

# Stand Density and Summer Thermal Environment: The Impact of Different Forest Types on Human Thermal Comfort

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## Abstract

As urbanization accelerates, the urban heat island effect has significantly impacted the ecological environment and public health. Plant communities, particularly different types of forests, play a crucial role in mitigating the heat island effect through transpiration and shading effects. This study explores the thermal environment regulation characteristics of evergreen forests, deciduous forests, and mixed forests across different seasons, with a particular focus on cooling benefits during the summer. The study also analyzes the influence of vegetation density and sky visibility factors on the thermal environment. The results show that the daytime temperature of evergreen forest (EF1) and mixed forest (MF1) ranged from 36°C to 38°C, whereas the temperature of the lawn (LA) rose to nearly 39°C. At night, the temperature of the lawn dropped sharply to 26°C, exhibiting a large diurnal temperature variation. The black globe temperature (from 14:00 to 16:00) showed smaller fluctuations in the evergreen forest and deciduous forest, with temperatures of 45°C and 47°C, respectively, while the black globe temperature of the lawn and control point reached 52°C and 50°C, respectively, demonstrating more dramatic temperature variations. Physiologically equivalent temperature (PET) values revealed that the lawn (LA) and control point (RP) had PET values of 44°C and 42°C during the day, which fell within the "hot" or "very hot" range, whereas the PET value of the evergreen forest (EF1) remained relatively low, in the "comfortable" range (around 35°C). The study suggests that urban green space design should prioritize the planting of evergreen and mixed forests, optimize canopy density, enhance ecological diversity, and avoid excessive exposure from lawns and open areas. Additionally, integrating techniques such as rooftop greening, vertical greening, and water body design can further improve the thermal comfort of urban green spaces and promote the development of livable green cities.

## Keywords

Microclimate; Human Comfort; Urban Heat Island; Plant Cooling.

## 1. Introduction

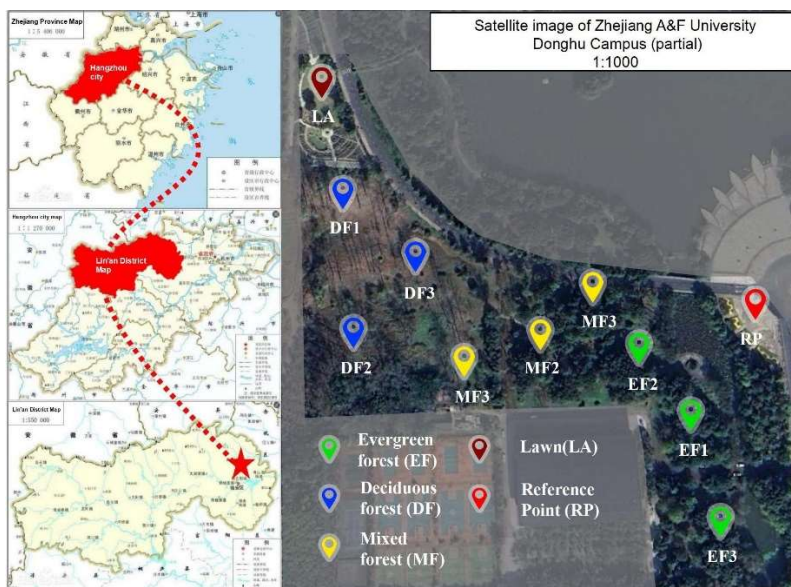
With the rapid acceleration of urbanization worldwide, the urban heat island effect has been intensifying, leading to increased local temperatures, air pollution, and other environmental issues that severely impact both the ecological environment and public health.[1] Plant communities effectively regulate urban temperature and humidity through transpiration and shading effects, alleviating the heat island effect.[2] Vegetation greening is considered one of the most cost-effective methods to mitigate the urban heat island effect.[3] Although previous studies have focused on the cooling benefits of plant communities, most have concentrated on a single season, overlooking the dynamic regulatory role of plant communities across different seasons.[4] Therefore, this study aims to explore the thermal environment regulation characteristics of plant communities in different seasons, with a particular focus on cooling benefits during the summer. It analyzes the cooling effects of different plant community types, such as evergreen forests, deciduous forests, and mixed forests, and investigates the

mechanisms of related influencing factors, including vegetation density and sky visibility factors.[5] The findings will reveal the seasonal variations of plant communities and their role in regulating the thermal environment, providing scientific evidence for urban greening planning. This research will help optimize green space configuration, enhance ecological benefits, and contribute to the development of livable green cities, addressing the challenges posed by climate change and further improving the quality of life and health of urban residents[6].

## 2. Research Methodology

### 2.1. Venue and Equipment

As illustrated in Figure 1, this study was conducted at the East Lake Campus of Zhejiang A&F University in Lin'an District, Hangzhou, Zhejiang Province. Lin'an is located in the northwest of Zhejiang Province and has a subtropical monsoon climate, characterized by a humid climate with an average annual temperature of 17.8°C and annual precipitation of 1454 mm. The area is predominantly covered by forested land, which accounts for 77% of the region, offering a favorable natural environment and unique ecological conditions. The East Lake Campus of Zhejiang A&F University covers 157.3 hectares, with a greening coverage area of 84.1 hectares. The campus has a high forest coverage and a diverse vegetation configuration, making it an ideal location for experimental research. Eleven measurement points were selected for the study, covering evergreen forests, deciduous forests, mixed forests, lawns, and control points. The evergreen forest measurement points were categorized by density into EF1 (high density), EF2 (medium density), and EF3 (low density). Similarly, three measurement points were set for the deciduous and mixed forests. Each measurement point covered a 15m x 15m area, with three trees planted in the low-density plots, five in the medium-density plots, and eight in the high-density plots.



**Figure 1.** Overview of the Research Location

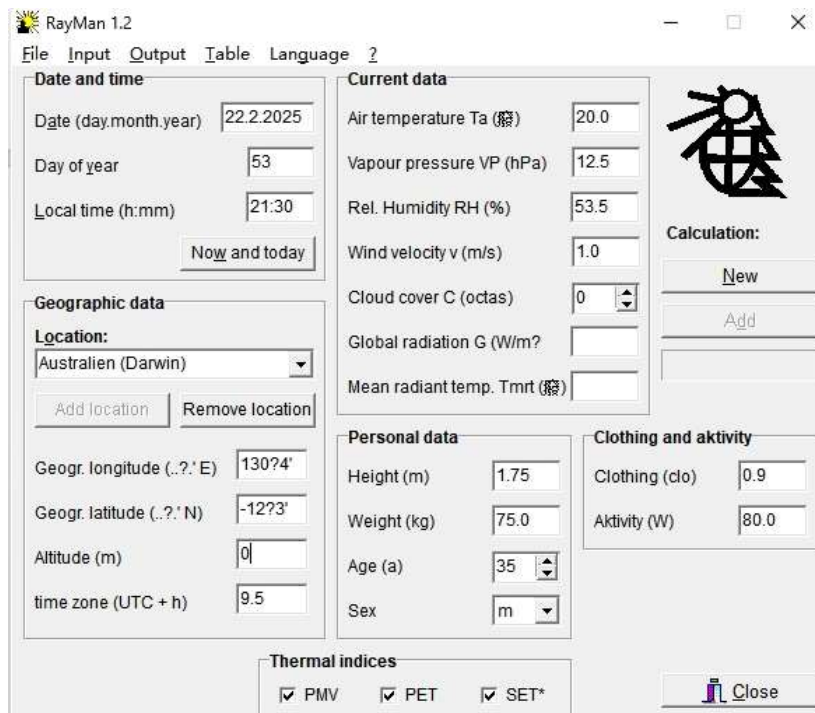
As illustrated in table 1, during the measurements, a small-scale meteorological station was used to monitor air temperature, relative humidity, and black globe temperature, while an infrared thermography camera was employed to capture surface temperature. Temperature data for each measurement point were recorded every two hours, with surface temperature obtained through the infrared thermography camera. These data allow for an analysis of the

impact of different vegetation densities on the microclimate, providing foundational data for further research.

**Table 1.** Information of Experimental Instruments

Instrument	Parameter	Range	Precision
AZ88162	Air temperature	-30°C ~ 70°C	±0.5°C
AZ88162	Relative Humidity	0.1% ~ 99.9%RH	±0.1%RH
TASITA642B	wind speed	0-45.0m/s	±0.2m/s±2%
AZ CHECKER 8778	Black Globe Temperature	0°C ~ 50°C	±0.6°C
HIKMICRO Handheld Infrared Thermometer or Thermal Imager	Surface Temperature	-40°C ~ 550°C	±0.1°C

## 2.2. Calculation of Thermal Comfort Index



**Figure 2.** RayMan 1.2 schematic diagram

To evaluate the impact of the Sky View Factor (SVF) on thermal comfort, this study employs the Mean Radiant Temperature (Tmrt) and Physiologically Equivalent Temperature (PET) as indicators for assessing the thermal environment.[7] Tmrt is a key factor affecting human thermal comfort, while PET combines the radiative environment and personal characteristics, reflecting subjective perceptions of comfort. The Tmrt and PET for different measurement points were calculated using RayMan 1.2 software, by inputting fisheye photographs and meteorological data. The calculations were based on the standard for Chinese adult males (height: 170 cm, weight: 70 kg), with summer clothing (0.5 clo) settings according to ISO 7730 and ASHRAE standards[8].

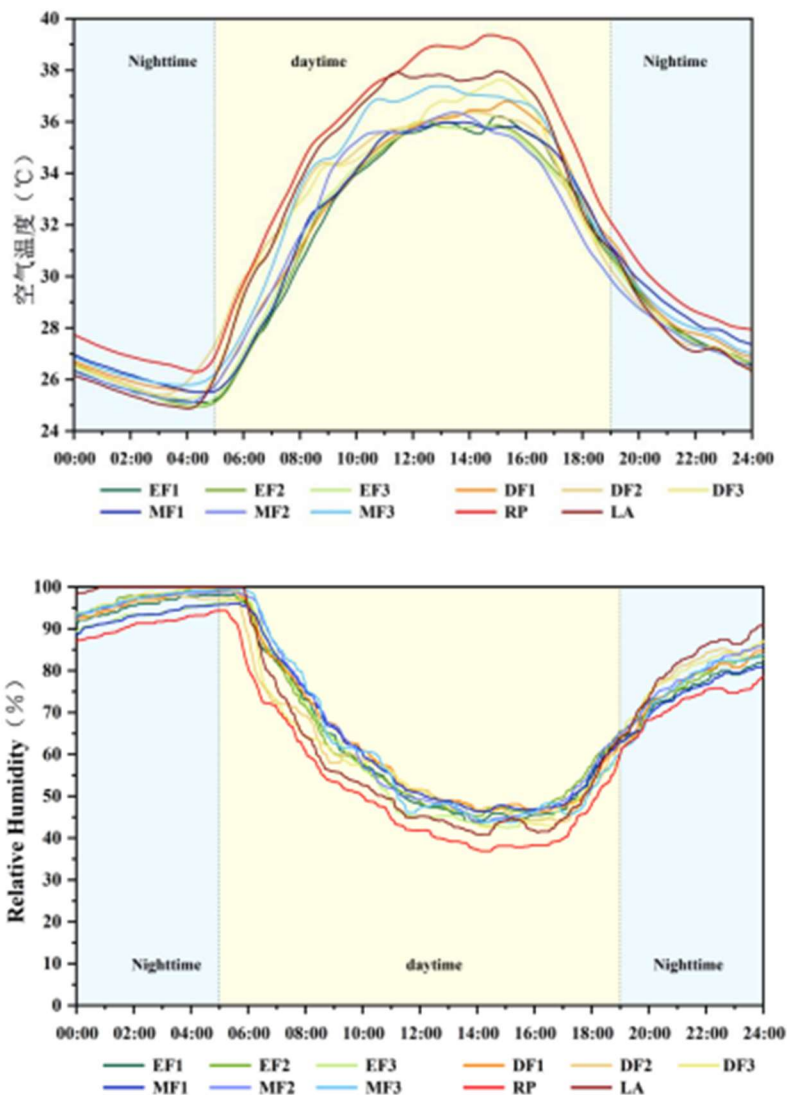
In addition, the Sky View Factor (SVF) was used to quantify the openness of the measurement points. Fisheye images were captured using a Canon EOS 6D Mark II camera and then imported into RayMan 1.2 software for analysis. All statistical analyses of the data were conducted using SPSS 26 software, performing normality tests and variance analysis. Tukey and Dunnett's T3 tests were employed to compare the differences between different sample points, and

Spearman's correlation coefficient was applied to explore the relationship between landscape factors and the thermal environment. Finally, a correlation heatmap was created to visually present the results. Based on these analyses, recommendations were proposed for improving the urban thermal environment and optimizing the design of outdoor activity spaces.

### 3. Results and Analysis

#### 3.1. Thermal Environment Characteristics of Different Forest Types in Summer

##### 3.1.1. Air Temperature and Relative Humidity



**Figure 3.** Diurnal Variation Trends of Air Temperature and Relative Humidity at Different Time Periods

According to the measurement data shown in Figure 3, the temperature is generally lower at night, with the peak temperature occurring between 14:00 and 16:00 during the day. Specifically, the peak temperatures of the evergreen forests (EF1, EF2, EF3) occur during the 14:00-16:00 period, with EF1 reaching over 38°C, EF2 at 37°C, and EF3 at 36°C. Nighttime temperatures are around 26°C, with EF1 and EF2 showing relatively stable temperature variations, while EF3 rises more slowly, resulting in a smaller diurnal temperature range.

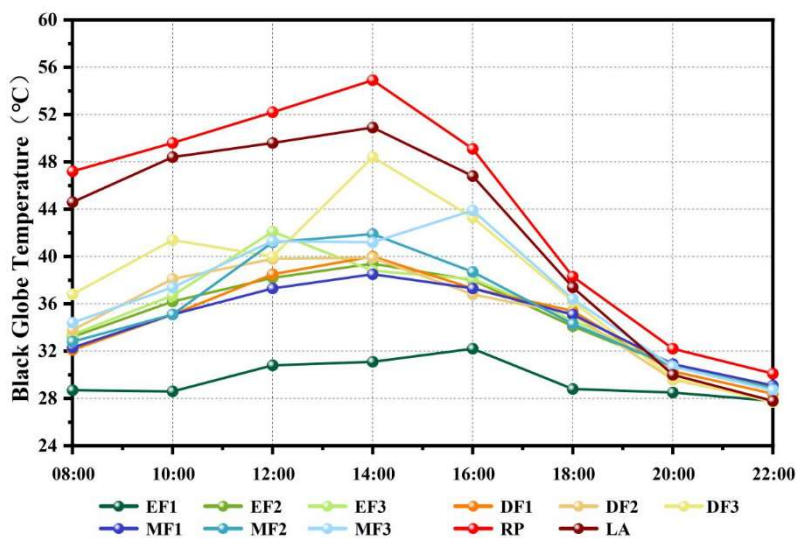
For deciduous forests (DF1, DF2, DF3), the daytime temperature variation is similar, with peak temperatures generally between 36°C and 37°C. DF3 has the lowest nighttime temperature,

around 24.5°C, while the other two measurement points maintain nighttime temperatures around 25°C. Mixed forests (MF1, MF2, MF3) also exhibit peak daytime temperatures in the range of 36°C to 37°C, with slightly higher nighttime temperatures, around 27°C. Compared to evergreen and deciduous forests, mixed forests show smaller temperature fluctuations, with quicker nighttime temperature recovery and a more moderate diurnal temperature range.

The temperature fluctuations at the lawn (LA) are the most significant, with a sharp increase during the day, reaching nearly 39°C between 14:00 and 16:00, noticeably higher than other measurement points. Nighttime temperatures rapidly drop back to around 26°C. The temperature variation at the control point (RP) is similar to that of the evergreen and deciduous forests, with daytime temperatures around 38°C and nighttime temperatures dropping to 26°C, showing a noticeable diurnal temperature difference.

In terms of relative humidity, most measurement points maintain high humidity levels at night, generally above 90%. During the day, humidity gradually decreases as temperature rises, with the lawn (LA) and control point (RP) showing the greatest drop, reaching minimum values of 40% and 45%, respectively. The humidity variation in evergreen forests (EF1, EF2, EF3), deciduous forests (DF1, DF2, DF3), and mixed forests (MF1, MF2, MF3) remains relatively stable, with the lowest humidity generally staying above 50%. In the evening, humidity gradually increases, returning to higher levels at night, demonstrating the vegetation types' role in regulating humidity.

### 3.1.2. Black Globe Temperature



**Figure 4.** Diurnal Variation Trends of Air Temperature and Relative Humidity at Different Time Periods

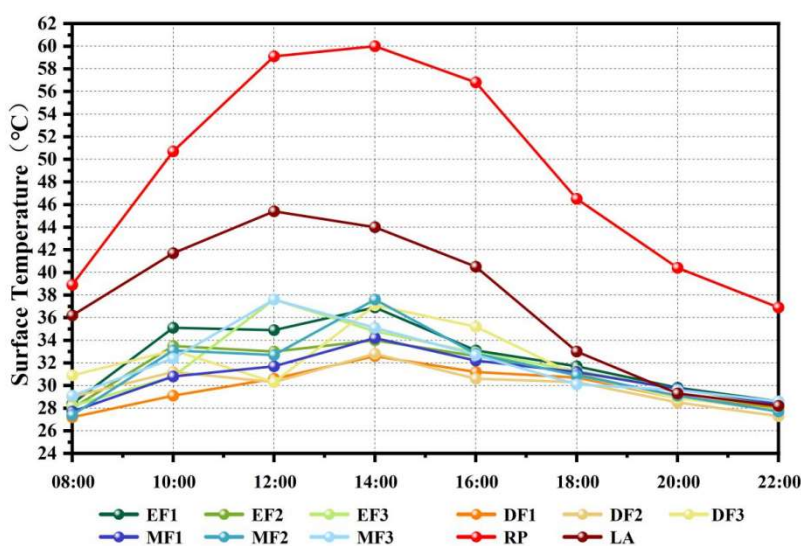
According to the data presented in Figure 4, the black globe temperature exhibits significant variations across different locations during the summer. The control point (RP) shows the greatest increase in black globe temperature during the day, rising sharply from about 30°C at 08:00 to nearly 50°C at 14:00, peaking at 52°C at 16:00, and then gradually decreasing, reaching around 32°C at night. In contrast, the temperature variation in Deciduous Forest 1 (DF1) is more stable, with an initial temperature of about 28°C at 08:00, rising to nearly 42°C at 12:00, then slowly decreasing to around 40°C at 16:00, and dropping to about 30°C in the evening. The fluctuations are notably smaller than those at the control point (RP).

The black globe temperature in Evergreen Forest 1 (EF1) also increases during the day, from 28°C in the morning to 38°C at 14:00, peaking at 36°C at 16:00. The overall temperature rise is smaller, and the nighttime temperature returns to 28°C. The black globe temperature at the

lawn (LA) increases gradually during the day, starting at 30°C at 08:00, peaking near 45°C, and then dropping back to around 30°C. The temperature fluctuations are less dramatic than those at the control point (RP), but the overall variation is relatively stable.

Deciduous Forest 3 (DF3) exhibits a moderate temperature increase, with an initial temperature of 28°C at 08:00, reaching nearly 43°C at 12:00, and then gradually decreasing to 41°C at 16:00, with nighttime temperatures returning to 28°C. Overall, the black globe temperature variations at the urban control point (RP) and the lawn (LA) are the most dramatic during the day, while the temperature fluctuations in forest types (EF, DF, MF) are relatively small.

### 3.1.3. Surface Temperature



**Figure 5.** Diurnal Variation Trends of Surface Temperature at Different Time Periods

According to the data presented in Figure 5, the surface temperature variation trends for different land cover types in summer are noticeably different. Below is an analysis of some points with significant temperature differences:

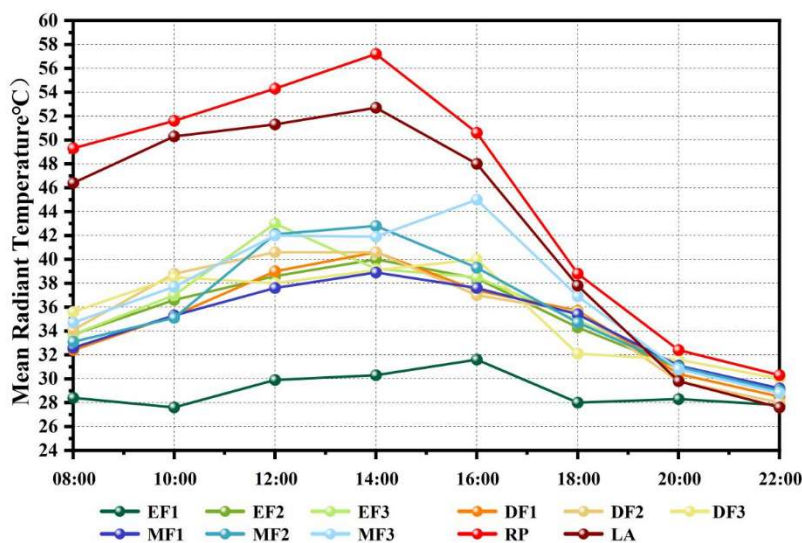
The surface temperature at the control point (RP) exhibits the most significant variation. Starting at around 28°C at 08:00, the temperature rapidly increases during the day, reaching nearly 56°C at 14:00, peaking at 60°C. Subsequently, the temperature rapidly decreases, dropping to around 38°C in the evening, and recovering to about 32°C by 20:00. The temperature variation at the control point is very large, displaying a clear ground radiation heat effect.

The surface temperature at the lawn (LA) also shows significant variation. Starting at 29°C at 08:00, the temperature gradually rises throughout the day, peaking close to 50°C. The temperature then gradually decreases to around 32°C. The temperature fluctuation at the lawn is smaller than at the control point (RP), but it still shows a noticeable diurnal temperature difference. The surface temperature at Evergreen Forest 1 (EF1) starts at 29°C in the morning, gradually increasing to nearly 42°C at 14:00. Afterward, the temperature begins to decline, reaching around 38°C at 16:00, and returning to about 30°C at night. The temperature fluctuation in the evergreen forest is relatively small, with a lower daytime temperature increase, reflecting the cooling effect of vegetation cover on surface temperature.

The surface temperature at Deciduous Forest 1 (DF1) starts at 29°C at 08:00, rising to a maximum value of about 43°C during the day. It then gradually decreases, reaching around 39°C at 16:00, and dropping to around 30°C at night. The temperature variation in the deciduous forest is slightly greater than in the evergreen forest, but overall, the changes are still

moderate. The surface temperature at Mixed Forest 1 (MF1) is relatively stable, starting at 30°C at 08:00, rising to a maximum value near 44°C during the day. The temperature then gradually drops in the evening, returning to around 30°C at night. The surface temperature increase in the mixed forest is between that of the evergreen and deciduous forests, with moderate changes. Overall, the surface temperature at the control point (RP) exhibits the most drastic changes, peaking near 60°C, with clear diurnal variations. The lawn (LA) also shows significant changes, with a peak temperature close to 50°C. In contrast, the surface temperature changes in evergreen forests (EF), deciduous forests (DF), and mixed forests (MF) are smaller, with peak temperatures generally ranging from 40°C to 45°C.

### 3.1.4. Mean Radiant Temperature



**Figure 6.** Diurnal Variation Trends of Mean Radiant Temperature (Tmrt) at Different Time Periods

Based on the data shown in Figure 6, the following analysis presents the diurnal variation trends of the mean radiant temperature (Tmrt) across 11 measurement points in the summer, with a focus on points showing significant differences: The mean radiant temperature at the control point (RP) exhibits the most dramatic variation. Starting at around 30°C at 08:00, the temperature increases sharply throughout the day, reaching nearly 55°C by 14:00, peaking at around 58°C at 16:00. Afterward, the temperature rapidly decreases, dropping to about 34°C by 20:00, and gradually returns to around 30°C during the night. The temperature fluctuation at RP is the largest, reflecting the typical ground radiation effect.

The mean radiant temperature at the lawn (LA) follows a similar trend to that of RP, but with smaller fluctuations. Starting at approximately 29°C at 08:00, the temperature gradually rises, reaching nearly 50°C at 14:00. It then starts to decline, dropping to 34°C by 20:00, and returns to around 30°C at night. While the fluctuations in temperature at the lawn are smaller than those at RP, there is still a noticeable diurnal temperature difference. The mean radiant temperature at Evergreen Forest 1 (EF1) changes more gradually. Starting at about 30°C at 08:00, the temperature increases slowly, reaching around 42°C by 14:00. The temperature then gradually decreases, dropping to around 39°C at 16:00, and returns to near 30°C at night. The temperature variation in the evergreen forest is smaller, with the peak temperature significantly lower than that at RP and the lawn.

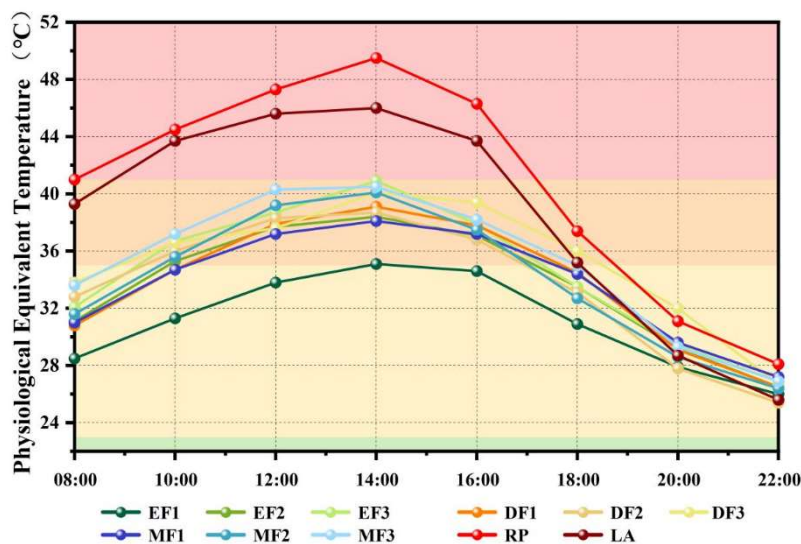
At Deciduous Forest 1 (DF1), the mean radiant temperature starts at 28°C, rising to a peak value of around 42°C during the day. It then decreases to about 38°C by 16:00, with a return to around 30°C at night. Compared to the evergreen forest, the deciduous forest has a faster temperature

increase, but the overall variation remains relatively steady. The temperature variation at Mixed Forest 1 (MF1) is similar to that of the evergreen and deciduous forests. Starting at 30°C, the temperature rises to around 43°C by 14:00, and then drops back to about 30°C at night. The fluctuation in temperature at the mixed forest is small, with relatively stable changes.

Overall, the mean radiant temperature variation at the control point (RP) and the lawn (LA) is the most significant, especially at RP, where the peak temperature exceeds 55°C and the night-time drop is rapid. In contrast, the temperature variation at the evergreen forests (EF), deciduous forests (DF), and mixed forests (MF) is more moderate, with smaller fluctuations and lower peak temperatures, reflecting the cooling effect of different vegetation types on the surface radiant temperature.

### 3.2. Summer Thermal Comfort Characteristics and Differences Across Different Forest Types

#### 3.2.1. Summer Thermal Comfort Characteristics under Different Forest Types



**Figure 7.** Diurnal Variation Trends of Physiological Equivalent Temperature (PET) at Different Time Periods

Based on the data presented in Figure 7, the diurnal variation characteristics of the summer thermal environment and the trends in Physiological Equivalent Temperature (PET) are evident. The data shows that PET fluctuates significantly during the day, with a clear diurnal pattern.

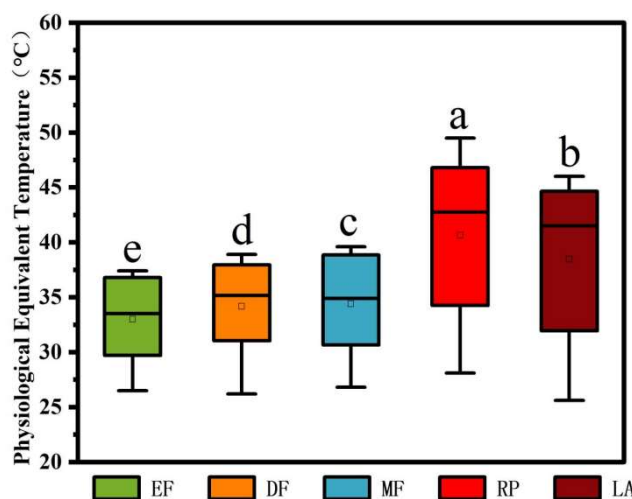
From 8:00 to 16:00, the PET values gradually increase, peaking between 14:00 and 16:00. During this period, temperatures approach or exceed 40°C, especially in open areas (RP) and high-density evergreen forests (EF3), where the temperature rise is the most pronounced. This reflects the strong sunlight and heat accumulation effects, making the thermal environment extremely hot. In contrast, PET values in deciduous forests (DF) and mixed forests (MF) are relatively lower, indicating their stronger cooling effect. In the evening, with the decrease in solar radiation, the temperature begins to decline. After 18:00, the PET values in evergreen forests, mixed forests, and deciduous forests start to decrease, but the cooling rate in open areas (RP) is slower, and the overall temperature remains relatively high. In contrast, the low-density evergreen forest (EF1) has a better cooling effect, with a faster drop in PET values.

Additionally, the comfort zones in the figure indicate that during the peak daytime hours, most areas' PET values fall within the "hot" or "very hot" range, particularly in open areas (RP) and high-density evergreen forests (EF3). However, low-density evergreen forests (EF1) and

deciduous forests (DF1, DF2) remain relatively warmer, staying within the "warm" or "comfortable" range. At night, the PET values in most areas gradually return to the "warm" range, but open areas and high-density evergreen forests still have higher temperatures.

Overall, the changes in the summer thermal environment demonstrate the regulatory effects of plant species and forest density on temperature. Evergreen and deciduous forests effectively reduce environmental temperatures, while open areas, lacking the shade and cooling effects of vegetation, exhibit higher PET values.

### 3.2.2. Differences in Summer Thermal Comfort among Different Forest Types



**Figure 8.** Differences in the Variation of Physiological Equivalent Temperature (PET) Across Different Forest Types

Figure 8 illustrates the differences in annual mean Physiological Equivalent Temperature (PET) among various forest types during summer, reflecting their thermal comfort characteristics. The boxplot data reveal the temperature distribution and thermal comfort levels of each forest type.

The evergreen forest (EF) exhibits the lowest PET values among all forest types, with a median value of approximately 35°C and a relatively compact distribution. This indicates that EF effectively provides cooler temperatures, demonstrating superior thermal comfort within a relatively cool range. The deciduous forest (DF) shows slightly higher PET values, with a median around 38°C and a broader distribution. Despite the relatively higher temperatures, DF still maintains favorable cooling performance, with moderate temperature variations. The mixed forest (MF) presents intermediate PET values between EF and DF, with a median approaching 40°C. MF demonstrates a balanced thermal environment, though slightly warmer than EF. The open area (RP) displays significantly higher PET values, with a median of approximately 44°C. Due to the lack of vegetation coverage and regulatory effects, RP experiences rapid temperature increases, resulting in poor thermal comfort. The wide distribution of PET values indicates substantial temperature fluctuations and extreme heat during summer. The bare land (LA) exhibits the highest PET values among all types, with a median approaching 46°C and an extensive distribution range. LA demonstrates the poorest thermal comfort, characterized by extremely high temperatures, particularly during summer months.

## 4. Discussion

### 4.1. Temperature Variation Trends

In terms of diurnal temperature variation, evergreen forests (EF1, EF2, EF3), deciduous forests (DF1, DF2, DF3), and mixed forests (MF1, MF2, MF3) generally exhibit smaller day-night

temperature differences. Notably, these forest types show rapid nighttime temperature recovery, maintaining relatively low levels. For instance, the nighttime temperature in EF1 is approximately 26°C, while lawns (LA) and control points (RP) display significant diurnal temperature fluctuations. Lawns experience daytime temperatures nearing 39°C, which sharply drop to 26°C at night. The control points exhibit the most pronounced temperature fluctuations, with daytime temperatures reaching nearly 52°C and nighttime temperatures dropping to 32°C, indicating strong radiative heating effects. Daytime temperature peaks occur between 14:00 and 16:00, with most measurement points reaching their highest temperatures during this period. Lawns and control points show the most substantial temperature increases, whereas forest types exhibit relatively lower temperature peaks. Evergreen and mixed forests maintain daytime temperatures around 36-38°C, while deciduous forests remain between 36-37°C.

#### 4.2. Humidity Variation Trends

Humidity variations exhibit distinct diurnal fluctuations, with higher relative humidity at night and significant decreases during the day as temperatures rise. Lawns (LA) and control points (RP) experience the most substantial daytime humidity drops, reaching minimums of 40% and 45%, respectively. In contrast, forest types such as evergreen, deciduous, and mixed forests show more stable humidity levels, generally maintaining minimum humidity above 50%. Humidity gradually recovers in the evening, highlighting the differential humidity regulation capabilities of various vegetation types. Evergreen and mixed forests, with their denser canopy coverage, maintain higher humidity levels, whereas lawns and open areas, lacking sufficient vegetation cover, experience faster humidity declines.

#### 4.3. Globe Temperature and Surface Temperature

Globe temperature and surface temperature trends reveal significant fluctuations in open areas (RP) and lawns (LA), particularly in surface temperature increases, reaching 60°C and 50°C, respectively. Evergreen, deciduous, and mixed forests exhibit more moderate surface temperature changes, with peaks generally between 40-45°C. Evergreen (EF1) and deciduous forests (DF1) show lower surface temperatures, reflecting their stronger mitigation of surface heat radiation. Globe temperature trends follow a similar pattern, with control points (RP) and lawns (LA) experiencing the most pronounced daytime temperature changes. Globe temperatures peak between 14:00 and 16:00, nearing 52°C and 45°C, respectively. In contrast, evergreen (EF1) and deciduous forests (DF1) exhibit more stable globe temperatures with smaller fluctuations and quicker nighttime recovery.

#### 4.4. Physiological Equivalent Temperature (PET) and Thermal Comfort

The PET trends reflect the varying capabilities of different forest types in regulating thermal comfort. Data indicate that open areas (RP) and lawns (LA) experience significant daytime PET increases, particularly between 14:00 and 16:00, entering "hot" or "very hot" ranges. Open areas reach the highest PET values at 44°C, while lawns maintain around 40°C. Conversely, evergreen (EF1) and deciduous forests (DF1) show lower PET values, generally remaining in the "comfortable" or "warm" ranges, especially in the evening when PET gradually decreases to the "warm" range.

Boxplot analysis reveals that evergreen forests (EF) exhibit the most stable PET values, with a median around 35°C, indicating effective environmental temperature regulation. Deciduous forests (DF) show slightly higher PET values, approximately 38°C, with moderate temperature variations still within a comfortable range. Mixed forests (MF) display balanced thermal environments, with PET values intermediate between evergreen and deciduous forests. Open areas (RP) show significantly higher and more variable PET values, reflecting extreme thermal conditions often in the high-temperature range.

## 4.5. Summary

The data demonstrate significant differences in the thermal regulation capabilities of various forest types during summer. Evergreen and mixed forests, with their dense canopy coverage and high plant density, exhibit superior cooling and humidity maintenance. They effectively reduce environmental PET and mitigate heat radiation effects. Deciduous forests, while providing some cooling benefits, are slightly less effective than evergreen forests due to seasonal variations. Lawns and open areas (RP), lacking sufficient vegetation cover, experience rapid temperature increases and higher PET values, indicating more severe thermal conditions. Overall, forest type and density play crucial roles in regulating summer thermal environments. Evergreen and deciduous forests provide more comfortable thermal conditions, particularly during daytime temperature peaks, through effective shading that reduces surface and air temperatures. Open areas, lacking shade, exhibit higher PET values and significant diurnal temperature fluctuations, resulting in poor thermal comfort. These findings offer valuable theoretical insights for future urban greening and landscape design, emphasizing the critical role of vegetation type and density in mitigating urban heat island effects[13].

## 5. Urban Greening Recommendations for Urban Development

Based on the findings of this study, urban greening designs should prioritize the selection of plant species and forest density to effectively improve urban thermal environments and enhance thermal comfort[14]. Below are planting recommendations derived from the thermal comfort differences among various forest types:

### 5.1. Increase Evergreen Forest Coverage and Optimize Canopy Density

Evergreen forests (EF) demonstrate superior thermal regulation capabilities, particularly during summer, where their dense canopies effectively reduce air and surface temperatures. Therefore, urban planning should prioritize the planting of evergreen species, especially in areas with high temperatures and significant heat island effects. Evergreen species such as pine, cypress, and ginkgo not only provide year-round greenery but also offer continuous shading, effectively lowering ambient temperatures and Physiological Equivalent Temperature (PET).

Recommendations: Increase evergreen forest coverage in urban green belts, street greening, and urban parks, particularly in high-density commercial and industrial zones, to provide residents with cooler environments. Focus on planting evergreen species in heat-vulnerable areas to mitigate urban heat island effects. Plant Mixed Forests to Enhance Ecological Diversity and Temperature Regulation Mixed forests (MF) exhibit balanced temperature and humidity regulation, combining the thermal advantages of evergreen species with the seasonal benefits of deciduous trees. Mixed forests provide ecological benefits across different seasons, offering moderate cooling in summer and allowing sunlight penetration in winter.

Recommendations: Incorporate mixed forest designs in urban greening plans, especially in city centers and large parks. Combine native deciduous species (e.g., poplar, willow) with evergreen trees to optimize ecological functions and enhance the aesthetic and environmental value of urban green spaces.

### 5.2. Utilize Deciduous Forests for Seasonal Landscape Design

While deciduous forests (DF) are slightly less effective than evergreen forests in summer cooling, their seasonal changes add richness to urban landscapes, particularly in autumn when foliage creates vibrant scenery. In winter, deciduous trees allow more sunlight to penetrate, aiding in natural warming. Recommendations: Use deciduous species as complementary elements in urban greening, particularly in parks and recreational areas. Plant species such as maple, ginkgo, and willow to provide seasonal beauty and sunlight exposure during colder months.

### 5.3. Optimize Lawn and Open Space Planning to Minimize Overexposure

Lawns (LA) and open areas (RP) exhibit significant heat island effects during summer, with surface temperatures rising sharply and contributing to "hot spot" formation. Therefore, the size of lawns and open spaces should be carefully managed to avoid excessive exposed ground, especially in urban centers and busy commercial areas.

Recommendations:

Adopt multi-layered planting models combining low grass, tall grass, and shrubs to increase ground coverage and reduce bare soil exposure.

Select drought- and heat-resistant grass species, such as ryegrass and Bermuda grass, to reduce maintenance costs and mitigate heat island effects.

### 5.4. Promote Rooftop and Vertical Greening

Rooftop and vertical greening are effective strategies for improving urban thermal environments[9]. By planting vegetation on building roofs and facades, thermal comfort can be enhanced, and ambient temperatures reduced, particularly during summer.

Recommendations: Implement rooftop and vertical greening using a combination of evergreen and climbing plants to reduce heat absorption and increase humidity. Encourage policies and incentives for green building designs to integrate vegetation into urban infrastructure[10].

### 5.5. Enhance Humidity Regulation to Improve Thermal Comfort

Forest types exhibit strong humidity regulation capabilities. Therefore, urban greening designs should focus on increasing plant density and vegetation coverage to promote humidity recovery. Recommendations: Incorporate moisture-tolerant and wetland plants in parks, streets, and public green spaces to enhance humidity regulation. Design green spaces with diverse plant species to maximize ecological benefits and thermal comfort.

### 5.6. Integrate Greening with Water Features to Enhance Thermal Comfort

The combination of water bodies and greenery can further improve urban thermal environments[11]. Water features, such as ponds, lakes, and fountains, reduce ambient temperatures through evaporation and increase humidity, mitigating heat island effects.

Recommendations: Strategically design water landscapes in urban areas

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