have learned how to use them or whether these methods are effective for landscape architects in different design stages. Research has identified ways that urban microclimates can be modified to reduce heat, but there is a need for a clear process for applying that information in urban design [23,30]. A recent paper [30] points out the gaps in research methodology and suggests the need for *implementation-oriented research*. It suggests action steps to take research from the theory to practice. The framework has five steps, and in our paper, we address four of those five steps: (1) understanding the needs of designers; (2) integrated research on urban microclimate factors including on-site measurements; (3) development of frameworks and guidance methods for better design; and (4) developing user-friendly tools.

2. Methods

2.1. Step 1: Understanding the Needs of Designers

Given that China has a large number of landscape practitioners [31] and an increasing number of journal articles on microclimate design by Chinese authors, understanding the knowledge and attitudes of Chinese landscape architects will help open up new avenues for microclimatic design practice.

The questionnaire was created by a Chinese online survey platform called Wengjuanxing. It was mainly spread through WeChat and Tencent QQ, which are widely-used Chinese multi-purpose messaging and social media apps. The questionnaire was distributed in WeChat via WeChat contacts and WeChat groups. WeChat contacts are mostly made up of the authors' former classmates, teachers, and colleagues who work in landscape architecture. These WeChat contacts helped spread this questionnaire to their landscape design-related WeChat groups, which are primarily divided into two types: school WeChat groups and firm WeChat groups. The school WeChat group mainly includes student WeChat groups from Tsinghua University, Peking University, Tongji University, Southeast University, Beijing Forestry University, etc. The firm WeChat group mainly includes the Turenscape WeChat group and some small landscape design companies' WeChat groups. The questionnaires in Tencent QQ were primarily distributed among three types of QQ groups: 1. landscape design QQ groups of specific provinces or cities, such as the Hubei Landscape Design Group, Shenzhen Landscape Design Group, Suzhou Landscape design Group, etc.; 2. QQ groups for landscape software, such as Sketchup Communication Group and Lumion Technology Exchange Group; 3. Other landscape architecture related QQ groups. This type of QQ group is distinguished by having a group name that includes the words "landscape design", "landscape architecture", or "landscape architect", and has more than 300 members. Landscape Architects Communication Group, China Landscape Architects Union, Chinese Landscape Design, and so on are some examples. Every respondent who participated in this questionnaire and submitted their answers received a random amount reward, about USD 0.5, on the app. Only respondents who pass the screening question can continue to complete the rest of the formal question. This study collected 200 valid questionnaires (a questionnaire that completed all formal questions is considered a valid questionnaire in this study).

This survey also investigated the respondents' age and gender, but they are not included in the screening standards. The exclusion criteria of this study were listed as follows: 1. Without bachelor's degrees. 2. Not holding one of the following degrees: architecture, landscape architecture, horticulture or garden architecture, environmental art design. 3. Not working in one of the following organizations: design firms, government, colleges and universities, real estate companies, and consulting firms. 4. Not engaging in the following professional practical directions: municipal green infrastructure, landscape renovation,

ecological restoration, urban parks and common landscape projects, residential design, and resort planning and design. 5. Not having more than three months of work experience.

The formal questions aimed to learn more about how Chinese landscape architects think about microclimates and how they use it in their work. Respondents were first asked how frequently they used microclimate knowledge in their daily work and how important microclimates are to landscape design. Then they were asked about their understanding of the four methods for applying microclimates to landscape architecture and how they used them during the design process. After that, they were asked if they thought an evidence-based microclimatic design prototype could help them learn microclimatic design. According to the definition of evidence-based design (EBD), which is the process of designing a building or physical environment to achieve the best possible results based on scientific research [3], the term evidence-based microclimatic design prototype in the questionnaire refers to a typical example of applying it in the microclimate field. Finally, respondents were asked to rate the importance of the ENVI-met and COMFA models (the questionnaire see Appendix A).

2.2. Step 2: Integrated Research on Urban Microclimate Factors

For illustrating an integrated analysis of urban microclimate factors, a case study with on-site measurements and modeling was proposed. The research was conducted at College Station, Texas, in the United States, where an urban park called Thomas Park was renovated to improve thermal comfort. College Station has a humid subtropical climate with hot, oppressive summers and short, cold, and wet winters. The existing master plan is shown as follows (Figure 1).



Figure 1. Thomas Park's existing master plan.

The site's current climate data were collected using a Maxi-met station (GMX501 Compact Weather Station, Gill; Hampshire, UK) and a thermal camera (FLIR E5 Wifi, Teledyne FLIR; Wilsonville, OR, USA). The Maxi-met station is a high-tech compact weather station that uses international standards to measure meteorological and environmental parameters. The collected data are used to calibrate the ENVI-met and COMFA models.

The investigator selected several key points that would be expected, based on theory, to provide a wide range of microclimates and walked around Thomas Park to measure them. The measured time was between 1:40 p.m. and 4:10 p.m., 19 June 2021. The procedure was set as follows: the investigator started by taking measurements in an open area as far from buildings and trees as possible. This provided baseline data. The investigator then took measurements in a range of microclimates from a location, that is: in the sun and out of the wind; in the sun and in the wind; in the shade of a tree and out of the wind; in the shade of a tree and in the wind; in the shade of a building and out of the wind; and in the shade of a building and in the wind. A measurement in the middle of an asphalt parking lot, a play structure, and tennis courts were also taken. It is worth emphasizing that all the measurements were taken over as short a time as possible following which the investigator then went back to the base location and took another reading. That helped to show whether the prevailing conditions had changed during the measurements.

A thermal camera was used to collect terrestrial radiation data. The measured time was from 2:00 p.m. to 2:50 p.m., 23 June 2021. The measuring points are basically the same as above. The difference is that these measurements also included some areas that have specific activities in the proposed design. In order to acquire a complete picture of the terrestrial radiation, a person was receiving in each location, and from each study location was taken one image looking directly to the north, one to the west, one to the south, and one to the east.

2.3. Step 3: Development of Guidance Methods for Better Design

The next step was to develop frameworks for implementing existing microclimate design methods through illustrating a concrete design work systematically. This design project aimed to create a microclimatically pleasant urban park for human activities. According to the study [23], there are four methods of applying microclimate to landscape architecture throughout the entire design process: principles and guidelines, strategies, mapping, and evaluations (Figure 2).



Figure 2. Stages of the approaches/design process.

These four methods were applied to this design in the following way: firstly, the prevailing climate information of the Thomas Park was collected, which included annual and monthly solar radiation, air temperature, humidity, wind speed, and prevailing wind directions at the site. Then, in the stage of site inventory and analysis, mapping was used to demonstrate the information. Overlaying mapping was used to find the microclimatically appropriate areas for development. At this stage, historical information on the site's microclimate was evaluated. After gaining an understanding of the site's microclimate, we move to the next stage, design development. In this stage, the designers set a series of design goals and objectives, design principles, and design criteria. As mentioned above, the design goal is to provide a thermal comfort environment for human activities. To achieve this, the objectives are to control the site radiation in summer, control the wind in winter, and add more deciduous trees and design various activities.

Based on the goals and objectives, the principles and guidelines were developed, which consist of two parts: principles and guidelines for a general objective (achieve thermal comfort) and principles and guidelines for a specific objective (control a specific microclimate parameter). In this project, principles and guidelines for a general objective include: 1. The primary task is to control solar radiation, followed by controlling wind. Intercepting solar radiation is the most effective way to reduce the heat load on people [16]. In overheated periods (e.g., summer), the design primarily needs to control solar radiation. Control of the wind is a secondary consideration [25]. 2. Planting rate should be increased by at least 30%. In the business and other districts most commonly used during the day, it

is recommended that parks and other open spaces be designed with less than 50% paved area and at least 30% trees, shrubs, and other shades, while in residential districts that are mostly used during the night, parks and other open spaces are recommended to have more trees [32]. 3. It is necessary to add water features. A psychological case can be made that the very sound of water has a cooling effect upon people in a hot climate. Even if the source is not apparent, the sound creates a sense of anticipation and is an attracting force [33]. Principles and guidelines for a specific objective (control a specific microclimate parameter) include: 1. Prioritize using wood plants to control solar radiation and wind. The landscape elements that have the greatest influence on solar radiation in a landscape are generally wood plants and solid structures [25]. Trees are probably the most effective landscape elements in modifying wind speed and direction [25]. 2. Paying attention to the arrangement pattern of the tree. Tree-planting pattern affects both the distribution of air temperature and the degree of local heat transfer [34].

After the stage of design development, a number of strategies were proposed during the period of transformation of design development into detailed design. The strategies also include two parts. The first part is object-oriented strategies: 1. Evergreen plants are extremely valuable to this project and should be prioritized when planting. Deciduous plants can have a great effect in summer but virtually no effect in winter. Evergreen plants are most useful in winter wind modification but can also affect wind flow in the other seasons [25]. 2. Prioritize the use of centralized water. Centralized water is very effective in regulating the partial microclimate while scattered water can improve the uniformity of microclimate; however, if each water area is too small, the regulating effect could be diminished [35]. 3. Arrange water close to the windward area. When the centralized water is selected, the water should be arranged close to the windward area of summer dominant wind direction. In this position, the water body's cooling effect could cover more areas of residential district [35]. The second part is goal-oriented strategies. In this project, this is shown as designing tree planting patterns according to the specific purpose. The cornered tree-planting, surround tree-planting, and no tree-planting patterns allow for higher ventilation, while the focused tree-planting and multi-row tree-planting patterns cause lower wind velocities and associated ventilation [34].

Design solutions were proposed after careful consideration of principles and guidelines, as well as strategies. First, more evergreen and deciduous plants, particularly oaks, should be added. More activities were suggested and incorporated into the trees. Second, create appropriate tree-planting patterns, such as the focused tree planting pattern, surrounded tree planting pattern, and multi-row tree planting pattern. Windbreaks can be created with focused tree planting patterns and multi-row tree planting patterns. While the surrounding tree-planting pattern benefits higher ventilation, it is primarily used in areas near water, where it is ideal for bringing more water vapor to the surrounding area. Third, add cooling amenities such as splash pad, fog installation, and swimming pool, etc.

Diverse microclimatic strategies and other design strategies need to follow microclimatic principles and guidelines. When the detailed design was completed, the design impact should be assessed. It can clearly and directly show the benefits that the design can provide. The proposed master plan is shown as follows (Figure 3).

2.4. Step 4: Developing User-Friendly Tools

In this study, microclimatic design impacts are simulated and evaluated using the ENVI-met and COMFA models. ENVI-met is a simulation software for the urban microclimate. The software can carry out computer simulations on the microclimate of small and medium-scale cities, comprehensively consider the influence factors of the microclimate, and can evaluate the influence of environmental factors such as the atmosphere, vegetation, buildings, and materials. The COMFA model is a tool for evaluating the thermal comfort of the human body, mainly used in the landscape field. Its characteristic is to provide the corresponding thermal comfort assessment by calculating the human energy balance under a given outdoor space condition.



Figure 3. Thomas Park’s proposed master plan.

Three different locations on the site were chosen to compare the microclimate factors and thermal comfort levels before and after the design. There are six spots: E1, P1, E2, P2, E3, and P3 (the naming method is the first letter of existing or proposed plus the serial number of the chosen location, see Figure 4).



Figure 4. Selected simulation locations on the site.

These three locations were selected because of the following three reasons: First, the proposed design has three different areas: recreation area, sports area, and green adventure area. The selected three locations can represent the three specific areas, respectively. Second, the three locations have similar existing site conditions and different proposed microclimatic designs: P1 (proposed design in the location 1) has dense trees and a small area of water; P2 has dense trees but without water; and P3 has relatively dense trees and a large area of water. These can be used to compare how different microclimate interventions aided in improving thermal comfort in the COMFA models (Table 1). Third, the graphs show that the difference between before and after in these three locations is quite noticeable, implying that thermal comfort in these areas may change dramatically before and after design.

After comparing the data collected by the Maxi-met station with data from the local historical weather report, the calibrated data were entered into the ENVI-met to perform the simulation. The maps of air temperature, wind speed, solar radiation, and relative humidity were developed in the ENVI-met.

Table 1. The human comfort feelings related to the budget values.

Budget W/m ²	Description
<−150	Would prefer to be much warmer
−150 to −50	Would prefer to be warmer
−50 to 50	No change
50 to 150	Would prefer to be cooler
>150	Would prefer to be much cooler

To acquire initial parameters for running COMFA models, the above maps were converted into corresponding specific values. Two methods were used in the calculation. Considering the air temperature, wind speed, and relative humidity did not change much throughout the site in the simulation, the mean of the Max and Min values in the maps was used as the corresponding value. Calculating the value of solar radiations used a different method. First, the area of different pixels was multiplied by their corresponding intervals, then they were added up, and, finally, the total area of the whole area's pixels was divided. After that, the value of air temperature, wind speed, solar radiation, and relative humidity were entered into the COMFA models to calculate the energy budget values. The COMFA method is based on the following basic formula, which expresses a person's energy budget in an outdoor environment.

$$\text{Budget} = M + \text{Rabs} - \text{Remit} - \text{Evap} - \text{Conv}$$

In order to obtain more accurate results, the value of terrestrial radiation was manually calculated and entered into COMFA models. The calculation of terrestrial radiation is based on the following formula:

$$L = 0.75 \times ((0.95 \times 5.67E - 0.08) \times ((T_{\text{sf}} + 273.15)^4))$$

The thermal camera measurement provides surface temperature maps. The value of surface temperature can be calculated using methods similar to those used to calculate solar radiation values. The mean value of the four directions was used.

3. Results

3.1. The Needs of Designers

Design can create pleasant microclimates, yet there are still many places being built that are not thermally comfortable. It would be valuable to know what landscape architects know about designing microclimates, and why they are or are not using that information in design.

3.1.1. Basic Information of the Questionnaire

Three questions were asked to ascertain the interviewees' basic information: gender, age, and whether or not they had experience studying or working abroad. The statistical result shows that the number of male interviewees was slightly higher than the number of female interviewees, with 52% of male interviewees and 46% of female interviewees; 98% of people responded to this question. A few people skipped some questions, so the total sum of the options was not 100%. The age group was primarily under 35, with under 25 accounting for 38%, and 26 to 35 accounting for 46%. It was found that the interviewees were mostly young landscape practitioners. The survey results on working years support this point as well. The interviewees with work experience ranging from three months to one year having the highest proportion, accounting for 31%, followed by those with work experience ranging from one year to three years, accounting for 23%. Sixteen percent of interviewees had worked for more than 5 years, which was the same as the proportion of people who had worked for 3–5 years and slightly higher than the proportion of people who had worked for 0 to 3 months, who were excluded from this survey. Furthermore, 30% of those respondents had worked or studied abroad, while 69% had not.

3.1.2. Understanding and Application of Microclimate

Question 1 to Question 2: Attitudes towards Microclimate

The first two formal questions asked respondents to estimate how often they use microclimate knowledge in their landscape design work and to rate the importance of taking microclimate issues into account when designing a landscape. The results show that 68% of respondents would consider microclimate issues in their landscape design work, while 31% would not; the most common situation among the interviewees is that they would occasionally consider the microclimate. A total of 72% of respondents believe it is critical to consider microclimate issues when designing a landscape, while 16% disagree; the remaining 12% were neutral.

Question 3 to Question 6: The Most Commonly Used Microclimatic Design Method and Its Use according to Which Design Stage

The results from questions 3 to 6 show that principles and guidelines are the most commonly used microclimatic design methods (see Figures 5 and 6), and they are most commonly used in the background study stage of landscape design work (see Figure 7). A total of 53% of interviewees understand these four methods of integrating microclimate into landscape architecture, while 45% of interviewees do not. Those who understand the four methods and those who do not were asked to respond separately (see Appendix A). According to the results, whether or not those who understand these four methods choose them directly, or those who do not understand these four methods choose them after reading the explanation, the selection of principles and guidelines still took the largest proportion, accounting for 34%. The difference between the two groups of people is that among those who understand the four methods, the second largest proportion of choice is mapping, which accounted for 29%, while among those who do not understand the four methods, the second largest proportion of choice is strategies, which accounted for 32%. The least commonly used method among those who understand the four methods is evaluation, which accounted for 7%, while the answer among those who do not understand the four methods is mapping, which accounted for 14%. In terms of the average of the choices of the two groups of people, the least number of people chose evaluations, accounting for 11%, followed by mapping, accounting for 21%.

Question 7 to Question 13: Attitudes towards Microclimate Design Prototypes and Microclimate Evaluation Software

The results of question 7 show the respondents' attitudes toward the evidence-based microclimatic design prototype. According to 75% of respondents, an evidence-based microclimatic design prototype can aid in learning microclimatic design. Only 10% of respondents polled disagreed with that statement. The responses to questions 8 through 13 reveal the respondents' knowledge of, and attitudes toward, the Envi-met and COMFA models. The Envi-met was recognized by 41% of the respondents. Envi-met is important to landscape design according to the 47% of respondents who are familiar with it, whereas 34% believe it is not. After reading the explanation, 58% of those who are unfamiliar with the Envi-met believe it is important, whereas 15% do not. COMFA models are understood by 37% of respondents, with 65% of those who understand COMFA models believe they are important in landscape design, whereas only 12% believe they are not; 56% of those who do not understand COMFA models and made a decision after reading an explanation about them believe it is important, whereas 15% do not.

Question 14: Interviewees' Thoughts on the Use of Microclimate

Question 14 was an open-ended question, whereby interviewees were asked their thoughts on the use of microclimate in landscape design. According to the results, the majority of interviewees support the use of microclimate in landscape architecture and believe it has a promising future. A variety of advantages of using microclimate in landscape design were mentioned by interviewees, including humidity regulation, heat island

mitigation, and plant combination design guidance, etc. While a few interviewees emphasized the effects of microclimate on the urban environment, water systems, and materials, the majority of responses focused on the effects of human and plants, with the majority of respondents believing that microclimate is primarily used in the design of small and medium scale landscapes, particularly in Chinese gardens and residential green spaces. At the same time, they stated that the applications of microclimate are currently very limited in China due to the following reasons: 1. In the landscape design industry, there is a lack of investment in microclimate issues. One interviewee believes that the concept is appealing, especially as current greenhouse effect is intensifying by the year. He further believes that issues such as what kinds of changes can be brought about before and after the specific application, what are the input costs, and whether the price/performance ratio is high enough need to be further discussed. 2. There are a lack of concrete methods and cases to guide design practice. One interviewee provided a significant comment that microclimate analysis includes various analysis methods, which may be too complicated for landscape architects, so they usually only use some basic microclimate knowledge to assist the design. 3. Although microclimate is widely used in some specific landscape practices, the importance of microclimate to the field of landscape architecture is not widely recognized by Chinese landscape architects. This was clearly expressed by an interviewee who said microclimate has not emerged as a major design factor or design theme. In regular landscape design, it is easily be overlooked.

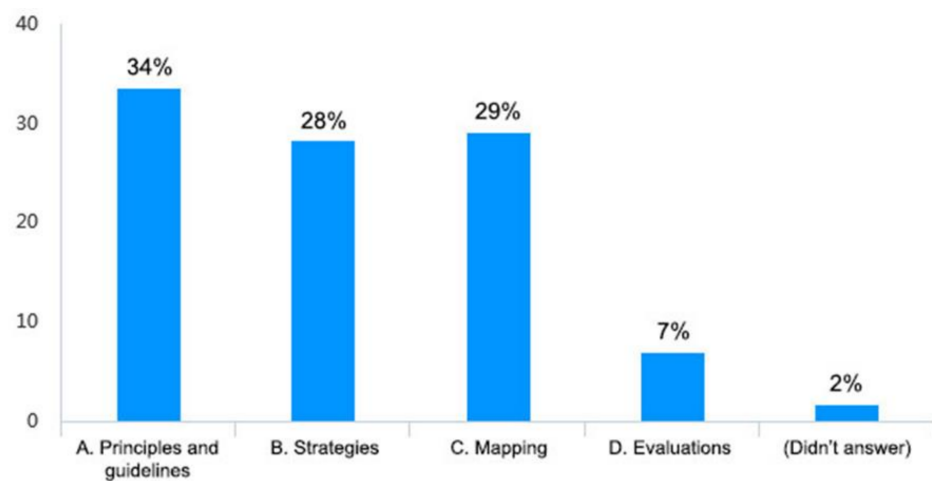


Figure 5. Question 4. The most commonly used microclimatic design method (respondents understand the four methods).

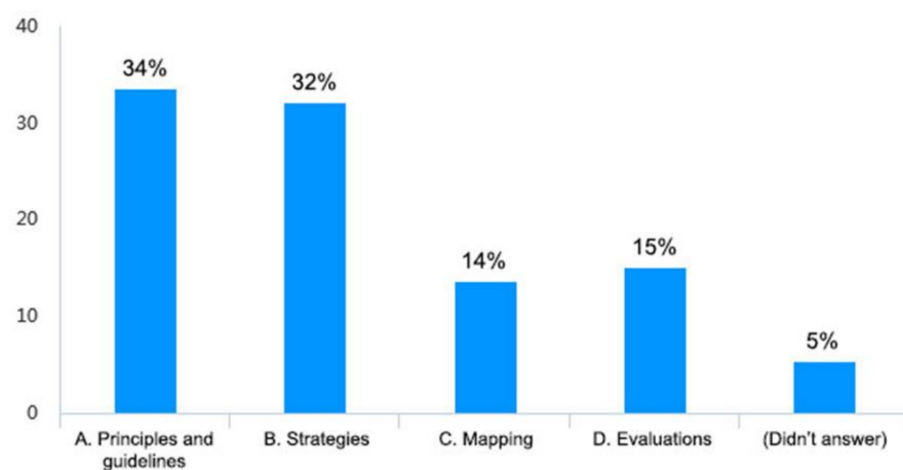


Figure 6. Question 5. The most commonly used microclimatic design method (respondents not understand the four methods).

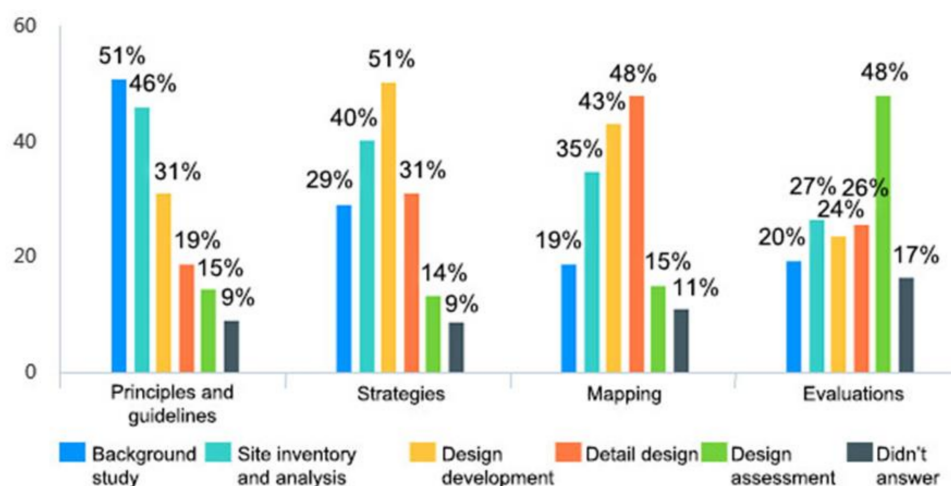


Figure 7. Question 6. The microclimatic design methods in different design stages.

3.2. Urban Microclimate Measurements

3.2.1. Maxi-Met Station

The field measurement results of the three locations are shown below (Table 2).

Table 2. Maxi-met Station results.

Location	E1	P1	E2	P2	E3	P3
Time	1:54–2:04	1:54–2:04	1:40–1:50	1:40–1:50	1:40–1:50	1:40–1:50
Condition	In the sun out of the wind	In the sun out of the wind	In the sun in the wind	In the sun in the wind	In the sun in the wind	In the sun in the wind
Wind speed (m/s)	0.9	0.9	1.2	1.2	1.2	1.2
Wind direction	215	215	152	152	152	152
Temperature (°C)	33.6	33.6	33.5	33.5	33.5	33.5

After collating the data, these three locations all adopted the south wind at 2 p.m. on 19 June 2021, and 34 degrees Celsius as the initial parameters for running ENVI-met. As for the wind speed, E1 and P1 use 0.9 m/s, E2, P2, E3, and P3 use 1.2 m/s.

3.2.2. Thermal Camera

According to the formula,

$$L = 0.75 \times ((0.95 \times 5.67E - 0.08) \times ((T_{sf} + 273.15)^4))$$

the terrestrial radiation value from the three locations chosen can be calculated. Terrestrial radiation values of 349 W/m², 344 W/m², and 342 W/m² were used to run COMFA models for E1, E2, and E3, respectively.

3.3. Guidance Methods: Modeling and Simulation

3.3.1. ENVI-Met

The changes in basic microclimate parameters before and after the design are shown in the table below (Table 3). The table shows that the air temperature, wind speed, and relative humidity did not change significantly after design. However, after the design, the solar radiation has changed noticeably.

Table 3. ENVI-met results.

Location	E1	P1	E2	P2	E3	P3
Air temperature (°C)	32	31	31	31	32	31
Wind speed (m/s)	0.6	0.5	1.1	0.7	0.9	0.7
Solar radiation (W/m ²)	635	291	567	289	701	368
Relative Humidity (%)	55	60	55	58	55	57

The MRT is one of the most important microclimate parameters governing human energy balance. It can be seen from the graph that the MRT values of the three selected areas are significantly reduced after the design (See Figure 8).

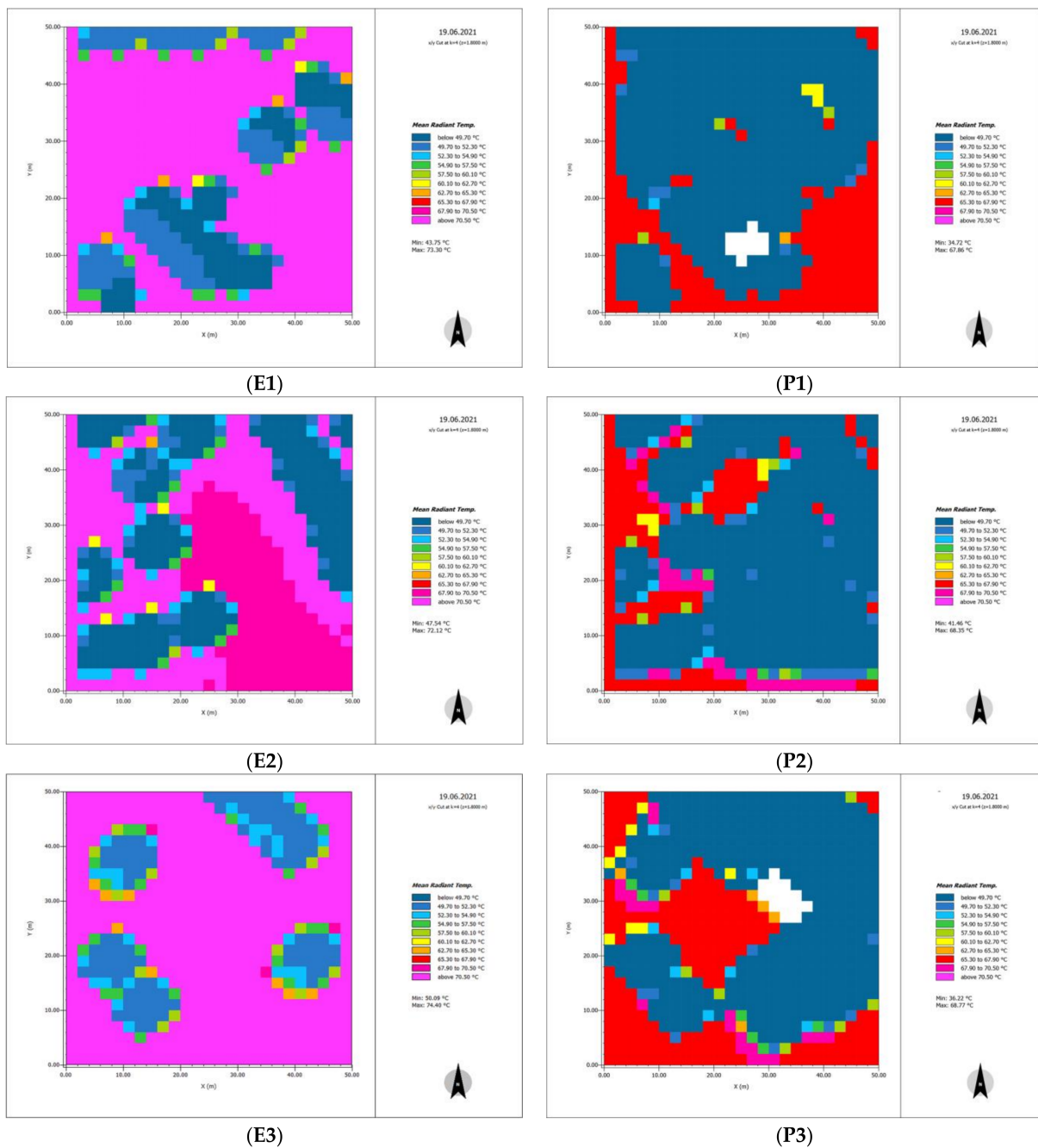


Figure 8. Mean radiant temperature results (The more blue areas there are, the lower the temperature; the white represents the building).

3.3.2. COMFA Models

Entering the microclimate parameters of air temperature, wind speed, humidity, solar radiation, terrestrial radiation, and other default parameters into the COMFA models yields energy budget values. The end result is as follows (Table 4). By comparing the energy budget values description (Table 1), it can be found that the thermal comfort level of all the three locations improved by one level after the design.

Table 4. COMFA models results.

Location	E1	P1	E2	P2	E3	P3
Energy Budget Values (W/m^2)	184	116	162	118	199	134
What the Budget Values mean for a Standing Adult	Would prefer to be much cooler	Would prefer to be cooler	Would prefer to be much cooler	Would prefer to be cooler	Would prefer to be much cooler	Would prefer to be cooler

4. Discussion

4.1. Needs of Designers

According to the findings, most Chinese landscape architects have a basic understanding of microclimate and will take it into account in their daily work. Nonetheless, they can still improve their knowledge of microclimatic design. Many Chinese landscape architects have a broad understanding of microclimates but a limited application of microclimatic design methods such as mapping and evaluations. The findings clearly demonstrate this point by demonstrating that principles and guidelines are the most commonly used method, followed by strategies, with mapping and evaluations occupying a lower frequency of use. According to the responses to question 6 (see Figure 8), mapping is primarily used in detail design, and mapping and evaluations are used infrequently during the background study and site inventory and analysis stages. This indicates that Chinese landscape architects are not fully aware of the importance of microclimate analysis in the early stages of design. Furthermore, given that evaluations are the least frequently used method among respondents and that the majority are unfamiliar with the Envi-met and COMFA models, it is clear that Chinese landscape architects lack understanding and application of microclimate evaluation software. However, a large percentage of respondents believe these two programs are important in landscape design, implying that Chinese landscape architects are willing to use microclimatic tools but are now using them less due to a lack of understanding. It is worth noting that these findings are slightly different with the statement in the previous study [23]. The previous study proposes that mapping mainly used in the transformation period of background study and site inventory and analysis, followed by detail design. In addition, the previous study mentioned that principles and guidelines should be used in the transformation stage of site inventory and analysis to design development, while the results of the questionnaire show that principles and guidelines are mainly used in background study by most Chinese landscape architects. When combined with the responses to question 14, we can infer that many Chinese landscape architects have only a rudimentary understanding of microclimate. They will be aware of the importance of microclimate at the start of the design process, but the use of microclimate in the design development is easy to overlook due to a lack of systematic theoretical method guidance.

To summarize, the findings are as follows: 1. Most Chinese landscape architects believe that microclimate is important in landscape design and will take it into account in their daily work. 2. Chinese landscape architects primarily use principles and guidelines, as well as strategies; they have a low-use frequency and understanding of mapping and evaluation methods. 3. The development of evidence-based microclimatic design prototypes is a positive response to Chinese landscape architects' desire to learn about microclimatic design. 4. Chinese landscape architects are unfamiliar with microclimate software, but

they are enthusiastic about it. By promoting microclimate software to Chinese landscape architects, it has the potential to improve their microclimatic design abilities.

Despite these findings, our research had several limitations. First, five percent of respondents did not respond to question 5, which asks them to choose the microclimatic design method they use most frequently in their work based on the given description. Possible reasons for the item nonresponse are that they do not use the microclimate design method in their daily work, or for other reasons, such as being overwhelmed with information, not understanding the terminology explanation, and so on. To reduce the bias introduced by missing answer options, it is necessary to include the option of not using microclimate design methods in daily work. Second, this study uses a convenience sample and may not represent the entire spectrum of background, education, and professional practices of Chinese landscape architects. Third, given that only a few papers mention the application of the COMFA model to design, and they are only published in English journals (e.g., [36,37]), the finding that 37% of the Chinese landscape architects surveyed are familiar with the model may reflect social disability bias.

4.2. Integrated Research and Design Guidance

The project design and its test results in this study support the previous research [23] by demonstrating the site's microclimate improvement after design and by clarifying the concrete process of employing four methods (principles and guidelines, strategies, mapping, and evaluations). After the design, the thermal comfort condition of the site was greatly improved: the value of mean radiant temperature (MRT) in ENVI-met simulation results was significantly reduced after the design; and the energy budget values in the COMFA models were also clearly decreased.

Among the three selected locations for simulation, the biggest change before and after the design was the addition of more trees and consideration of the use of water features. As a result, the simulation results can support Brown's theory that the primary task of creating thermal comfort is to control solar radiation and, generally, woody plants have the great influence on solar radiation in a landscape [16]. It also confirms Jin's claim that the water feature has a positive effect on improving outdoor thermal comfort, especially the centralized water body [35].

4.3. User-Friendly Tools

The advantage of this study is innovatively providing a prototype with microclimate design methods and matched effectiveness test methods. This makes it much easier for practitioners to understand microclimates and use them in design practices. There are two models that were used in the effectiveness test, ENVI-met and COMFA. The similarity of them is that both of them can be used to help evaluating thermal comfort conditions. While the differences between them are shown as follows: 1. Compared to COMFA models, ENVI-met has a wider range of application. It can simulate a variety of microclimate factors and perform all kinds of microclimate analysis and evaluation, such as solar analysis, building physics, wind flow, and so on. Its applicable evaluation area ranges from square meters to small and medium-sized cities; COMFA models place a greater emphasis on evaluating human body thermal comfort, which involves more human-related parameters. As a result, its applicable scale is tied to the range of daily human activities and is more limited than the range of ENVI-met. 2. In terms of display form, ENVI-met can generate images, which is clear and easy to understand. COMFA models do not have images, but have formulas and calculation processes, which help users understand the principles behind them. 3. The ENVI-met has a higher use threshold than COMFA models. To use ENVI-met, users must first master specific microclimate knowledge and software operation skills. While for running COMFA models, users only need to enter basic microclimate parameters into COMFA models to quickly obtain a human thermal comfort evaluation result. Considering the advantages and disadvantages of ENVI-met and COMFA models, their combination will make the microclimate evaluation more comprehensive.

One important component of the COMFA model is the reporting of the magnitude of the various streams of energy to and from a person's body. This allows the designer to see which stream is most problematic and address it specifically. Previous publications [25] has identified that control of radiation is most important during hot weather, whereas control of the wind is most important during cold weather. The convective cooling power of the wind is a function of the temperature difference between a person's skin and the air. In winter this can be very large, while in summer the difference can become almost zero, so no convective cooling would occur.

4.4. Limitation and Future Research

One limitation of the study is that the design evaluation did not test all microclimate design solutions, such as arranging water near the windward area and designing planting patterns. Although the thermal comfort of the designed environment has improved, it is unclear whether the other non-tested microclimate design approaches played a significant role in this. Furthermore, because this is a single case study, it is difficult to generalize the findings. More research is required to substantiate this.

By comparing the energy budget value before and after the three site designs, an unexpected finding in this study is that in a given same-sized small-scale landscape design, the site designed by densely planted trees with a small area of a central water feature has the best thermal comfort improvement effect, outperforming densely planted trees without a water feature and densely planted trees with a large scale water feature.

The following aspects could be the focus of future research: 1. Proposing more microclimate design prototypes and testing more microclimate design methods, such as selecting different planting patterns, combining water features and trees, and so on. 2. Using the comparative study method, investigate the most effective design method of combined landscape elements for improving thermal comfort. 3. Investigating a method for evaluating microclimate design methods at various stages of development. The microclimate design methods and a prototype are now available, but more research is needed to ensure that the methods are used effectively.

5. Conclusions

This study articulated an effective response to a recent study [30] that proposed action steps to move microclimatic design from theory to practice. The framework consisted of five steps, and we have addressed four of them in our paper: (1) understanding the needs of designers; (2) integrated research on urban microclimate factors including on-site measurements; (3) development of frameworks and guidance methods for better design; and (4) developing user-friendly tools. A fifth step that suggested linking research with economy and politics was beyond the scope of this study.

This study first identified *Principles and Guidelines* and *Strategies* as the two main methods used by Chinese landscape architects to apply microclimate information to their designs. *Mapping* and *Evaluation* were used less frequently. They also indicated a desire to learn more about microclimatic design and how they could use it more effectively in their practice. Then, an integrated study on microclimate factors was conducted using a case study with on-site measurements and modeling. Based on the above results, an *evidence-based method* for utilizing microclimate information in design was illustrated and tested. The results indicated a substantial increase in the thermal comfort levels of the designed sites. The process that was followed illustrated user-friendly tools. The combination of ENVI-met and COMFA models can serve as a user-friendly tool to assist landscape architects in optimizing their responses to climate-related environmental problems.

This study is a first step in identifying the needs and wants of practitioners and in providing a method by which they can apply microclimate information in landscape architecture. The growing body of knowledge published in scholarly journals should be similarly communicated to practitioners in understandable and effective ways so that landscape architects can apply the information to ameliorate future climates.

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Appendix A

The following are the formal questions part of the questionnaire:

1. Will you consider microclimate factors in your landscape design work?
 - a. Never
 - b. Rarely
 - c. Sometime
 - d. Often
 - e. Always
2. Do you agree or disagree with the following statement: It is essential to consider microclimate issues when designing a landscape?
 - a. Strongly disagree
 - b. Disagree
 - c. Neutral
 - d. Agree
 - e. Strongly agree
3. Do you understand the following common methods for incorporating microclimate into landscape design practice? Principles and guidelines, strategies, mapping, and evaluations. (Question skip logic: if you select Yes, jump to question 4; if you select No, jump to question 5.)
 - a. Yes
 - b. No
4. Please select the method you use most frequently in your work:
 - a. Principles and guidelines
 - b. Strategies
 - c. Mapping
 - d. Evaluations
5. Based on the following description, please select the method you use most frequently in your work:

The principles and guidelines method refers to using basic microclimate design rules and adhering to a broad indication and outline of conduct during the design process; the strategies method refers to the use of specific methods that can improve the site's microclimate environment rather than just tips that help guide in the right direction; the mapping method refers to the process of connecting microclimate information with the necessary spatial information through mapping, in order to display the final information more clearly; and the evaluations method refer to the use of software simulations to predict or test whether the microclimate of the practical project meets the expected goal.

 - a. Principles and guidelines
 - b. Strategies

- c. Mapping
 - d. Evaluations
6. If you use the methods listed above, at what stage of the design process do you use them (multiple choice)?

	Background Study	Site Inventory and Analysis	Design Development	Detail Design	Design Assessment
Principles and guidelines	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
Strategies	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
Mapping	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
Evaluations	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>

7. Do you agree or disagree with the following statement: An evidence-based microclimatic design prototype would be useful in assisting your learning microclimatic design?
- a. Strongly disagree
 - b. Disagree
 - c. Neutral
 - d. Agree
 - e. Strongly agree
8. Do you know the microclimate design software ENVI-met? (Question skip logic: if you select Yes, jump to question 9; if you select No, jump to question 10)
- a. Yes
 - b. No
9. How important do you consider ENVI-met to be in landscape design?
- a. Very unimportant
 - b. Unimportant
 - c. Neutral
 - d. Important
 - e. Very important
10. Based on the following description, how important do you consider ENVI-met to be in landscape design?
ENVI-met is a simulation software about urban microclimate. The software can carry out computer simulations on the microclimate of small and medium-scale cities, comprehensively consider the influence factors of the microclimate, and can evaluate the influence of environmental factors such as the atmosphere, vegetation, buildings, and materials.
- a. Very unimportant
 - b. Unimportant
 - c. Neutral
 - d. Important
 - e. Very important
11. Do you know the COMFA model? (Question skip logic: if you select Yes, jump to question 12; if you select No, jump to question 13)
- a. Yes
 - b. No
12. How important do you consider COMFA model to be in landscape design?
- a. Very unimportant
 - b. Unimportant
 - c. Neutral
 - d. Important

- e. Very important
13. Based on the following description, how important do you consider COMFA model to be in landscape design?
COMFA model is a tool for evaluating the thermal comfort of the human body, mainly used in the landscape field. Its characteristic is to provide the corresponding thermal comfort assessment by calculating the human energy balance under a given outdoor space condition.
- a. Very unimportant
b. Unimportant
c. Neutral
d. Important
e. Very important
14. What are your thoughts on the use of microclimate in landscape design?

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