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Research Paper

Forests are chill: The interplay between thermal comfort and mental wellbeing

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HIGHLIGHTS

- Forests were on average 9.2 °C (max 18.4 °C) mPET cooler than non-forest baselines.
- For a 1 °C mPET increase at non-forest baselines, forests only warmed by 0.25 °C mPET.
- In forests, participants never felt hot and two-thirds felt very comfortable.
- At the same mPET, participants were 2.7 times as likely to feel warmer at baselines.
- Thermal comfort may be even further improved via enhanced mental wellbeing in forests.

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ABSTRACT

As global warming and urbanisation intensify unabated, a growing share of the human population is exposed to dangerous heat levels. Trees and forests can effectively mitigate such heat alongside numerous health co-benefits like improved mental wellbeing. Yet, which forest types are objectively and subjectively coolest to humans, and how thermal and mental wellbeing interact, remain understudied. We surveyed 223 participants in *peri*-urban forests with varying biodiversity levels in Austria, Belgium and Germany. Using microclimate sensors, questionnaires and saliva cortisol measures, we monitored intra-individual changes in thermal and mental states from non-forest baseline to forest conditions. Forests reduced daytime modified Physiologically Equivalent Temperature (mPET; an indicator for perceived temperature) by an average of 9.2 °C. High diversity forests were the coolest, likely due to their higher stand density. Forests also lowered thermal sensation votes, with only 1 % of participants feeling 'warm' or 'hot' compared to 34 % under baseline conditions. Despite the desire for a temperature increase among 47 % participants under cool forest conditions, approximately two-thirds still reported feeling very comfortable, in contrast to only one-third under baseline conditions. Even at a constant perceived temperature, participants were 2.7 times more likely to feel warmer under baseline conditions compared to forests. A forest-induced psychological effect may underlie these discrepancies, as supported by significant

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improvements in positive and negative affect (emotional state), state anxiety and perceived stress observed in forests. Additionally, thermal and mental wellbeing were significantly correlated, indicating that forest environments might foster a synergy in wellbeing benefits.

1. Introduction

Heat stress poses a growing concern for public health worldwide, with far-ranging impacts resulting in reduced labour productivity, increased risk of cardiovascular complications and, in severe cases, increase in heat-caused mortality (Ebi et al., 2021; Romanello et al., 2022). In Europe, approximately 100,000 elderly persons died from heat-related causes between 2019 and 2021 (Romanello et al., 2022). Climate warming is already responsible for over one-third of heat-related mortality (Vicedo-Cabrera et al., 2021), and will likely progressively exacerbate this trend. Under current climate-related political pledges, a person born in 2020 will experience an average of 30 heatwaves in their lifetime, seven times more than those born in 1960 (Thiery et al., 2021). Even under the most optimistic emissions scenario, half of the global population is expected to experience at least 20 potentially lethal heat days annually by 2100 (Mora et al., 2017). In parallel, rapidly growing urbanisation rates accentuate these risks because cities are generally warmer than rural regions, especially during heat waves. Urban infrastructure effectively traps solar radiation while surplus heat is generated by anthropogenic activities like transport and air-conditioning (Ebi et al., 2021; Taleghani, 2018). This urban heat island effect (UHI) in itself contributes to a large share of heat deaths (Iungman et al., 2023). With 68 % of the world's population predicted to live in cities by 2050 (United Nations, 2019), the number of people exposed to amplified heat levels will continue to rise (Ebi et al., 2021).

Implementing heat mitigation solutions is thus imperative in cities worldwide. Among these solutions, urban greening as a nature-based solution stands out as a particularly promising option despite potential costs related to water use and maintenance (Akbari, 2002; Shashua-Bar, Pearlmutter, & Erell, 2011). Green elements such as parks, green walls and roofs, trees and forests mitigate heat by reducing the share of heat-trapping surfaces, and facilitating evapotranspiration (Taleghani, 2018). Trees offer the additional advantage of creating shade, which strongly influences human thermal perception and reduces solar radiation reaching man-made surfaces (Nikolopoulou & Lykoudis, 2006; Taleghani et al., 2018; Thorsson, Lindberg, Eliasson, & Holmer, 2007). For example, while low vegetation such as lawns only cooled human-perceived daytime temperatures by 0.9 °C, a study showed that street trees were on average 5.5–8.5 °C cooler than a paved reference (Lehnert, Tokar, Jurek, & Geletič, 2020). Similarly, a modelling study reported an average daytime cooling in perceived temperature of 1.0 °C (up to 4.9 °C) for grasslands, compared to 3.0 °C (up to 17.4 °C) for trees (Lee, Mayer, & Chen, 2016).

Forests demonstrate comparable or even greater cooling capacities compared to single trees. In the Singapore Botanic Gardens, the presence of a rainforest canopy reduced perceived temperatures up to 10 °C compared to an open grass field (Chow, Akbar, Assyakirin, Heng, & Roth, 2016). Similar cooling magnitudes were found in Freiburg, Germany, when comparing a tall spruce forest with a paved urban canyon under hot conditions (Mayer & Höppe, 1987). Yet, such studies do not differentiate among forest types, even though results from forest microclimate ecology highlight large inter-forest differences in air and soil temperature (Meeussen et al., 2021; Zellweger et al., 2019). How well this translates to changes in human thermal comfort remains largely unexplored, although a recent pan-European study demonstrated that stand structure and species composition are key variables that maximised cooling capacity (Gillerot et al., 2022).

Besides physical microclimate factors (hereafter 'objective thermal comfort'), forest-induced psychological benefits may also play a role in shaping people's experience of their thermal environment. Objective thermal comfort only accounts for half of the variation in subjective thermal comfort observed among individuals, while other physiological (e.g. age, biological sex, acclimatisation) and psychological factors (e.g. experience, expectations, perceived control) contribute to the remaining variation (Höppe, 2002; Lai et al., 2020; Nikolopoulou & Steemers, 2003). However, the investigation of how the forest environment mediates the relationship between subjective thermal comfort and psychological factors is limited to a few pioneering studies. One study found perceived temperature to correlate with mental aspects like mood and anxiety (Elsadek, Liu, Lian, & Xie, 2019), while others have observed a wider range of 'acceptable' temperatures in forests, suggesting psychological benefits as a potential explanation (Jeong, Park, & Song, 2016). Inversely, higher thermal comfort levels in forests were shown to correlate with positive affect (Park et al., 2011). Together, these results suggest that thermal and mental states may interact, but little is known about the strength and generality of this interaction and about the forest as a mediating agent. To close this knowledge gap, we conducted an interdisciplinary multicenter study in *peri*-urban forests with varying biodiversity levels in Austria, Belgium and Germany. Combining methods from forest microclimate ecology, human biometeorology and environmental psychology, we investigate following questions:

1) To which extent can improvements in objective thermal comfort generated by different forest types be translated to subjective thermal comfort?
2) To which extent can different forest types improve mental wellbeing?
3) Does mental wellbeing interact with thermal wellbeing in forests?

2. Methods

2.1. Study sites and plot selection

We conducted the study in three highly visited *peri*-urban forests in September 2021: the Leipzig Auwald in Leipzig (Germany; September 3–4), the Wienerwald near Vienna (Austria; September 10–11) and the Bois de Lauzelle in Ottignies-Louvain-La-Neuve (Belgium; September 24–25). The climate for September (1999–2019) is characterised by an air temperature of 15.5 °C with 41.5 mm of precipitation for the region around Leipzig, 16.1 °C and 60.3 mm for Vienna, and 15.7 °C and 56.7 mm for Louvain-La-Neuve, respectively (Zepner, Karrasch, Wiemann, & Bernard, 2021).

Forest plots were selected according to tree species diversity as the primary selection criterion. 'Low' biodiversity plots were dominated by a single tree species (>90 % of plot-level basal area; a common stand density metric), 'medium' biodiversity plots harboured two or three tree species (together > 90 % of basal area) and 'high' biodiversity plots contained at least five tree species (Table 1). The irregular spacing in biodiversity levels were chosen to account for the expected flattening (asymptotic) trend with increasing biodiversity found in existing biodiversity-ecosystem functioning research (Cardinale et al., 2012). The range in local tree species numbers in 314 m^2 subplots is representative of what can be expected in these temperate forests, for both low and highly diverse stands (Baeten et al., 2013). A forest inventory was conducted for all plots, and the ecological characteristics are detailed in supplementary methods S1.

We had a total of nine plots (n = 3 plots for each level of biodiversity × 3 sites). We implemented a dilution design, where the low biodiversity plot was dominated by species 'a', the medium biodiversity plot by species 'a' and 'b', and the high biodiversity plot by species 'a', 'b', 'c',

Table 1

Overview of *peri*-urban forests, control plots and their characteristics. Dominant canopy height is the average height of the dominant tree in each of three subplots. Basal area is the cross-sectional area of tree stems at breast height in m^2 per hectare. Canopy closure is based on hemispherical pictures, quantified by the proportion of obstructed sky area. The Shannon diversity index quantifies tree species diversity based on species-specific proportions in basal area or canopy cover. The authenticity index accounts for stand structure, woody and herbaceous vegetation, and deadwood, and is expressed as a unitless score of maximum 100 (very biodiverse). MAT = mean annual temperature for 1999–2019, based on averages of the region around the cities. Inter-forest differences are presented visually in Fig. S1. More details are found in the supplementary methods S1.

Plot type	Dominant canopy height (m) and vertical structure profile	Basal area (m^2/ha)	Canopy closure (forest) or share of covered sky (non-forest)	Geographic coordinates	Scaled Shannon diversity (basal area – canopy cover)	Authenticity Index	Tree species-specific proportions in basal area (DBH > 7 cm) and description of controls
Leipzig Auwald, Leipzig, Germany. All plots within 7 km from the city's centre. **Survey**: September 3 & 4, 2021 **Köppen climatic classification:** Dfb **MAT:** 10.2 °C							
Non-forest baseline			29.5 %	51° 21′ 41.6″ N 12° 16′ 40.2″ E			Emptied parking at the city's periphery with moderate influence of surrounding trees and nature. Asphalted surface. Distance from other plots: ≤ 1.3 km. LCZ 9_B.
Low diversity forest	26.0 Single-layered	24.7	68.9 %	51° 22′ 15.8″ N 12° 16′ 17.8″ E	1.0 – 1.0	28	*Fraxinus americana* (100 %)
Medium diversity forest	28.2 Multi-layered	20.3	88.2 %	51° 22′ 22.0″ N 12° 15′ 54.9″ E	3.7 – 4.2	38	*Fraxinus excelsior* (39.4 %), *Acer pseudoplatanus* (30.3 %), *Acer campestre* (19.8 %), *Carpinus betulus* (10.0 %)
High diversity forest	20.4 Multi-layered	19.0	94.3 %	51° 22′ 12.1″ N 12° 16′ 14.2″ E	4.5 – 4.9	38	*Fraxinus excelsior* (24.3 %), *Acer pseudoplatanus* (1.7 %), *Acer campestre* (35.6 %), *Quercus robur & Q. petraea* (21.0 %), *Rhamnus frangula* (1.0 %), *Tilia cordata* (1.4 %), *Alnus incana* (14.0 %)
Urban control			61.6 %				Fully asphalted crossing of two medium-sized streets, with minimal influence of vegetation. Surrounded by four-story buildings. LCZ 2.
Wienerwald, Vienna, Austria. All plots within 14 km from the city's centre. **Survey**: September 10 & 11, 2021 **Köppen climatic classification:** Dfb **MAT:** 11.2 °C							
Non-forest baseline			2.1 %	48° 16′ 56.4″ N 16° 13′ 40.6″ E			Large grass field within a forest complex, next to a small asphalted road and storage building. Grassy surface. Distance from other plots: ≤ 1.7 km. LCZ D.
Low diversity forest	36.4 Single-layered	37.2	87.1 %	48° 17′ 16.8″ N 16° 13′ 53.8″ E	1.0 – 1.0	30	*Fagus sylvatica* (100 %)
Medium diversity forest	33.6 Multi-layered	42.0	90.7 %	48° 17′ 38.7″ N 16° 15′ 06.6″ E	2.4 – 2.5	40	*Fagus sylvatica* (19.9 %), *Pseudotsuga menziesii* (66.9 %), *Quercus robur & Q. petraea* (13.1 %)
High diversity forest	29.1 Multi-layered	46.4	96.3 %	48° 17′ 03.1″ N 16° 14′ 21.8″ E	3.0 – 3.5	36	*Fagus sylvatica* (59.2 %), *Quercus robur & Q. petraea* (19.0 %), *Fraxinus excelsior* (14.9 %), *Larix decidua* (6.1 %)
Urban control				48° 17′ 24.1″ N 16° 11′ 40.0″ E			Small asphalted square at the intersection of two moderately busy streets. Vegetation visible from a distance. Surrounded by low buildings. LCZ 6_D.
Bois de Lauzelle, Louvain-La-Neuve, Belgium. All plots within 2 km of the city's centre. **Survey**: September 24 & 25, 2021 **Bio climatic zone:** Cfb **MAT:** 11.1 °C							
Non-forest baseline			6.8 %	50° 40′ 05.9″ N 4° 36′ 48.7″ E			Empty parking near the city centre without any influence of vegetation. Asphalted surface. Distance from other plots: ≤ 2.2 km. LCZ 2_E.
Low diversity forest	26.0 Multi-layered	32.9	57.2 %	50° 40′ 44.2″ N 4° 35′ 11.1″ E	1.0 – 1.5	26	*Pinus sylvestris* (100 %)
Medium diversity forest	28.9 Multi-layered	52.5	77.2 %	50° 40′ 45.1″ N 4° 35′ 20.5″ E	1.2 – 2.4	32	*Pinus sylvestris* (95.9 %), *Betula pendula* (3.7 %)
High diversity forest	26.0 Multi-layered	35.4	94.4 %	50° 40′ 44.0″ N 4° 35′ 22.0″ E	3.2 – 4.5	50	*Pinus sylvestris* (37.3 %), *Betula pendula* (16.9 %), *Quercus robur & Q. petraea* (42.4 %), *Castanea sativa* (2.0 %), *Corylus avellana* (1.2 %)
Urban control			70.5 %	50° 40′ 9.5″ N 4° 36′ 39.4″ E			Fully asphalted pedestrian square near the city centre without any influence of

(*continued on next page*)

…, etc. The final selection of species aimed to represent local species while maximising overall species diversity. As such, the monoculture species (species ‘a’) varied across sites, and had highly contrasting functional traits. The monoculture species for Wienerwald was European beech (*Fagus sylvatica* L.) and for Bois de Lauzelle, Scots pine (*Pinus sylvestris* L.). For Leipzig Auwald, European ash (*Fraxinus excelsior* L.) was present in the medium and high biodiversity plots, but was replaced by American ash (*Fraxinus americana* L.) in the low biodiversity plot because nearby suitable monospecific European ash stands were unavailable. We assumed that divergences in psychological effects and thermal conditions would be limited. Considering microclimatic effects, earlier studies would imply that little differences should occur based on driving functional traits (Gillerot et al., 2022; Zellweger et al., 2019). Additionally, both species (*F. excelsior, F. americana*) were visually challenging for participants to differentiate and participants were exposed to only one of the two species, limiting the potential bias on psychological effects. Similarly, the dilution design was not followed in the Wienerwald because Douglas fir (*Pseudotsuga menziesii* (Mirb.) Franco) was present as species ‘b’ in the medium- but not the high biodiversity plot.

We employed two types of control conditions. The first control provided a non-forest reference point, and served as a baseline measure for every participant (hereafter ‘baseline’). Baseline plots had minimal visual and thermal influence of woody vegetation and were as close to forest plots as possible, preferably at a similar distance from each plot. Because of these constraints and the contrasting wider spatial contexts of selected *peri*-urban forests, baseline plots varied in imperviousness and urbanicity. For example, the Wienerwald baseline was a large grassy meadow with trees located more than 50 m away from participants, with modest influence of asphalt and other man-made surfaces. In contrast, the Bois de Lauzelle baseline was a large parking lot near the city centre, with no vegetation but high imperviousness. The Leipzig Auwald baseline was something in between: a parking lot at the city’s edge with moderate presence of both natural and man-made elements. Despite these differences, participants always visited both the baseline and one of the three forests or an urban plot as control (see below). This ensured that their *relative* experience is reflected in the subjective data and differences among forest plots remained unaffected. The second control type was visited by only 25 % of participants, and was always as urbanised as possible relative to baseline, with minimal influence of vegetation. Both type of controls are classified according to Local Climate Zones (LCZ) in Table 1 (Stewart & Oke, 2012).

2.2. Survey design and procedure

We selected the two best weather days out of five potential days for each city. Hot summer days were absent, with the advantage that participants were not subjected to potentially hazardous heat during the survey, which lasted approximately 30–50 min per plot/condition. Nonetheless, local air temperatures reached maximum values ranging between 25 and 30 °C every day at the baseline plots except for the second day in Leipzig where temperatures were in the 15—–20 °C range. To ensure comparable light conditions for the mental wellbeing aspect of the study, participants were surveyed between 9:15am and 4 pm. The surveys were conducted in four daily cohorts (9:15am, 10:15am, 12:30 pm or 13:30 pm), with a maximum of 20 participants in each cohort.

Upon arrival at the baseline, participants were seated on chairs spaced 1.5 m apart, and oriented in the same direction to ensure a consistent viewing experience (Fig. 1). Participants were briefed about the schedule and subsequently completed a questionnaire about their subjective thermal comfort and mental wellbeing. Additionally, a salivary cortisol sample was taken as a biomarker reflecting stress levels with a 20–30 min delay (Kirschbaum & Hellhammer, 1989). Participants were then randomly assigned to one of three forest conditions, or the urban control. They were transported to their randomly assigned location in minivans that had windows covered with opaque fabric to prevent any exposure to nature (and potential impacts on psychological states) during transport. Upon arrival at the designated plots, participants were again instructed to focus on what they saw and heard for 20 min. They subsequently completed a second questionnaire, and provided a second saliva sample. At both points in time, participants were exposed to local microclimates for at least 20 min when completing the thermal comfort section of the questionnaires.

The current thermal comfort study was conducted in parallel with a second study that focused on mental aspects. Further details are found in Rozario et al. (*in press*).

2.3. Survey participants

Survey participants were recruited via flyers spread over the three cities and using online platforms such as social media of universities, medical houses and city administrations. Interested people were screened by phone for selection criteria related to thermal and mental wellbeing. Criteria included good physical and mental health, a body mass index between 18 and 30, normal vision and hearing (correction allowed) and no consumption of medication that affects the central nervous system, such as antidepressants. Participants were instructed to refrain from smoking and consuming caffeinated drinks on the survey day to minimise the impact of caffeine on saliva cortisol concentrations. They were also instructed not to eat, drink or brush their teeth 30 min prior to the start of the survey. Participants did not receive financial compensation but were offered a free forest bathing session after participation. A total of 223 participants were surveyed, with 70 in Leipzig Auwald, 66 in Wienerwald and 87 in Bois de Lauzelle. Overall, 161 (72 %) participants were women (and one diverse person) and the average age was 35.6 (SD = 12.7).

Guidelines of the Declaration of Helsinki were respected and ethical clearance was granted by the institutional ethical committees of Leipzig University (reference: 2021.05.13_eb_91), the Medical University Vienna (reference: 01509146/2021) and the University of Louvain (reference: 2021–30). Participants gave written informed consent prior to participation and personal data were anonymized.

2.4. Physical microclimate and objective thermal comfort

We measured all necessary indicators of human thermal perception, namely, air temperature, relative humidity, mean radiant temperature (T_{mrt}) and wind speed (Johansson, Thorsson, Emmanuel, & Krüger, 2014; Matzarakis, Mayer, & Iziomon, 1999; Mayer & Höppe, 1987). Air temperature, relative humidity and wind speed were all directly measured using Kestrel 5400 Heat Stress Trackers (Nielsen-Kellerman, Pennsylvania, U.S.). The Kestrels also measure the black globe

Table 1 (*continued*)

Plot type	Dominant canopy height (m) and vertical structure profile	Basal area (m^2/ha)	Canopy closure (forest) or share of covered sky (non-forest)	Geographic coordinates	Scaled Shannon diversity (basal area – canopy cover)	Authenticity Index	Tree species-specific proportions in basal area (DBH > 7 cm) and description of controls
							vegetation. Surrounded by six-story buildings. LCZ 2.
Total							**18 tree species** (DBH > 7 cm)

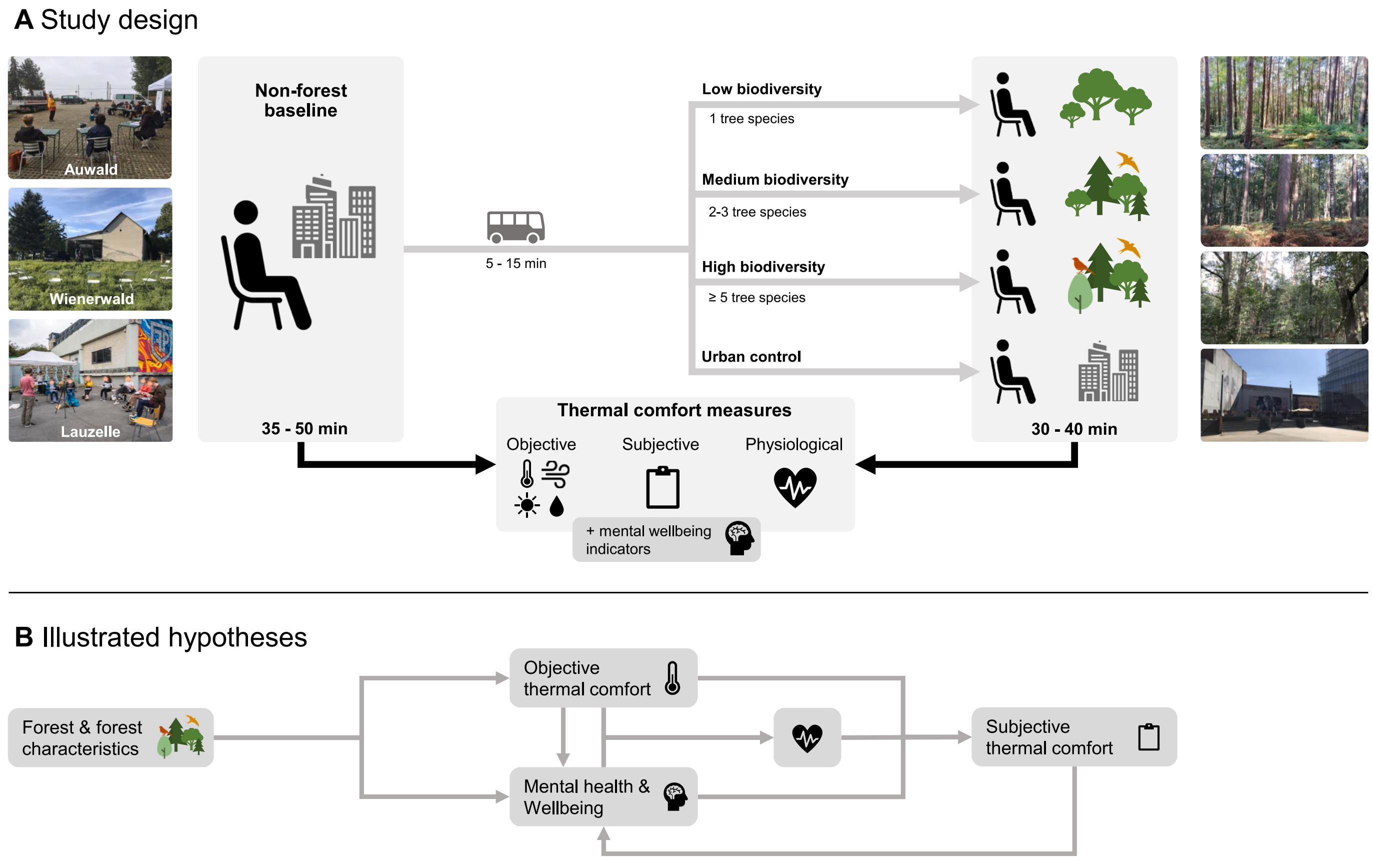

Fig. 1. Study design (A). Each participant was first subjected to the non-forest baseline and then one of three possible forest conditions varying in tree species diversity, or the urban control. Questionnaires on subjective thermal comfort and mental wellbeing were filled in after both interventions. The objective thermal comfort was continuously measured on all locations except for the urban control. Saliva cortisol samples were obtained after completing questionnaires as a physiological biomarker of stress. These data were then used to test hypothesised associations as illustrated in B.

temperature needed to calculate T_{mrt}. Each Kestrel was mounted on a wind vane, and placed on a tripod at 1.1 m height, representing the average centre of gravity of a standing adult person (ISO, 1998; Johansson et al., 2014). All microclimatic variables were recorded continuously every ten seconds on all plots (except urban controls) between approximately 9am and 5 pm for each of the six survey days, resulting in about 70,000 data points.

Black globe temperature values were converted to T_{mrt} using an empirical formula adapted for outdoor conditions (Thorsson et al., 2007):

$$T_{mrt} = \left[(T_g + 273.15)^4 + \frac{1.335*10^8 {V_a}^{0.71}}{\varepsilon * D^{0.4}} *(T_g - T_a) \right]^{\frac{1}{4}} - 273.15$$

where T_g is the globe temperature (°C), V_a is the wind speed (m/s), ε is the globe emissivity (0.95) and T_a is the air temperature (°C). D is the globe diameter, equalling 0.025 m on the Kestrel. However, the device readily extrapolates these measures to what a standard 0.15 m black globe would measure (Carter, Zaitchik, Gohlke, Wang, & Richardson, 2020), so D = 0.15 m was used here to account for this implicit calculation. Remark that a grey globe may better represent radiant properties of clothing and skin, while a black globe may overestimate T_{mrt} (Thorsson et al., 2007). However, the typically recommended grey globe was also found to slightly underestimate T_{mrt} under clear sky conditions (Thorsson et al., 2007). Because deviations remain modest and both colours seem suboptimal, we decided to interpret the Kestrel's black globe readings without further corrections as done in similar studies (e.g. Chow et al., 2016).

We chose the modified Physiologically Equivalent Temperature (mPET) (Chen & Matzarakis, 2018) as our main indicator for objective thermal comfort because it incorporates the energy balance of the human body, and is based on the widely used PET index. It is measured in degrees Celsius (°C) and can represent a wide range of thermal conditions ranging from extremely cold to extremely hot (Matzarakis et al., 1999; Mayer & Höppe, 1987; Potchter, Cohen, Lin, & Matzarakis, 2018). PET is based on the Munich Energy-balance Model for Individuals (MEMI) and is defined as "*the air temperature at which, in a typical indoor setting (without wind and solar radiation), the heat budget of the human body is balanced with the same core and skin temperature as under the complex outdoor conditions to be assessed*" (Höppe, 1999). The mPET is superior to PET as it automatically adapts the clothing factor in function of thermal conditions (Chen & Matzarakis, 2018). As a result, mPET values are more conservative than PET values because temperatures are buffered by the adapted clothing (Fig. S2).

We calculated mPET using standard settings in RayMan V3.1 (Matzarakis et al., 2007, 2010), i.e. for a man aged 35, 175 cm tall and with 80 W of internal heat production (Chen & Matzarakis, 2018; Höppe, 1999; Mayer & Höppe, 1987). Calculations were made for a seated person. Assuming that thermal perception is also determined by the period before completing questionnaires and not just one point in time, a rolling average of 10 min was applied. This also accounts for the Kestrel 5400 sensor lag in measurement accuracy of the T_a and T_g components for mPET (Johansson et al., 2014) (Fig. S3). Thermal data was matched to personal data using timestamps. These approaches assisted to smooth out strong mPET fluctuations caused by factors such as wind gusts and sunflecks passing through the forest canopy.

Kestrel devices were calibrated *a posteriori* in climate chambers. Results showed a very good fit among devices ($R^2 > 0.999$), but a small under- and overestimation (≤ ±0.5 °C) of, respectively, cool and hot conditions when compared to a high-grade mercury thermometer. A calibration factor was therefore applied to correct for this slight mismatch (supplementary methods S2).

2.5. *Subjective thermal comfort*

As the physical microclimate only explains part of how an individual will subjectively perceive its thermal environment, thermal comfort should also be subjectively assessed (Lai et al., 2020; Nikolopoulou, 2011). The latter can be done using different standardised scales (Johansson et al., 2014). We combined multiple standardised scales to assess participants' thermal sensation and preference, as per Chow et al. (2016). The ASHRAE seven-point scale was first employed to obtain the Thermal Sensation Vote (TSV), ranging from cold (−3), cool (−2), slightly cool (−1), neutral (0), slightly warm (+1), warm (+2), to hot (+3). We then presented analogous five-point scales (−2, −1, 0, +1, +2) to obtain a humidity-, wind- and sun sensation vote. As participants' thermal preference may differ from their thermal sensation, we next used three-point preference scales to ask whether they preferred warmer, no change, or cooler conditions. We repeated this for humidity, wind and sun conditions. Participants also indicated which of the four microclimatic parameters they found most unpleasant (or none), and rated their overall comfort on a four-point scale (i.e. uncomfortable to very uncomfortable). As per Chow et al. (2016), we queried participants' demographic data, including age, biological sex and length of residence in the country, which are potential confounders of thermal comfort. Questionnaires were translated to Dutch, English, German and French by native speakers and can be found as Supplementary Text S1-4.

Spearman correlation analyses suggested that the 10-minute rolling average in mPET was best in explaining variation in subjective thermal comfort ($p < 0.0001$, $\rho = 0.71$), better than the air temperature ($\rho = 0.53$), T_{mrt} ($\rho = 0.70$), PET ($\rho = 0.69$) and non-averaged mPET ($\rho = 0.70$). The averaged mPET was hence given priority in further analyses.

2.6. *Physiological measures*

For maximal comprehensiveness in heat stress studies, data can be complemented with relevant physiological measures. Such studies are less common but have included the heart rate, heart-rate variability, blood oxygen saturation, blood pressure, skin temperature, skin conductivity and salivary cortisol (Chaudhuri, Zhai, Soh, Li, & Xie, 2018; Jafari, Khosrowabadi, Khodakarim, Khodagholi, & Mohammadian, 2021; Nazarian et al., 2021; Rathmann et al., 2020). Here, physiological measures were limited to saliva cortisol sampling. This is a common measure to assess delayed physiological stress responses related to the Hypothalamic-Pituitary-Adrenal pathway, where higher cortisol levels typically indicate higher levels of stress (Kirschbaum & Hellhammer, 1989). Samples were stored at −20 °C and analysis was done using ELISA (Tecan - IBL International, Hamburg, Germany; catalogue number R52611).

2.7. *Mental wellbeing*

To assess potential short-term psychological responses resulting from a change in environments, we employed three complementary scales to measure mental wellbeing.

Emotional state and mood were evaluated using the the Positive And Negative Affect Schedule (PANAS; Watson, Clark, & Tellegen, 1988), which has previously been employed in studies investigating the effect of (forest) biodiversity on mental wellbeing (Marselle, Irvine, Lorenzo-Arribas, & Warber, 2015; Nghiem, Wong, Jeevanandam, Chang, Tan, Goh, & Carrasco, 2021; Wolf & zu Ermgassen, Balmford, White, & Weinstein, 2017). The PANAS consists of 10 items related to positive affect (e.g. "inspired"), and 10 items related to negative affect (e.g. "distressed"). Participants rated their current emotional state on a 5-point Likert scale (1 = "very slightly or not at all" to 5 = "extremely"). Scores for positive and negative affect are summed separately, resulting in values between 10 and 50. Higher values indicate a stronger positive or negative affect.

Momentary anxiety was assessed using the State-Trait Anxiety Inventory (STAI; Spielberger, Gonzalez-Reigosa, Martinez-Urrutia, Natalicio, & Natalicio, 1971), which has been also applied in biodiversity and mental health studies (Wolf & zu Ermgassen, Balmford, White, & Weinstein, 2017). It consists of 20 items (e.g. "I feel calm"). Participants rate their responses on a 4-point Likert scale, ranging from 1 ("not at all") to 4 ("very much so"). Scores were then summed, and ranged from 20 to 80, with higher values indicating higher levels of state anxiety.

Subjective stress was quantified using a single item. Participants were asked to indicate how stressed they felt in the present moment using a Visual Analogue Scale (VAS) that ranged from 0 ("not stressed at all") to 100 mm ("extremely stressed"). Similar measures have been used in studies on the stress mitigating effects of biodiversity (Schebella, Weber, Schultz, & Weinstein, 2020).

The full questionnaire can be found under Supplementary Text S1-4 and details on psychological aspects of this study are found in Rozario et al. (*in press*).

2.8. *Data analyses*

Objective thermal comfort — We applied linear mixed models (LMM) to investigate differences in objective thermal comfort (mPET) between forest types. In order to facilitate interpretation and modelling of the forest cooling capacity, we specified offset values as the LMM response variable (De Frenne et al., 2021). Offset values were calculated by subtracting non-forest baseline measures from forest measures. 'Plot' nested within 'site' was specified as a random effect to account for within-forest and between-forest variability, while temporal autocorrelation was accounted for using an AR1 correlation function (function *lme*). We chose to focus on assessing diversity levels instead of forest characteristics (e.g. canopy closure, tree height) to avoid potential bias caused by the strong intercorrelations between forest characters (Fig. S1). Besides analyses focused on species diversity levels, analyses were also performed on grouped forest data to obtain overall forest effects.

Subjective thermal comfort — The relative change from baselines to forests in the share of votes for the ten scales was first analysed as such, without statistics (e.g. Chow et al., 2016). Next, the effect of tree species diversity and demographic factors on subjective thermal comfort (7-point TSV) was modelled using two complementary statistical methods. Although many studies assume that TSV can be modelled as a continuous response variable, these votes are actually of ordinal nature and this can affect results (Favero, Luparelli, & Carlucci, 2023). As a compromise, we applied both linear (*lme*) and ordinal mixed model (*clmm* with logistic link) - using 'participant' nested in 'site' as the random effect. Using this combination of approaches, the effect of tree species diversity on thermal comfort was tested. Besides these, more information concerning so-called 'neutral' and 'preferred' temperatures can be found in the supplementary methods S3.

Interactions with mental wellbeing — Differences in psychological outcomes and cortisol levels between baseline and forest or urban control conditions were expressed as relative changes (forest minus baseline) to compensate for inter-individual differences, and tested using mixed ANOVA (function *lme*) with 'site' as random factor. This analysis was conducted on two subsets of the data. First, we compared data collected from pooled forest plots with urban plots to examine the difference between forested and urban areas. Second, using only data collected from forest plots, we investigated inter-forest differences and overall change relative to the baseline where a significant intercept indicates a significant change.

Our final set of analyses assessed associations between mental wellbeing and either objective or subjective thermal comfort data. Polynomial quadratic LMMs (function *lme*) were applied using either mPET (objective) or TSV (subjective) data as predictors. As a second, complementary, way to model TSV data, mixed-model ANOVAs were used with TSV as a categorical predictor. While, the continuous approach was used to test the expected quadratic relationships (both '1 - cold' and '7 - hot' votes leading to more negative outcomes), the discrete approach accounts for the ordinal nature of the data and can thus confirm trends.

LMMs were built using the packages *nlme* (Pinheiro, Bates, Debroy, Sarkar, 2021) and *lme4* (Bates, Bolker, & Walker, 2015). Ordinal analyses (cumulative link mixed models) were done using the package *ordinal* (Christensen, 2022). Analyses were done in R version 4.2.2 (R Core Team, 2013).

3. Results

3.1. Objective thermal comfort

We captured a wide variety in thermal conditions over six days on the non-forest baselines. Air temperature (T_a) ranged from 12.1 to 28.9 °C, while mPET ranged from 13.1 to 41.9 °C (Fig. 2). Notable day-to-day differences were also observed, with the second day in Leipzig Auwald recording an average T_a of 15.7 ± 1.3 °C and mPET of 17.9 °C ± 1.5 °C mPET for non-forest baseline measurements. The warmest conditions occurred on the second day in Wienerwald with an average T_a of 22.4 ± 1.9 °C and mPET of 35.7 ± 2.7 °C. Considering the thermal stress categories by Matzarakis et al. (1999), recorded daytime averages on baselines cover conditions representing 'slight cold-' to 'strong heat stress' (originally intended for PET). Cloudiness and solar radiation also strongly varied between days and are a main driver of thermal comfort patterns in Fig. 2 (black lines). Survey conditions Auwald, for example, were prevalently sunny in the morning of the first day, but very cloudy in the afternoon and the second day. In contrast, Wienerwald conditions were very sunny with sporadic clouds.

In contrast to non-forest baseline measures, forest plots were substantially cooler and strongly buffered fluctuations. Only on the second cooler survey day in Leipzig Auwald, differences were less pronounced (partly due to cloudy conditions). Grouping the three forest plots together, daytime averages (9:30am – 4:30 pm) reached 15.0 °C T_a and 17.0 °C mPET on Leipzig Auwald's second day and 20.8 °C T_a and 21.2 °C mPET on Wienerwald's first day. Offsets ranged from + 3.3 to −8.9 °C (T_a) and + 3.7 to −18.4 °C (mPET), with an overall mean cooling effect of −1.9 ± 1.4 °C T_a and −9.2 ± 6.1 °C mPET (Table S1-2). Generally, the warmer the baseline conditions, the stronger the cooling by the forest. Accordingly, the strongest mean daytime cooling was observed on the second day in Wienerwald, with an offset of −2.4 ± 1.3 °C T_a and −15.25 ± 1.7 °C mPET.

We observed significant differences between non-forest and forest conditions, while differences between forest types were subtler (Fig. 2). In terms of daytime averages, 'high' tree diversity forests consistently exhibited the coolest temperatures. 'Medium' diversity plots were also generally cooler than 'low' diversity plots, except for the second day in Wienerwald. However, the daytime temperature differences between forests never exceeded 2.1 °C mPET (mean 1.3 °C). Similar patterns were also observed when reanalysing the data in two-hour intervals. The greatest overall cooling effect was observed on the second day in Wienerwald in the high tree diversity plot with an offset of −2.5 ± 0.9 °C T_a and −16.9 ± 0.8 °C mPET (Table S1). The mixed model analysis suggested that these differences were statistically significant ($p < 0.001$), indicating that medium and high diversity forests were on average 0.35 and 1.09 °C mPET cooler than the low diversity forests. Furthermore, for every degree increase in baseline mPET, the grouped forests exhibited a cooling effect of 0.75 °C relative to the baseline. The high pseudo-R^2 values (marginal and conditional $R^2 \approx 0.91$) suggest that a large share of variation was explained, but a skewness of 0.61 in residuals indicated a moderate fit.

3.2. Subjective thermal comfort

The wide range in microclimatic measures effectively translated to well-distributed thermal sensation votes (Fig. 3A). Under baseline conditions, participants felt 'cool' to 'hot', but never 'cold'. About 24 % felt 'warm' and 10 % felt 'hot', with participants feeling warmest in Wienerwald, followed by Lauzelle and Leipzig Auwald baselines. In contrast, no one felt 'hot' in the forest and only two participants (1 %) felt 'warm'.

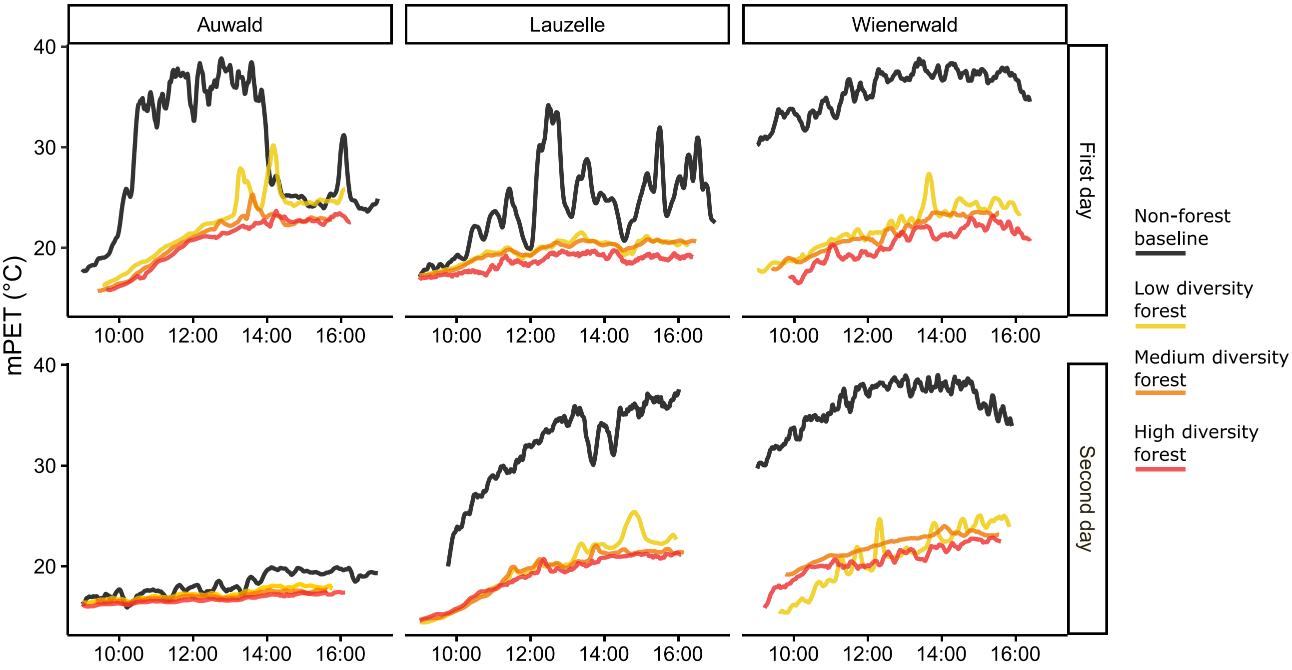

Fig. 2. Complete time series of the 10-minute rolling average in modified Physiologically Equivalent Temperature (mPET) for the two survey days at each of three *peri*-urban forests. Temperatures were slightly adapted following a post-hoc calibration (Supplementary methods S2). Time series of the air temperature are found in Fig. S4.

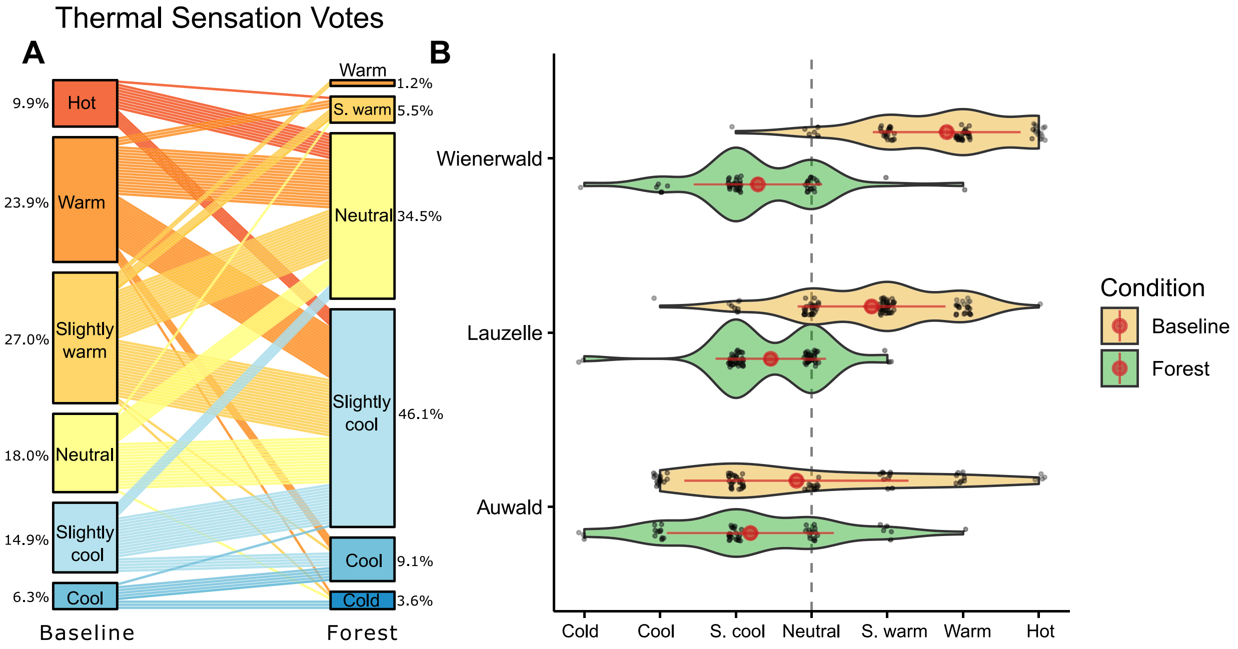

Fig. 3. Change in thermal sensation votes under non-forest baseline and forest conditions. (A) shows how votes of each participant changed from baseline to forest and how the shares in the 7-point scale were affected. (B) shows site-specific distributions in votes, illustrating large differences related to contrasting weather conditions (see Fig. 2). Red circles and lines represent the mean vote and standard deviation, respectively. The thicker the violin plot, the higher the point density. Analogous figures of the humidity, wind and sun sensation votes are found in Fig. S5. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

While the average baseline vote was approximately neutral to warm with a lot of variation according to prevailing weather conditions, 81 % of forest votes were situated between neutral and slightly cool and were thus more constant (Fig. 3B). Results in humidity, wind and sun sensation votes are found in Fig. S5. Models found no significant effects of age, sex and residence time. No significant differences were found between forest tree species diversity levels ($p = 0.63$).

Thermal preference scores also showed clear contrasts between baselines and forest conditions, with only one participant in the forest (0.6 %) who would have liked it to be colder, compared to 15.8 % under baseline conditions (Fig. 4A). In fact, many more participants desired it to be warmer in the forest (47.0 %) than at the baseline (25.2 %). Overall, more participants desired a temperature change in the forest (47.6 %) than at the baseline (41.0 %). Results in humidity, wind and sun preference votes are found in Fig. S6.

Concerning comfort ratings (Fig. 4B), 36 % were very comfortable at the baseline compared to 67.9 % in forests. More participants felt uncomfortable at the baseline (6.3 %) than in forests (3.1 %). Results concerning conditions voted to be the most unpleasant are found in Fig. S7.

3.3. *Interactions with mental wellbeing*

Since forest diversity levels did not show significant differences in terms of TSV, they were grouped together and compared to baseline measures. The LMM indicated that participants rated the forests as cooler by 0.47 points ($p < 0.001$) (Fig. 5A) given the same mPET. The complementary ordinal approach confirmed that forests were perceived

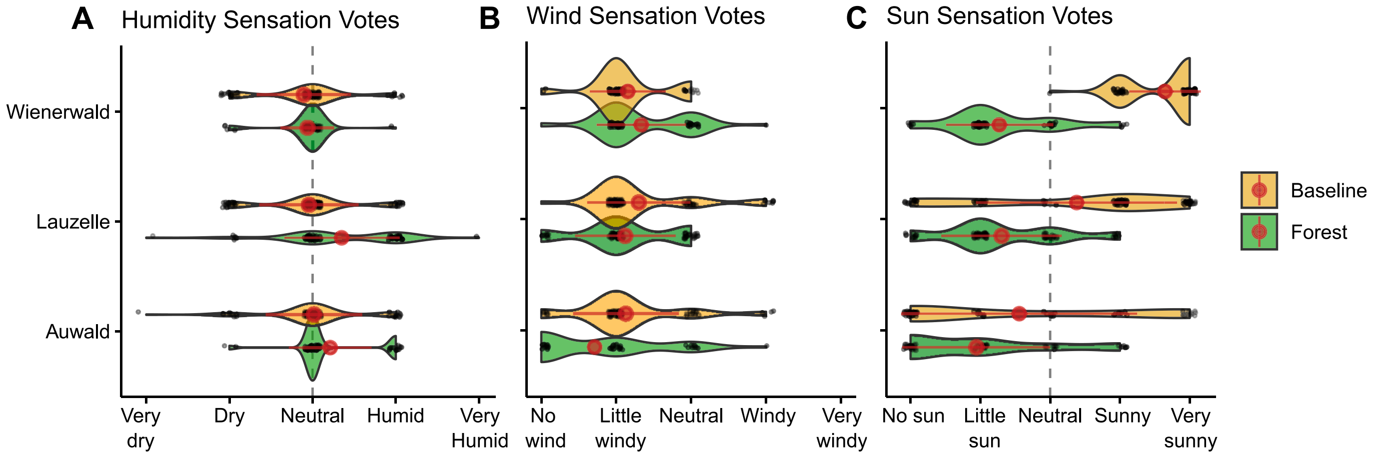

Fig. 4. Thermal preference votes (A) and overall comfort level (B) under non-forest baseline and forest conditions for our three study sites Leipzig Auwald (DE), Lauzelle (BE) and Wienerwald (AT). Analogous results for humidity, wind and sun preference votes are found in Fig. S6.

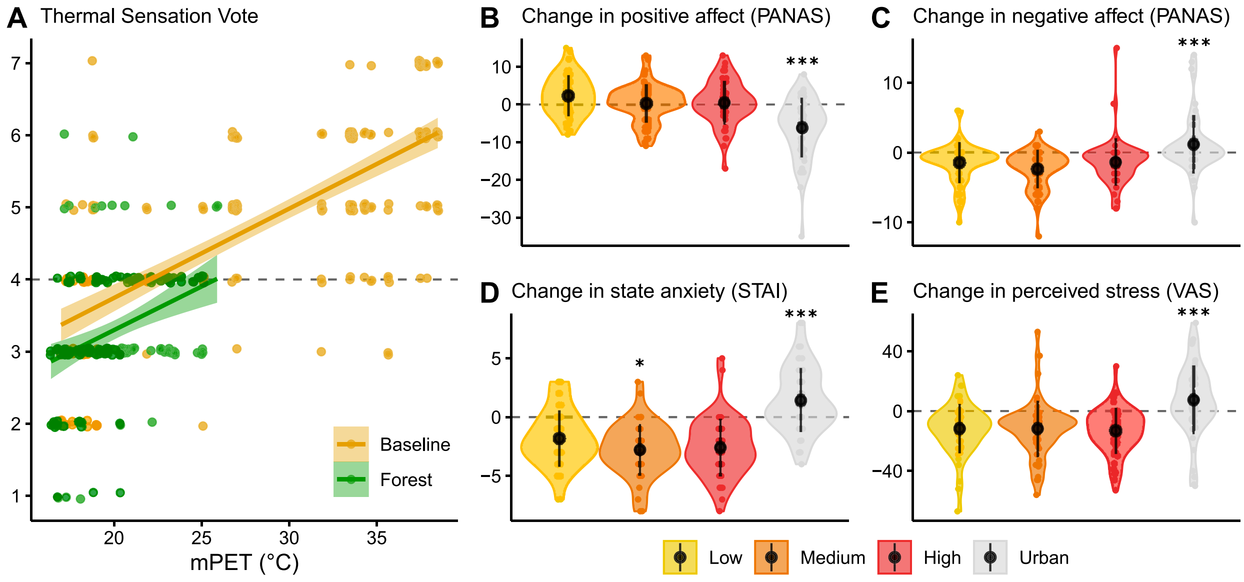

Fig. 5. Left (A), 7-point scale scores for the thermal sensation vote, ranging from 1 = cold, 4 = neutral to 7 = hot, representing subjective thermal comfort. Given the same perceived temperature value (10-min rolling average mPET), participants felt cooler in the forest than under baseline conditions (tested using linear and ordinal approaches). This discrepancy could result from psychological effects which may be forest-induced. Indeed, compared to the urban control, forests lead to higher positive affect (B), reduced negative affect (C), reduced state anxiety (D) and reduced perceived stress (E). The change in mental wellbeing levels (B-E) is compared to the baseline. The thicker the violin plot, the higher the point density. Significance levels are denoted as follows: *$p < 0.05$; **$p < 0.01$; ***$p < 0.001$. When grouped, forests were always significantly different from the baseline for B-E. Figures B-E adapted from Rozario et al. (*in press*). Cortisol results are found in Fig. S8.

to be colder. A back-transformation of coefficients yielded an odds ratio of 2.72 (95 % confidence interval = 1.62–4.57; $p < 0.001$), indicating that participants at the baseline were 2.72 times more likely to give a warmer vote than in the forest, while holding all other variables constant (i.e. mPET). These patterns persisted even when the analysis was restricted to the overlapping range of mPET values between baseline and forest conditions. To ensure that results were not biased due to assumptions inherent to the mPET model (e.g. in terms of radiation), we repeated all analyses using air temperature, non-modified PET and T_{mrt}. The statistical conclusions remained consistent, but were weaker for T_{mrt} (odds of 1.64 for baseline vs. forest), and more pronounced for PET (odds 3.23) and air temperature (odds 12.61).

Because thermal wellbeing was hypothesised to interact with forest-induced mental wellbeing, we briefly report essential mental wellbeing results needed to interpret the next section. Detailed results are found in Rozario et al. (*in press*). Mental wellbeing questionnaires revealed substantial differences between non-forest baselines, urban control conditions and forests as a whole, but not between forests (Fig. 5B-E). Relative to baselines and urban control, respectively, forest environments lead to higher positive affect ($p < 0.01$ and $p < 0.001$), lower negative affect (both $p < 0.001$), lower perceived stress (both $p < 0.001$) and lower state anxiety (both $p < 0.001$). Concerning cortisol levels, all conditions showed decreasing levels compared to the baseline ($p < 0.01$), but there were no differences between plots – even with the urban control (Fig. S8).

Matching objective thermal comfort (mPET) to mental outcomes did not lead to significant associations. However, subjective thermal comfort (TSV) was significantly linearly associated with positive affect ($p <$

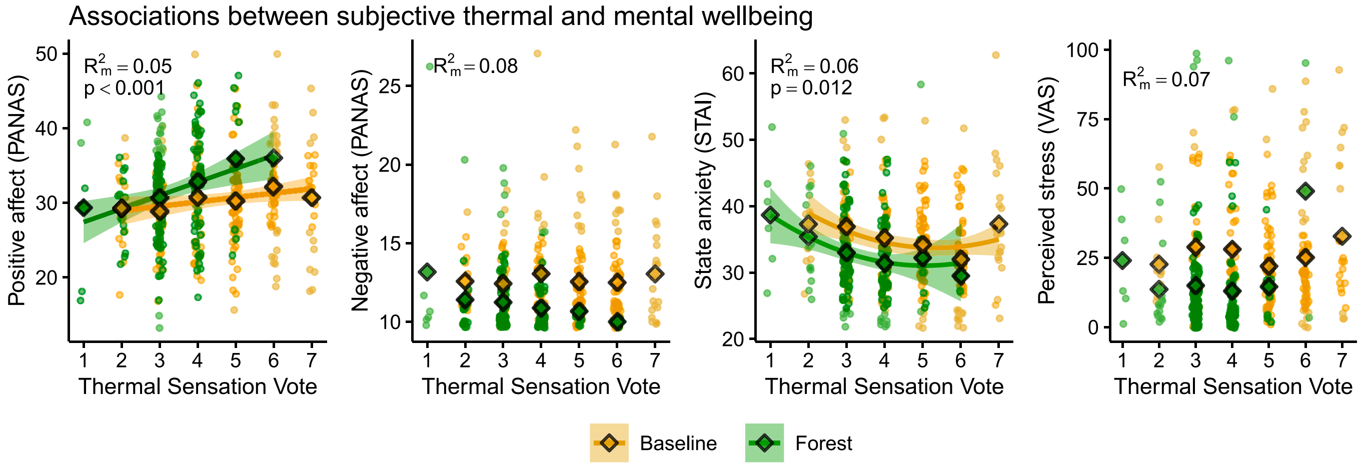

Fig. 6. Associations between subjective thermal wellbeing and four mental wellbeing outcomes, tested using mixed-model ANOVA and linear polynomial quadratic mixed model (LMM) approaches accounting for mPET. Marginal R^2 (R^2_m) are based on LMMs, as are p-values which relate to the relationship between thermal sensation votes and mental outcomes. In the case of state anxiety, the p-value is related to the second order term of the polynomial equation. The diamonds represent mean values per thermal sensation vote. For differences between baseline and forest, see Fig. 5B-E.

0.001) and quadratically with state anxiety ($p = 0.012$ for the second order term) (Fig. 6). According to the statistical trendlines, state anxiety is minimized around a TSV of 5 or 6, corresponding to slightly warm to warm conditions.

4. Discussion

In this study, we show that *peri*-urban forests strongly reduce objective heat stress and that this is effectively translated to subjective perception in participants. In the forest, participants felt even cooler than expected, and this may be linked to psychological effects which are forest-induced themselves. Furthermore, we propose that thermal and mental wellbeing mutually reinforce each other.

4.1. Objective thermal comfort

On average, forests exhibited a cooling effect of 9.2 °C mPET (ranging between + 3.7 °C and −18.4 °C mPET), strongly surpassing the cooling effects of air temperature alone (mean −1.9 °C). This highlights the need to consider all relevant microclimate variables affecting the human body. In this sense, the observed mean air temperature reduction of 4.1 °C in forests worldwide (De Frenne et al., 2019) is also expected to be substantially greater when using indices based on human physiology. Other studies using physiological indices found effects sizes similar to ours. A study in Freiburg, Germany, found a temperature reduction of over 10 °C PET in a *peri*-urban spruce forest compared to a south-exposed urban canyon on a very hot day (Mayer & Höppe, 1987). Another study in Campinas, Brazil, found cooling by tree clusters to range between 0.3 and 15.7 °C PET (de Abreu-Harbich, Labaki, & Matzarakis, 2015) and a study on 131 forest stands across Europe reported heat stress reductions of 10–14.5 °C PET under ‘strong heat stress’ or higher (Gillerot et al., 2022). Such temperature reductions have important implications, as increasing the urban canopy cover to 30 % has been projected to reduce over one third of UHI-attributable deaths in 93 European cities (Iungman et al., 2023). Moreover, trees and forests become increasingly important as global temperatures rise, since their cooling capacity gradually intensifies the hotter it becomes. This is shown in the current study but also by both global observational (De Frenne et al., 2019, De Frenne et al., 2021) and modelling studies (De Lombaerde et al., 2021).

Given that increasing tree coverage has great potential to prevent heat-related deaths, there is a need to identify specific trees and forest characteristics that contribute to maximising cooling effects. Generalisations using individual tree traits are starting to be possible (Rahman et al., 2020), but little is known at the forest level. We found significant differences between forest diversity levels, with high diversity plots being 1.1 °C cooler than low diversity plots. However, these differences cannot be solely attributed to tree diversity levels *per se*, because high diversity plots also had denser canopies – which is the most important stand structural driver (Gillerot et al., 2022; Zellweger et al., 2019). Therefore, the effects of diversity are likely indirect, with higher tree diversity leading to more efficient filling of the available canopy space (Jucker, Bouriaud, & Coomes, 2015). Forests with a diversity of small-leaved tree species with complementary crown shapes, sizes and heights which cast a deep shade, will probably generate the coolest conditions (Gillerot et al., 2022; Zellweger et al., 2019).

4.2. Subjective thermal comfort

We found that objective thermal comfort effectively explained variation in subjective perception. The wide range in objective conditions resulted in a diverse range of thermal sensation votes at the non-forest baseline, spanning from ‘cool’ to ‘hot’. In contrast, the majority of participants (81 %) reported feeling ‘neutral’ or ‘slightly cool’, and none reported feeling ‘hot’ in forests. Interestingly, more participants were satisfied with thermal conditions at baselines (59.0 %) compared to forests (52.4 %) based on preference scores, generally because forests were cooler than desired. This means that thermal conditions are in fact not always most optimal in forests under all conditions, though forests will consistently benefit heat mitigation. Yet, despite the desire for warmer forest conditions, fewer participants felt bothered by weather conditions and much more participants felt ‘very comfortable’ compared to the non-forest baseline. Analogous results were found in Bhopal, India, where participants reported greater comfort in a forested park despite rating all settings as hot (Ali & Patnaik, 2018). The modest difference of 1.1 °C mPET between low and high diversity forests did not appear to lead to significant differences in subjective data, possibly due to the limited number of participants per forest stand.

Most studies found forests to improve subjective thermal comfort. For example, a study in Seoul, Korea, reported that 60.3 % of participants were ‘hot’ at an urban location compared to 23.8 % in a nearby forest, with 2.5 times more participants feeling more comfortable in forests during summer (Jeong et al., 2016). In Xi’an, China, a deciduous canopy substantially improved thermal conditions to an extent comparable with a man-made pavilion in summer, while also offering superior subjective thermal comfort in winter from increased sunlight transmission through leafless trees (Xu, Hong, Jiang, An, & Zhang, 2019). In Xindu, China, participants desired shading by trees as PET increased (Guo et al., 2022). These studies, including ours, emphasise the disproportionately important role of solar radiation and therefore the importance of tree shading (Hiemstra, Saaroni, & Amorim, 2017; Mayer & Höppe, 1987; Middel, Selover, Hagen, & Chhetri, 2016), potentially surpassing the role of evapotranspiration. Yet, this is likely strongly context-dependent, as exemplified by a study in tropical Singapore where thermal perception was primarily influenced by wind and humidity (Chow et al., 2016). The same study also found the rainforest site to be perceived warmer than more open sites, which matches results from a subtropical study that found the most densely forested site to even be the least comfortable despite having the lowest PET (Wang, Ni, Peng, & Xia, 2018). These findings suggest that the applicability of our results may not be valid in hot and highly humid environments.

4.3. Interactions with mental wellbeing

Outdoor thermal comfort is directly influenced by physical, physiological and psychological factors (Höppe, 2002; Lai et al., 2020; Nikolopoulou & Steemers, 2003). We found that, for the same physical factors, participants perceived cooler temperatures in the forest by about half a TSV point. This discrepancy is unlikely to be attributable to (indirect) factors related to physiology such as age, sex, thermal history and metabolic activity, because the change occurred in the same individuals and their seated position standardised activity levels. The discrepancy is therefore most likely caused by psychological changes that are forest-induced, although it could also partly relate to subtle microclimatic differences not accounted for by the mPET model.

The forest in general, but not its specific characteristics, was found to have very consistent positive effects on all indicators of mental wellbeing, including positive and negative affect, state anxiety and perceived stress. Synthesising reports confirm the forest’s beneficial role in multiple mental wellbeing benefits throughout all human life stages (Konijnendijk, Devkota, Mansourian, & Wildburger, 2023; Wolf et al., 2020). A few rare studies do hint at differences among forests, including diversity levels. In a lab-based study, tree diversity levels were found to improve positive affect and anxiety (Wolf & zu Ermgassen, Balmford, White, & Weinstein, 2017). *In situ* research related to our study showed that, not actual tree species diversity, but subjectively perceived biodiversity was significantly associated with positive mental outcomes Rozario et al. (*in press*). As for salivary cortisol, we unexpectedly found a significant but slight decrease under both forest and urban conditions, starting from already relatively low initial levels (Kirschbaum & Hellhammer, 1989). A *meta*-analysis found comparable forest interventions to lead to significant short-term decreases in cortisol levels, although some studies found no effect and little data is available in general (Antonelli, Barbieri, & Donelli, 2019).

Psychological states are well known to affect subjective thermal comfort, which is typically explained by experience, expectation and perceived control (Nikolopoulou & Steemers, 2003). Much less studied are the effects of 'naturalness' and other psychological factors like emotional states (Lai et al., 2020). Our results indicate that the natural environment of the forest fosters positive mental wellbeing outcomes, the latter which might subsequently affect thermal comfort as suggested by the significant associations with positive affect and state anxiety. Such a mechanism was carefully alluded to by Jeong et al. (2016) after they found that the range of comfortable temperatures was wider in the forest. There is also evidence for the opposite effect where better thermal comfort has mental wellbeing benefits. This is what was suggested by a study that found a correlation between subjective thermal comfort and positive mood variables – although, unlike our study, differences in objective thermal comfort between forest and city were not accounted for (Park et al., 2011). At last, another study found correlations between objective thermal comfort (PET) and mood outcomes, anxiety, vitality and restorativeness (Elsadek et al., 2019).

Given these sources of evidence and our own results, there may be a consistent association between thermal and mental wellbeing, which might mutually reinforce themselves. The forest, by improving both independently, might foster this potential synergy, leading to higher mental and thermal wellbeing than expected based on observations under non-forest conditions.

4.4. Weaknesses, strengths and recommendations for future studies

Several considerations should be considered when interpreting our results, which can also guide future studies. Firstly, our study sample size (446 TSV votes) is relatively small compared to the median of 662 votes reported by a large review (Potchter et al., 2018). However, most of these studies used convenience sampling, generating one vote per participant. In contrast, our study involved the same participants voting under both non-forest baseline and forest conditions. This accounts for inter-individual variation, enabling the detection of more subtle environmental effects. The study's standardisation was additionally enhanced by ensuring participants spent at least 20 min seated under both conditions, which would be challenging with convenience sampling (Heng & Chow, 2019). Additionally, ensuring an equal sample size in biological sex may have reduced potential biases, but we have not found significant differences in our data – echoing conclusions on gender and neutral temperatures in a literature review (Karjalainen, 2012).

Another issue was that baseline conditions were not comparable across countries due to varying urbanicity of the surrounding environments. Comparing temperature reductions in forests compared to baselines between countries should thus be done with caution. Yet, the largest reductions were observed in Wienerwald which had the greenest baseline but also the warmest days. Again, this issue was partly compensated thanks to the within-subject design, but also addressed statistically using 'site' as a random factor.

The order of exposure may represent another potential bias, as participants were always exposed to non-forest baseline conditions first. For example, participants could systematically give cooler votes as the survey progresses, confounding the forest effect. However, based on generally slightly warmer votes at the urban control compared to non-forest baselines, this is probably not be the case (although urban controls were chosen to be potentially hotter and thus a suboptimal reference). Future studies may consider randomising the order of the interventions whenever logistically possible.

A last issue is the absence of very hot days during our study period, given our focus on heat stress. The objective measurements rarely exceeded 'moderate' heat stress, and therefore the reported cooling effects are conservative estimates of potential magnitudes. Still, our results do indicate that a meaningful share of participants experienced heat-related discomfort, which was almost entirely absent in forests.

Future studies that aim to explore more nuanced differences between various forest or vegetation types could take these considerations into account. Firstly, the conceptual model presented in Fig. 1B could be taken as a starting point for studies at the nexus of physical, physiological and mental influences on thermal comfort for a better understanding of causal pathways (paired with e.g. structural equation modelling). Some of the other limitations could be addressed through a within-subject survey design, where each participant is exposed to all forest conditions, varying factors such as stand structure and species composition independently. A study on hotter days could lead to more pronounced forest effects (Gillerot et al., 2022), although safety risks in control conditions would need to be minimised, for example, by exposing participants to forest conditions exclusively. Acclimatising participants while seated such as done here is also recommended, as this will limit potential bias caused by physical activity. Finally, we strongly encourage future studies to work from an interdisciplinary angle to combine knowledge from microclimate ecology, biometeorology, psychology and medicine. This way, we can move beyond coarse definitions of 'greenness' to identify which natural elements have the greatest potential to safeguard humans from heat stress.

5. Conclusions

Forest microclimates fostered stable and cool thermal environments which are strongly decoupled from non-forest conditions. This is evident in both the objectively measured conditions (T_a and mPET), and the subjective experiences of participants. While tree diversity levels had a slight influence on cooling, this was not detected by participants and is overshadowed by the forest in general. Surprisingly, participants were much more comfortable in the forests than expected based on thermal sensation and preference votes, and perceived the forest as cooler compared to baseline despite similar temperatures. We propose that this additional sense of cooling in the forest is linked to psychological effects induced by the forest environment. Furthermore, there were significant interrelationships between various thermal and mental outcomes. We therefore posit that forest environments could mediate a synergy between thermal and mental wellbeing. Forests can be employed by foresters and urban landscape planners as a nature-based solution to protect our environments against heat stress in an urbanising and warming world, with the particular advantage of simultaneously fostering multiple other health benefits such as improved mental wellbeing.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

The complete dataset, including forest ecological characteristics, biometeorological variables and subjective temperature votes, is available in Figshare at https://doi.org/10.6084/m9.figshare.24420487.v1.

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Appendix A. Supplementary data

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References

Akbari, H. (2002). Shade trees reduce building energy use and CO2 emissions from power plants. *Environmental Pollution, 116*, S119–S126. https://doi.org/10.1016/S0269-7491(01)00264-0

Ali, S. B., & Patnaik, S. (2018). Thermal comfort in urban open spaces: Objective assessment and subjective perception study in tropical city of Bhopal, India. *Urban Climate, 24*, 954–967. https://doi.org/10.1016/j.uclim.2017.11.006

Antonelli, M., Barbieri, G., & Donelli, D. (2019). Effects of forest bathing (shinrin-yoku) on levels of cortisol as a stress biomarker: A systematic review and meta-analysis. *International Journal of Biometeorology, 63*(8), 1117–1134. https://doi.org/10.1007/s00484-019-01717-x

Bates, D., Bolker, B., & Walker, S. (2015). Fitting linear mixed-effects models using lme4. *Journal of Statistical Software, 67*(1), 1–48.

Carter, A. W., Zaitchik, B. F., Gohlke, J. M., Wang, S., & Richardson, M. B. (2020). Methods for estimating wet bulb globe temperature from remote and low-cost data: A comparative study in central alabama. *GeoHealth, 4*(5), Article e2019GH000231. https://doi.org/10.1029/2019GH000231

Chaudhuri, T., Zhai, D., Soh, Y. C., Li, H., & Xie, L. (2018). Random forest based thermal comfort prediction from gender-specific physiological parameters using wearable sensing technology. *Energy and Buildings, 166*, 391–406. https://doi.org/10.1016/j.enbuild.2018.02.035

Chen, Y.-C., & Matzarakis, A. (2018). Modified physiologically equivalent temperature—Basics and applications for western European climate. *Theoretical and Applied Climatology, 132*(3), 1275–1289. https://doi.org/10.1007/s00704-017-2158-x

Chow, W. T. L. (2016). Assessment of measured and perceived microclimates within a tropical urban forest. *Urban Forestry & Urban Greening, 16*, 62–75. https://doi.org/10.1016/j.ufug.2016.01.010

Christensen, R. H. B. (2022). ordinal—Regression Models for Ordinal Data.

de Abreu-Harbich, L. V., Labaki, L. C., & Matzarakis, A. (2015). Effect of tree planting design and tree species on human thermal comfort in the tropics. *Landscape and Urban Planning, 138*, 99–109. https://doi.org/10.1016/j.landurbplan.2015.02.008

De Frenne, P., Lenoir, J., Luoto, M., Scheffers, B. R., Zellweger, F., Aalto, J., … Hylander, K. (2021). Forest microclimates and climate change: Importance, drivers and future research agenda. *Global Change Biology*. https://researchportal.helsinki.fi/en/publications/forest-microclimates-and-climate-change-importance-drivers-and-fu.

De Frenne, P., Zellweger, F., Rodríguez-Sánchez, F., Scheffers, B. R., Hylander, K., Luoto, M., … Lenoir, J. (2019). Global buffering of temperatures under forest canopies. *Nature Ecology & Evolution, 3*(5), 744–749. https://doi.org/10.1038/s41559-019-0842-1

De Lombaerde, E., Vangansbeke, P., Lenoir, J., Van Meerbeek, K., Lembrechts, J., Rodríguez-Sánchez, F., … De Frenne, P. (2021). Maintaining forest cover to enhance temperature buffering under future climate change. *Science of The Total Environment, 151338*. https://doi.org/10.1016/j.scitotenv.2021.151338

Ebi, K. L., Capon, A., Berry, P., Broderick, C., de Dear, R., Havenith, G., … Jay, O. (2021). Hot weather and heat extremes: Health risks. *The Lancet, 398*(10301), 698–708. https://doi.org/10.1016/S0140-6736(21)01208-3

Elsadek, M., Liu, B., Lian, Z., & Xie, J. (2019). The influence of urban roadside trees and their physical environment on stress relief measures: A field experiment in Shanghai. *Urban Forestry & Urban Greening, 42*, 51–60. https://doi.org/10.1016/j.ufug.2019.05.007

Favero, M., Luparelli, A., & Carlucci, S. (2023). Analysis of subjective thermal comfort data: A statistical point of view. *Energy and Buildings, 281*, Article 112755. https://doi.org/10.1016/j.enbuild.2022.112755

Gillerot, L., Landuyt, D., Oh, R., Chow, W., Haluza, D., Ponette, Q., … Verheyen, K. (2022). Forest structure and composition alleviate human thermal stress. *Global Change Biology, 28*(24), 7340–7352. https://doi.org/10.1111/gcb.16419

Guo, W., Jiang, L., Cheng, B., Yao, Y., Wang, C., Kou, Y., … Xian, D. (2022). A study of subtropical park thermal comfort and its influential factors during summer. *Journal of Thermal Biology, 109*, Article 103304. https://doi.org/10.1016/j.jtherbio.2022.103304

Heng, S. L., & Chow, W. T. L. (2019). How 'hot' is too hot? Evaluating acceptable outdoor thermal comfort ranges in an equatorial urban park. *International Journal of Biometeorology, 63*(6), 801–816. https://doi.org/10.1007/s00484-019-01694-1

Hiemstra, J. A., Saaroni, H., & Amorim, J. H. (2017). The Urban Heat Island: Thermal Comfort and the Role of Urban Greening. In , P. (1999). The physiological equivalent temperature—A universal index for the biometeorological assessment of the thermal environment. International Journal of Biometeorology, 43(2), 71–75. https://doi.org/10.1007/s004840050118.

Höppe, P. (1999). The physiological equivalent temperature—A universal index for the biometeorological assessment of the thermal environment. *International Journal of Biometeorology, 43*(2), 71–75. https://doi.org/10.1007/s004840050118

Höppe, P. (2002). Different aspects of assessing indoor and outdoor thermal comfort. *Energy and Buildings, 34*(6), 661–665. https://doi.org/10.1016/S0378-7788(02)00017-8

Iungman, T., Cirach, M., Marando, F., Barboza, E. P., Khomenko, S., Masselot, P., … Nieuwenhuijsen, M. (2023). Cooling cities through urban green infrastructure: A health impact assessment of European cities. *The Lancet*. https://doi.org/10.1016/S0140-6736(22)02585-5

Jafari, M. J., Khosrowabadi, R., Khodakarim, S., Khodagholi, F., & Mohammadian, F. (2021). The effects of combined exposure to noise and heat on human salivary cortisol and blood pressure. *International Journal of Occupational Safety and Ergonomics, 27*(3), 831–839. https://doi.org/10.1080/10803548.2019.1659578

Jeong, M.-A., Park, S., & Song, G.-S. (2016). Comparison of human thermal responses between the urban forest area and the central building district in Seoul, Korea. *Urban Forestry & Urban Greening, 15*, 133–148. https://doi.org/10.1016/j.ufug.2015.12.005

Johansson, E., Thorsson, S., Emmanuel, R., & Krüger, E. (2014). Instruments and methods in outdoor thermal comfort studies – The need for standardization. *Urban Climate, 10*, 346–366. https://doi.org/10.1016/j.uclim.2013.12.002

Jucker, T., Bouriaud, O., & Coomes, D. A. (2015). Crown plasticity enables trees to optimize canopy packing in mixed-species forests. *Functional Ecology, 29*(8), 1078–1086. https://doi.org/10.1111/1365-2435.12428

Karjalainen, S. (2012). Thermal comfort and gender: A literature review. *Indoor Air, 22*(2), 96–109. https://doi.org/10.1111/j.1600-0668.2011.00747.x

Kirschbaum, C., & Hellhammer, D. H. (1989). Salivary cortisol in psychobiological research: An overview. *Neuropsychobiology, 22*(3), 150–169. https://doi.org/10.1159/000118611

Konijnendijk, C., Devkota, D., Mansourian, S., & Wildburger, C. (2023). Forests and Trees for Human Health: Pathways, Impacts, Challenges and Response Options. A Global Assessment Report (IUFRO World Series Volume 41, p. 232). IUFRO.

Lai, D., Lian, Z., Liu, W., Guo, C., Liu, W., Liu, K., & Chen, Q. (2020). A comprehensive review of thermal comfort studies in urban open spaces. *Science of The Total Environment, 742*, Article 140092. https://doi.org/10.1016/j.scitotenv.2020.140092

Lee, H., Mayer, H., & Chen, L. (2016). Contribution of trees and grasslands to the mitigation of human heat stress in a residential district of Freiburg, Southwest Germany. *Landscape and Urban Planning, 148*, 37–50. https://doi.org/10.1016/j.landurbplan.2015.12.004

Lehnert, M., Tokar, V., Jurek, M., & Geletič, J. (2020). Summer thermal comfort in Czech cities: Measured effects of blue and green features in city centres. *International Journal of Biometeorology*. https://doi.org/10.1007/s00484-020-02010-y

Marselle, M. R., Irvine, K. N., Lorenzo-Arribas, A., & Warber, S. L. (2015). Moving beyond Green: Exploring the relationship of environment type and indicators of perceived environmental quality on emotional well-being following group walks. *International Journal of Environmental Research and Public Health, 12*(1), Article 1. https://doi.org/10.3390/ijerph120100106

Matzarakis, A., Mayer, H., & Iziomon, M. G. (1999). Applications of a universal thermal index: Physiological equivalent temperature. *International Journal of Biometeorology, 43*(2), 76–84. https://doi.org/10.1007/s004840050119

Matzarakis, A., Rutz, F., & Mayer, H. (2007). Modelling radiation fluxes in simple and complex environments—Application of the RayMan model. *International Journal of Biometeorology, 51*(4), 323–334. https://doi.org/10.1007/s00484-006-0061-8

Matzarakis, A., Rutz, F., & Mayer, H. (2010). Modelling radiation fluxes in simple and complex environments: Basics of the RayMan model. *International Journal of Biometeorology, 54*(2), 131–139. https://doi.org/10.1007/s00484-009-0261-0

Mayer, H., & Höppe, P. (1987). Thermal comfort of man in different urban environments. *Theoretical and Applied Climatology, 38*(1), 43–49. https://doi.org/10.1007/BF00866252

Middel, A., Selover, N., Hagen, B., & Chhetri, N. (2016). Impact of shade on outdoor thermal comfort—A seasonal field study in Tempe Arizona. *International Journal of Biometeorology, 60*(12), 1849–1861. https://doi.org/10.1007/s00484-016-1172-5

Mora, C., Dousset, B., Caldwell, I. R., Powell, F. E., Geronimo, R. C., Bielecki, C. R., … Trauernicht, C. (2017). Global risk of deadly heat. *Nature Climate Change, 7*(7), 501–506. https://doi.org/10.1038/nclimate3322

Nazarian, N., Liu, S., Kohler, M., Lee, J. K. W., Miller, C., Chow, W. T. L., … Norford, L. K. (2021). Project Coolbit: Can your watch predict heat stress and thermal comfort sensation? *Environmental Research Letters, 16*(3), Article 034031. https://doi.org/10.1088/1748-9326/abd130

Nghiem, T. P. L., Wong, K. L., Jeevanandam, L., Chang, C. C., Tan, L. Y. C., Goh, Y., & Carrasco, L. R. (2021). Biodiverse urban forests, happy people: Experimental evidence linking perceived biodiversity, restoration, and emotional wellbeing. Urban Forestry and Urban Greening, 59(September 2020), 127030. https://doi.org/10.1016/j.ufug.2021.127030.

Nikolopoulou, M. (2011). *Outdoor thermal comfort. Frontiers in Bioscience (Scholar Edition), 3*, 1552–1568. https://doi.org/10.2741/245

Nikolopoulou, M., & Lykoudis, S. (2006). Thermal comfort in outdoor urban spaces: Analysis across different European countries. *Building and Environment, 41*(11), 1455–1470. https://doi.org/10.1016/j.buildenv.2005.05.031

Nikolopoulou, M., & Steemers, K. (2003). Thermal comfort and psychological adaptation as a guide for designing urban spaces. *Energy and Buildings, 35*(1), 95–101. https://doi.org/10.1016/S0378-7788(02)00084-1

Park, B.-J., Furuya, K., Kasetani, T., Takayama, N., Kagawa, T., & Miyazaki, Y. (2011). Relationship between psychological responses and physical environments in forest settings. *Landscape and Urban Planning, 102*(1), 24–32. https://doi.org/10.1016/j.landurbplan.2011.03.005

Pinheiro, J., Bates, D., Debroy, S., & Sarkar, D. (2021). nlme: Linear and nonlinear mixed effects models. *Core Team.* URL https://CRAN.R-project.org/package=nlme.

Potchter, O., Cohen, P., Lin, T.-P., & Matzarakis, A. (2018). Outdoor human thermal perception in various climates: A comprehensive review of approaches, methods and quantification. *Science of The Total Environment, 631–632*, 390–406. https://doi.org/10.1016/j.scitotenv.2018.02.276

R Core Team. (2013). R: A language and environment for statistical computing.

Rahman, M. A., Stratopoulos, L. M. F., Moser-Reischl, A., Zölch, T., Häberle, K.-H., Rötzer, T., … Pauleit, S. (2020). Traits of trees for cooling urban heat islands: A meta-analysis. *Building and Environment, 170*, Article 106606. https://doi.org/10.1016/j.buildenv.2019.106606

Rathmann, J., Beck, C., Flutura, S., Seiderer, A., Aslan, I., & André, E. (2020). Towards quantifying forest recreation: Exploring outdoor thermal physiology and human well-being along exemplary pathways in a central European urban forest (Augsburg, SE-Germany). *Urban Forestry & Urban Greening, 49*, Article 126622. https://doi.org/10.1016/j.ufug.2020.126622

Romanello, M., Di Napoli, C., Drummond, P., Green, C., Kennard, H., Lampard, P., … Costello, A. (2022). The 2022 report of the Lancet Countdown on health and climate change: Health at the mercy of fossil fuels. *The Lancet, 400*(10363), 1619–1654. https://doi.org/10.1016/S0140-6736(22)01540-9

Rozario, K., Ying Oh, R.R., Marselle, M., Schröger, E., Gillerot, L., Ponette, Q., … Bonn, A., (in press). The more the merrier? Perceived forest biodiversity promotes short-term mental health and well-being - a multicentre study Accepted in People and Nature.

Schebella, M. F., Weber, D., Schultz, L., & Weinstein, P. (2020). The nature of reality: Human stress recovery during exposure to biodiverse, multisensory virtual environments. *International Journal of Environmental Research and Public Health, 17* (1), 1–24. https://doi.org/10.3390/ijerph17010056

Shashua-Bar, L., Pearlmutter, D., & Erell, E. (2011). The influence of trees and grass on outdoor thermal comfort in a hot-arid environment. *International Journal of Climatology, 31*(10), 1498–1506. https://doi.org/10.1002/joc.2177

Spielberger, C. D., Gonzalez-Reigosa, F., Martinez-Urrutia, A., Natalicio, L. F., & Natalicio, D. S. (1971). The state-trait anxiety inventory. *Revista Interamericana de Psicologia/Interamerican Journal of Psychology, 5*(3 & 4).

Stewart, I. D., & Oke, T. R. (2012). Local climate zones for urban temperature studies. *Bulletin of the American Meteorological Society, 93*(12), 1879–1900. https://doi.org/10.1175/BAMS-D-11-00019.1

Taleghani, M. (2018). Outdoor thermal comfort by different heat mitigation strategies- A review. *Renewable and Sustainable Energy Reviews, 81*, 2011–2018. https://doi.org/10.1016/j.rser.2017.06.010

Thiery, W., Lange, S., Rogelj, J., Schleussner, C.-F., Gudmundsson, L., Seneviratne, S. I., … Wada, Y. (2021). Intergenerational inequities in exposure to climate extremes. *Science, 374*(6564), 158–160.

Thorsson, S., Lindberg, F., Eliasson, I., & Holmer, B. (2007). Different methods for estimating the mean radiant temperature in an outdoor urban setting. *International Journal of Climatology, 27*(14), 1983–1993. https://doi.org/10.1002/joc.1537

United Nations. (2019). World urbanization prospects: The 2018 revision.

Vicedo-Cabrera, A. M., Scovronick, N., Sera, F., Royé, D., Schneider, R., & Tobias, A. (2021). The burden of heat-related mortality attributable to recent human-induced climate change. *Nature Climate Change, 11*(6), Article 6. https://doi.org/10.1038/s41558-021-01058-x

Wang, Y., Ni, Z., Peng, Y., & Xia, B. (2018). Local variation of outdoor thermal comfort in different urban green spaces in Guangzhou, a subtropical city in South China. *Urban Forestry & Urban Greening, 32*, 99–112. https://doi.org/10.1016/j.ufug.2018.04.005

Watson, D., Clark, L. A., & Tellegen, A. (1988). Development and validation of brief measures of positive and negative affect: The PANAS scales. *Journal of Personality and Social Psychology, 54*(6), 1063.

Wolf, K. L., Lam, S. T., McKeen, J. K., Richardson, G. R. A., van den Bosch, M., & Bardekjian, A. C. (2020). Urban trees and human health: A scoping review. *International Journal of Environmental Research and Public Health, 17*(12), Article 12. https://doi.org/10.3390/ijerph17124371

Wolf, L. J. (2017). Is variety the spice of life? An experimental investigation into the effects of species richness on self-reported mental well-being. *PLoS One1, 12*(1), e0170225.

Xu, M., Hong, B., Jiang, R., An, L., & Zhang, T. (2019). Outdoor thermal comfort of shaded spaces in an urban park in the cold region of China. *Building and Environment, 155*, 408–420. https://doi.org/10.1016/j.buildenv.2019.03.049

Zellweger, F., Coomes, D., Lenoir, J., Depauw, L., Maes, S. L., Wulf, M., … Frenne, P. D. (2019). Seasonal drivers of understorey temperature buffering in temperate deciduous forests across Europe. *Global Ecology and Biogeography, 28*(12), 1774–1786. https://doi.org/10.1111/geb.12991

Zepner, L., Karrasch, P., Wiemann, F., & Bernard, L. (2021). ClimateCharts.net – An interactive climate analysis web platform. *International Journal of Digital Earth, 14*(3), 338–356. https://doi.org/10.1080/17538947.2020.1829112