Global Change Biology

WILEY

Global Change Biology

RESEARCH ARTICLE

Interactive Effects of Weather and Forest Structure on Microclimate Buffering in European Deciduous Forests

Liping Wei[1,2,3] | Pieter Sanczuk[1] | Pieter Vangansbeke[1,4] | Karen De Pauw[1] | Thomas Vanneste[1] | Kurt Bollmann[5] | Jörg Brunet[6] | Kim Calders[7] | Sara A. O. Cousins[8] | Martin Diekmann[9] | Cristina Gasperini[10] | Bente J. Graae[11] | Per-Ola Hedwall[6] | Giovanni Iacopetti[10] | Jonathan Lenoir[12] | Anna Orczewska[13] | Quentin Ponette[14] | Jan Plue[8] | Ilaria Santi[10] | Federico Selvi[10] | Fabien Spicher[12] | Hans Verbeeck[7] | Florian Zellweger[5] | Pieter De Frenne[1]

[1]Forest & Nature Lab, Department of Environment, Faculty of Bioscience Engineering, Ghent University, Melle-Gontrode, Belgium | [2]Institute of Biodiversity, Ecology and Evolution, Friedrich-Schiller-University Jena, Jena, Germany | [3]Senckenberg Institute for Plant Form and Function (SIP) Jena, Jena, Germany | [4]Research Institute for Nature and Forest (INBO), Brussels, Belgium | [5]Swiss Federal Institute for Forest, Snow and Landscape Research WSL, Birmensdorf, Switzerland | [6]Southern Swedish Forest Research Centre, Swedish University of Agricultural Sciences, Lomma, Sweden | [7]Q-ForestLab, Department of Environment, Faculty of Bioscience Engineering, Ghent University, Ghent, Belgium | [8]Department of Physical Geography, Stockholm University, Stockholm, Sweden | [9]Vegetation Ecology and Conservation Biology, Institute of Ecology, FB2, University of Bremen, Bremen, Germany | [10]Department of Agriculture, Food, Environment and Forestry, University of Florence, Florence, Italy | [11]Department of Biology, Norwegian University of Science and Technology, Trondheim, Norway | [12]UMR CNRS 7058 «Ecologie et Dynamique Des Systèmes Anthropisés», Université de Picardie Jules Verne, Amiens, France | [13]Institute of Biology, Biotechnology and Environmental Protection, Faculty of Natural Sciences, University of Silesia, Katowice, Poland | [14]Earth and Life Institute, Université Catholique de Louvain, Louvain-la-Neuve, Belgium

Correspondence: Liping Wei (liping.wei228@hotmail.com)

Received: 27 March 2025 | **Revised:** 5 November 2025 | **Accepted:** 6 November 2025

Keywords: air temperature offset | daily weather | long-term observation | plant area index | seasonal climate patterns | soil temperature offset | temperate forests

ABSTRACT

The microclimate temperature within forests can substantially deviate from measurements outside forests. Yet, the amount and direction of this buffering strongly depend on meteorological conditions outside forests, such as free-air temperature, wind speed, soil moisture, precipitation and solar radiation. Most studies on microclimate buffering focus on long-term averages at coarse temporal resolution (e.g., monthly to seasonal), potentially overlooking the impact of daily fluctuations, which are nonetheless critical for many forest species and processes. Here, we linked in situ measured air and soil temperatures, at the daily resolution over a period of more than 5 years across 45 European deciduous forests spanning a 2300-km latitudinal gradient, to daily variation in weather conditions (i.e., free-air temperature, precipitation, wind speed, soil moisture, solar radiation, day length and snow cover). We assessed the interactive effects of weather conditions and forest structural complexity (plant area index) and distance to the forest edge on air and soil temperature offsets. Temperature offsets are the difference between understory air or soil temperature and macroclimate reference conditions measured at weather stations in the open field. We show that relative effect sizes of free-air temperature prevailed over the effects of other weather variables to determine air and soil temperature buffering. In general, higher free-air temperatures, soil moisture, wind speed and snow cover led to more negative air and soil temperature offsets, with variations depending on forest structural complexity and season. Conversely, slightly increased air and soil temperature offsets were found as precipitation and solar radiation increased. Our study highlights the dominant role of daily free-air temperature fluctuations outside forests in shaping microclimatic buffering. We emphasize complex interaction paths between

daily weather conditions, and forest structure and edge effects, offering valuable insights for next-generation microclimate models and enhancing our understanding of forest ecosystem responses to environmental change that account for microclimate.

1 | Introduction

Trees are ecosystem engineers modulating the climatic conditions experienced by forest biota and affecting forest ecosystem functioning (De Frenne et al. 2019; Beugnon et al. 2024). In forests, tree canopies can significantly reduce levels of direct solar radiation and wind speed, resulting in understory microclimatic conditions that are buffered from the extreme fluctuations of free-air temperatures as measured by weather stations (Geiger et al. 2009; Zellweger et al. 2019; De Frenne et al. 2021). Microclimate influences the survival, growth, and dispersal of forest organisms as well as key ecosystem processes like rates of litter decomposition, carbon sequestration, microbial activity and nutrient cycling (Riutta et al. 2012; Sanczuk et al. 2023; Vanneste et al. 2024; Wei et al. 2024).

Microclimate temperature and its offset—that is, the difference between micro- and macroclimate temperature—are influenced by weather conditions, at both coarse and fine temporal resolutions, including free-air temperature, precipitation, wind, soil moisture, solar radiation and snow cover (Von Arx et al. 2013; De Frenne et al. 2019; Zellweger et al. 2019). The temperature offset in forests is negatively correlated with free-air temperature outside forests during the growing season, and this offset is magnified as free-air temperatures become more extreme (De Frenne et al. 2019). The ability of forest canopies to buffer temperature extremes also decreased in areas where changes in precipitation regimes lead to decreased water availability and higher climatic water deficit (Davis et al. 2019). Solar radiation also shapes microclimate conditions, as increased incoming radiation elevates surface temperatures and can further reduce the effectiveness of canopy shading when drought stress leads to early leaf senescence or canopy dieback (De Frenne et al. 2021; Zellweger et al. 2024). While wind patterns affect the heat fluxes and evaporation rates, lower wind speeds are probably associated with more buffering due to decreased air mixing (Chen et al. 1993; Ashcroft and Gollan 2013). Snow cover, with its low thermal conductivity and high albedo, strongly impacts the soil thermal regime and microclimate by decoupling near-ground temperature from above-snow temperature (Zhang et al. 2008; Aalto et al. 2022). Decreased snow cover at high latitudes and elevations, for instance, leads to colder soils and deeper soil frost (Hardy et al. 2001; Decker et al. 2003).

The effects of weather conditions on forest microclimates may also be modified—either strengthened, weakened, or even reversed—by stand characteristics shaped by forest disturbances and edge effects. Forest structure, tree species composition and canopy density, along with distance from the forest edge, play crucial roles in shaping and modifying microclimatic conditions (Zellweger et al. 2019; Meeussen et al. 2021; Díaz-Calafat et al. 2023). Forests with greater structural complexity, characterized by denser canopies, greater vertical layering, and higher biomass, enhance temperature buffering by promoting evapotranspiration and energy dissipation (e.g., Frey et al. 2016; Kovács et al. 2020; Menge et al. 2023). For example, higher canopy cover and a multi-layered canopy in summer increase the cooling effect on temperatures, leading to more stable temperatures in forest interiors (Greiser et al. 2018; Jucker et al. 2018; De Frenne et al. 2019). In contrast, management practices that simplify structure, such as clear-felling, diminish these cooling effects and lead to warmer microclimates (Kovács et al. 2020; Menge et al. 2023). Distance to the forest edge can also directly influence microclimate buffering by increasing exposure to solar radiation, wind, and atmospheric mixing near the forest boundary, as well as reducing nighttime insulation (Matlack 1993; Davies-Colley et al. 2000; Schmidt et al. 2017; Meeussen et al. 2021). While such abiotic influences can act independently of forest composition or canopy traits, indirect effects linked to changes in structural complexity along the edge-to-interior gradient may also contribute (Harper et al. 2005; Meeussen et al. 2020). Moreover, the combined effects of external weather conditions and internal forest characteristics vary across seasons, with the most obvious differences occurring between the leaf-on and leaf-off seasons in deciduous forests (Zellweger et al. 2019; Gril et al. 2023). In summer, the canopy provides shade and deciduous trees transpire vast amounts of water, while subcanopy and understory layers further enhance moisture retention, thus reducing light and temperature levels and increasing relative air humidity from open to dense forests (Von Arx et al. 2013; De Frenne et al. 2019). In winter, the absence of foliage in deciduous forests stops transpiration and allows more solar radiation to reach the forest floor, as well as higher wind speeds and more intensive air mixing in forest interiors compared to the leaf-on period, thus altering temperature and humidity patterns.

Most studies focus on temperature offsets aggregated at the monthly, seasonal, or even annual resolution, thereby overlooking signals brought about by weather conditions that vary from day to day (Bramer et al. 2018; Greiser et al. 2018; Díaz-Calafat et al. 2023). Studies investigating microclimatic fluctuations at finer temporal resolutions are necessary to capture daily variations or extremes (John et al. 2024; Zellweger et al. 2024). With climate change bringing longer and more frequent and intense extreme temperatures and precipitation patterns (IPCC 2021), it is uncertain if forest microclimates can still buffer those extremes and serve as long-term refugia for species (Lenoir et al. 2017; De Frenne et al. 2021; Richard et al. 2021). Developing the next generation of microclimate models requires high-resolution daily data to better understand the climatic and biotic drivers shaping forest microclimates and their role in sustaining biodiversity and ecosystem functioning under climate change (Frey et al. 2016; De Frenne et al. 2021; Hes et al. 2024).

Long-term in situ measurements of local temperatures are essential for understanding the full range of spatial and temporal variability in daily forest microclimates and their determinants, and for accurately assessing their impact on forest ecosystems over time (De Frenne et al. 2021, 2025). Here we analyzed air and soil temperature offsets at a daily resolution for 219 plots installed along a latitudinal gradient from central Norway to the Mediterranean region and spanning a period of more than 5 years. Although our data were collected at hourly resolution, we focused our analysis at the daily scale, as this is standard in meteorology and to address the current lack of systematic studies examining multiple weather and temperature variables across large spatial extents at this temporal resolution. Aggregating to daily values also reduces noise from transient fluctuations in hourly measurements, resulting in more reliable and representative data. Temperature data loggers were positioned in a standardized design along gradients of forest density and an edge-to-interior gradient in 45 European deciduous forests, primarily dominated by oaks (*Quercus* sp.) and beech (*Fagus sylvatica*). By including eight weather variables presenting daily weather conditions outside the forest (i.e., daily free-air temperature and its range, solar radiation, precipitation, wind speed, soil moisture, day length and snow cover), our study focused on two key questions:

1. How do weather conditions and their interactions with forest structure and edge distance influence temperature offsets at a daily temporal resolution, a higher temporal resolution than typically studied?
2. Do the effects of weather variables differ between the summer and winter season?

2 | Material and Methods

2.1 | Study Area and Experimental Design

This study was carried out in nine regions spanning a 2300-km long latitudinal gradient across Europe (from north to south): Norway, central and southern Sweden, Germany, Poland, Belgium, France, Switzerland and Italy (Figure 1). The studied latitudinal gradient spans a large variation in mean annual temperature (MAT) of >10°C and annual precipitation variation of 700mm (data retrieved from the CHELSA database for the period 1979–2013 at a spatial resolution of ~1km^2; Karger et al. 2017). In three of these regions (Italy, Belgium and Norway), an additional elevational gradient was established; forests were selected at low (21–200m above sea level), intermediate (201–600ma.s.l.), and high (601–908ma.s.l.) elevations, corresponding to a smaller macroclimate gradient of 1.5°C–4°C MAT. The inclusion of sites across different elevations aimed to broaden environmental coverage within regions and enhance the generality and robustness of our findings. In the other six regions, only one forest per region was selected, with elevations between 7.5 and 451m above sea level. We focused on deciduous forests dominated by oaks (*Quercus* sp.) and beech (*Fagus sylvatica*), with *Betula pubescens, Populus tremula, Ulmus glabra, Alnus incana* and *Carpinus betulus* as other (sub) dominant tree species (Govaert et al. 2020).

In each region, three types of forest stand structures representing different management intensities and vertical complexities, in terms of vegetation layering and canopy opening, were selected. The first type of forest stands was “dense forests”, which were not thinned for at least 10–30years before the installation of the temperature loggers. These forests had a well-developed understory shrub layer and a complex vertical structure leading to low canopy openness (5.8% ± 0.6% SD) and high basal area (mean and standard error of 28.8 ± 1.5m^2/ha). The second type of forest stand was classified as ‘intermediate forests’, corresponding to forests that were regularly thinned with the most recent thinning event happening 5–10years prior to sampling. The shrub layer of this forest type was sparser and the vertical structure less complex (canopy openness of 6.5% ± 0.6% SD and mean basal area of 31.4 ± 1.9 SD m^2/ha) than the dense forests. The third type was ‘open forests’, without any understory shrub layer and without a subdominant tree layer as they were intensively thinned one or up to 4years before sampling, leading to very simple vertical structures. Where possible, these forests were selected based on a high canopy openness (30%–50%) and low basal area (<10–15m^2 per ha). Further details on the study design, stand structure and site selection can be found in Govaert et al. (2020).

In each of the three forest stand types, a 100-m edge-to-interior transect was established perpendicular to a south-facing forest edge to ensure comparability since edge orientation can considerably affect forest microclimate (Matlack 1993; Honnay et al. 2002; Orczewska and Glista 2005). Along each edge-to-interior transect, five plots were established with their plot centers at an exponentially increasing distance from the forest edge, namely at 1.5, 4.5, 12.5, 35.5 and 99.5m from the edge, as the strongest changes in microclimatic conditions were expected to occur near the forest edge (Matlack 1993; Young and Mitchell 1994; Davies-Colley et al. 2000; Meeussen et al. 2021). Thus, in total 45 forest edge-to-interior transects were established and sampled ((6 lowland regions +9 from 3 regions with elevation gradients) × 3 forest types), totaling 225 plots (45 forest edges × 5 plots per edge-to-interior transect).

2.2 | Data Collection and Calculation

2.2.1 | In-Situ Microclimate Temperatures

We measured hourly air and soil temperatures over more than 5years, from January 2018 to October 2023 (data contributed to the SoilTemp database; Lembrechts et al. 2020). We extracted data from March 2, 2018, to June 4, 2023 (1921days), covering the period when all regions were actively recording. Both air and soil temperatures were recorded using Lascar temperature loggers (EasyLog EL-USB-1, accuracy: ±0.5°C). Air temperature loggers were installed at a height of 1m above the forest floor. The sensors were attached to the north side of a wooden pole placed at the center of each plot and protected by plastic white radiation shields to prevent direct solar radiation on the sensors. Soil temperature loggers were buried horizontally in protective plastic tubes at a depth of 5cm and positioned 5cm away from the wooden poles.

2.2.2 | Weather Data

We extracted hourly weather data from the ERA5-Land database (Muñoz-Sabater et al. 2021) for the same period and locations as the temperature logger measurements, at a spatial resolution of 0.1 × 0.1 degrees (native resolution of 9 × 9km near the equator) [EPSG:4326]. Note that plots within the same transect most often share the same ERA5-Land data due to the coarser spatial resolution of the ERA5-Land database (9 × 9km). The ERA5-Land data provide interpolated free-air temperatures at a 2-m height, precipitation regimes (m), eastward (u, m s^{-1}) and northward (v, m s^{-1}) components of the horizontal 10-m wind,

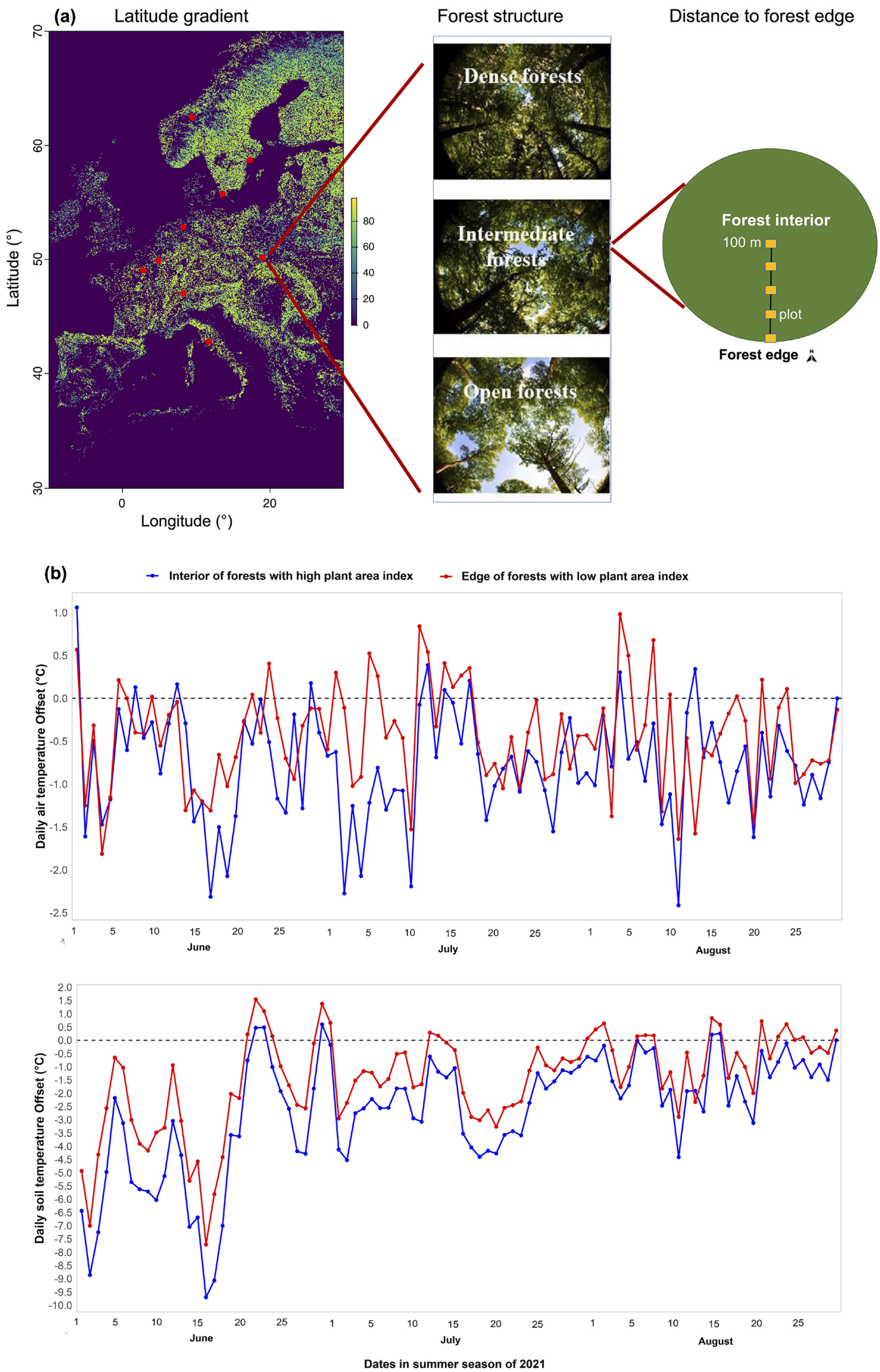


FIGURE 1 | Legend on next page.

FIGURE 1 | (a) Overview of the study design with macroclimatic gradients and forest structural gradients (management and distance to the edge). Left: The nine study regions (Central Italy, Northern Switzerland, Northern France, Belgium, Southern Poland, Northern Germany, Southern Sweden, Central Sweden, and Central Norway) along a latitudinal gradient. The background shows the 2010 tree cover map from https://www.globalforestwatch.org/map. Middle: The three forest structure types. Right: An example of a 100 m-long edge-to-interior gradient, where the forest edge is defined as the outermost line of tree trunks bordering the non-forested matrix. The forest interior refers to areas not influenced by edge effects, where abiotic and biotic conditions remain relatively homogeneous. (b) An example figure showing daily air and soil temperature offsets for the Belgium region during the summer of 2021. The figure demonstrates that the plot located in the interior of the forest and with a high plant area index has a stronger buffering of air and soil microclimate compared to those close to the forest edge, with a low plant area index.

soil moisture as volume of water in the 0–7 cm soil layer ($m^3\,m^{-3}$) from the ECMWF Integrated Forecasting System, surface solar radiation (J/m^2) as hourly accumulated values and snow cover (%) represented by the fraction (binary) of the cell/grid box occupied by snow. Wind speed ($m\,s^{-1}$) was calculated based on the eastward (u) and northward (v) components using the formula: wind speed = sqrt($u^2 + v^2$). Since the solar radiation values from ERA5-Land are provided as hourly accumulations (i.e., the total radiation over each hour), we subtracted the accumulated value of the previous hour from that of the current hour to obtain the actual hourly radiation. The resulting hourly net radiation was then converted to hourly surface solar radiation (SSR, W/m^2) using the formula: SSR (W/m^2) = SSR (J/m^2)/3600 s.

For each plot, we summarized the daily median values of free-air temperature data, wind speed, soil moisture, snow cover, precipitation using the ERA5-Land data. For solar radiation, we used the daily 0.95 quantile instead of the median, because the daily median frequently takes a value of zero during winter, due to very short day lengths especially in northern European regions. The ERA5-Land daily free-air temperature range was also calculated using daily maximum temperature value minus daily minimum temperature value. Day length for each plot was extracted based on the date and coordinate using the daylength function from the geosphere R package (Hijmans et al. 2024).

2.2.3 | Forest Structure

Plant area index (PAI) was used to represent forest structural complexity and canopy density, a metric which is inversely related to light availability on the forest floor (Meeussen et al. 2020). In short, PAI is defined as half the surface area of all aboveground plant components (stems, branches, and leaves) per unit of horizontal ground surface area. Compared to the categorical classification (i.e., open, intermediate, and dense), PAI provides a more precise and quantitative representation of forest structure. In our models, it was treated as a fixed variable representing the structural attribute for each plot, meaning the same PAI value was used for both summer and winter analyzes. Although PAI may vary seasonally (e.g., lower values in winter due to leaf fall), in this study we use it primarily to compare structural differences across plots rather than to assess seasonal variation. In addition, summer and winter data are analyzed in separate models to minimize confounding effects. The reliability of PAI as an indicator of forest structure has been supported by previous studies (Jucker et al. 2018; Meeussen et al. 2021; Vanneste et al. 2024). Although PAI does not explicitly resolve the vertical stratification and horizontal variability of forest structure, it serves as a robust and quantitative indicator of overall forest structure, allowing reliable comparisons of structural complexity among forest types in our study (Meeussen et al. 2021; Vanneste et al. 2024). We calculated PAI for each plot by integrating vertically resolved plant area density profiles (in $m^2\,m^{-3}$). These profiles were derived from terrestrial laser scanning conducted from a single position at the center of each plot, using a RIEGL VZ400 (RIEGL Laser Measurement Systems GmbH) (Meeussen et al. 2020).

2.2.4 | Temperature Offsets Calculation

We first cleaned our air and soil temperature time series using a sequential and reproducible protocol. We applied several criteria to ensure the accuracy and reliability of the recorded measurements by filtering out extreme temperatures and large deviations between consecutive readings (see the specific cleaning steps in S1 and final data availability for each and region in Figures S1–S4 in Supporting Information). Finally, 219 and 204 sensors of the original 225 air and 225 soil temperature sensors were retained, respectively. We calculated the daily temperature offsets using the daily median values of both microclimate forest plot temperature and ERA5-land free-air temperature data. Negative daily temperature offset values indicate cooler microclimate temperatures compared to the free-air temperature outside forests, and vice versa. We used the daily median values rather than means to calculate offsets to avoid large influences of high midday maximum temperatures (e.g., when solar radiation reached the radiation shield, heating up the shield and the air directly surrounding the logger). Median temperature values are also less biased than means when daily temperature distributions are not normal, as they give less weight to outliers. All subsequent analyzes are carried out at the daily resolution from March 2018 to June 2023, with a total of 375,871 (summer vs. winter: 90,634 vs. 87,663) and 305,245 (summer vs. winter: 75,574 vs. 69,001) daily records for air and soil, respectively (Wei et al. 2025). The mean, SD and range of each predictor and response variable are summarized in Table 1.

2.3 | Statistical Analyzes

Pearson correlations between each pair of the eight weather conditions (free-air temperature and its daily range, precipitation, wind speed, soil moisture, solar radiation, day length and snow cover) were computed to check for collinearity issues (Figure S5 in Supporting Information). We constructed and ran linear mixed-effects models (LMMs) to assess the response of daily offset values, separately for air and soil temperatures, to the two-way interaction between each of the weather condition variables and plant area index or distance to forest edge. All models contained 'region/transectID/plot' and 'year/month/date' as random intercept terms.

The lme function from the nlme R package was applied (Pinheiro et al. 2023). The model was run separately for summer (all data for the months of June, July, and August) and winter (all data from the months of December, January, and February), with the variable snow cover only used to model winter offset values. We focused on summer and winter because we expect distinct patterns between the leaf-on and leaf-off periods in these two seasons, while spring and autumn are transitional and exhibit less stable temperature dynamics compared to summer and winter. Yet, we also ran the same model for spring and autumn air temperature offsets as a reference (Tables S1 and S2 and results in S2). Prior to running the models, we square root transformed precipitation data and log-transformed wind speed and distance to edge data. All predictor variables were scaled to be able to compare their effect sizes. To account for temporal autocorrelation of microclimate data (Ruel and Ayres 1999; Koenig and Liebhold 2016), we incorporated the corAR1(form = ~year/month/date) variance structure (Zuur et al. 2007). The model fit was evaluated by marginal R^2 (R^2m) and conditional R^2 (R^2c) (Nakagawa and Schielzeth 2013). The model structures for summer and winter, are shown separately below:

1. The interactive effects of weather variables and plant area index:

$$\text{offset. daily. summer} \sim \begin{array}{l}(\text{free-air temperature} + \text{daily range of free-air temperature} + \text{precipitation} \\ + \text{wind speed} + \text{soil moisture} + \text{solar radiation} + \text{day length}) \\ \times \text{plant area index, random} = \text{list}(\sim 1 | \text{region/transectID/plot}, \sim 1 | \text{year/month/date})\end{array}$$

$$\text{offset. daily. winter} \sim \begin{array}{l}(\text{free-air temperature} + \text{daily range of free-air temperature} + \text{precipitation} \\ + \text{wind speed} + \text{soil moisture} + \text{solar radiation} + \text{day length} + \text{snow cover}) \\ \times \text{plant area index, random} = \text{list}(\sim 1 | \text{region/transectID/plot}, \sim 1 | \text{year/month/date})\end{array}$$

2. The interactive effects of weather variables and distance to forest edge:

$$\text{offset. daily. summer} \sim \begin{array}{l}(\text{free-air temperature} + \text{daily range of free-air temperature} + \text{precipitation} \\ + \text{wind speed} + \text{soil moisture} + \text{solar radiation} + \text{day length}) \\ \times \text{distance to forest edge, random} = \text{list}(\sim 1 | \text{region/transectID/plot}, \sim 1 | \text{year/month/date})\end{array}$$

$$\text{offset. daily. winter} \sim \begin{array}{l}(\text{free-air temperature} + \text{daily range of free-air temperature} + \text{precipitation} \\ + \text{wind speed} + \text{soil moisture} + \text{solar radiation} + \text{day length} + \text{snow cover}) \\ \times \text{distance to forest edge, random} = \text{list}(\sim 1 | \text{region/transectID/plot}, \sim 1 | \text{year/month/date})\end{array}$$

We initially ran the models described above. If a weather variable showed no significant interaction effect with plant area index or distance to the edge, we excluded that specific interaction term from the model. To test whether our model fully considered the temporal autocorrelation, the autocorrelation function (ACF) and partial autocorrelation function (PACF) plots for each LMM model were plotted (Figures S6–S9). We also ran generalized additive mixed models (GAMMs) with a similar structure and autocorrelation structure as in the above LMMs, using the gamm function from the mgcv R package (Wood 2017), to further assess temporal autocorrelation (Figures S10–S13).

To explore regional trends, similar model formulas for air temperature offsets as an example were applied separately to each of the nine regions, with adjustments to the random intercept terms specified as *random = list(~1|transectID/plot, ~1|year/month/date)* (see Figures S14–S29 and results description in S3 in Supporting Information). Because of very high winter snow cover in some years (higher than 1 m above the soil surface temporarily covering the air temperature sensor with snow), temperature records in Norway were very different compared to the other eight regions. Therefore, we also ran analyzes without Norway (only for air temperature as an example) to check for the robustness of our findings (see Table S3 and results in S4). To test the potential effects of shared ERA5_Land weather variables across several plots on the model results, we retained only one representative plot per region located in the forest interior with a complex structure with unique ERA5_Land weather values, and tested the effects of the studied weather variables on air temperature offsets (see Table S4 and results in S5).

3 | Results

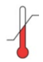
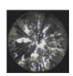
3.1 | Seasonal Patterns of Temperature Offsets

Our study showed that mean daily temperature offsets were negative (cooler microclimate temperature than free-air temperature) in summer and positive (warmer microclimate temperature than free-air temperature) in winter (Table 1). This pattern was more pronounced for soil temperature offsets than for air temperature offsets which were close to zero– that is, air: −0.71°C ± 2.15°C and soil: −2.34°C ± 2.74°C in summer and 0.68°C ± 2.87°C, soil: 1.86°C ± 3.48°C in winter.

3.2 | Effects of Weather Conditions, Forest Structure and Edge Distance on Air Temperature Offsets

Among the eight weather variables studied, the effects of free-air temperature prevailed in driving air temperature offsets (Table 2 and Figure 2). In both summer and winter (Table 2

TABLE 1 | Predictor and response ecological variables.

		Variable	Explanation	Unit	Summary data				
					Season	Mean	SD	0.05 quantile	0.95 quantile
Predictor variables		Weather variable (hourly data with a 9×9 km grid from ERA5-Land)							
		Free-air temperature	Daily median of 2-m height free-air temperatures	°C	Summer	18.53	5.12	8.68	26.24
					Winter	1.86	6.23	−10.90	9.80
		Free-air temperature range	Daily range of free-air temperature	°C	Summer	8.57	2.91	3.94	13.28
					Winter	5.06	2.71	1.54	10.39
		Precipitation	Daily median of precipitation	mm	Summer	0.80	1.68	0.00	4.72
					Winter	1.09	1.88	0.00	5.55
		Wind speed	Daily median wind speed	$m\,s^{-1}$	Summer	2.16	1.45	0.52	5.02
					Winter	2.69	2.06	0.45	6.93
		Soil moisture	Daily median of top-soil moisture content	$m^3\,m^{-3}$	Summer	0.26	0.09	0.12	0.41
					Winter	0.37	0.05	0.26	0.42
		Solar radiation	Daily 0.95 quantile of solar radiation	$W\,m^{-2}$	Summer	632.83	181.54	283.80	878.87
					Winter	191.25	138.45	26.01	464.84
		Day length	Daily duration of time between sunrise and sunset	h	Summer	16.14	1.65	13.88	19.86
					Winter	8.48	1.51	5.20	10.61
		Snow cover	Daily median of snow cover	%	Summer	2.32	14.43	0.00	0.07
					Winter	26.88	39.92	0.00	99.94
		Forest structure and complexity (measured in situ for each plot in 2018)							
		Plant area index	Plant area index (PAI) is defined as half the surface area of all aboveground plant components (stems, branches, and leaves) per unit of ground surface area.	$m^2\,m^{-3}$	/	4.27	1.43	1.60	6.42
		Distance to edge	Distance to forest edge	m	/	29.94	35.38	1.50	99.50

(Continues)

TABLE 1 | (Continued)

Variable	Explanation	Unit	Summary data				
			Season	Mean	SD	0.05 quantile	0.95 quantile
Response variables							
Air temperature offset	Daily air temperature offsets calculated using the daily median plot temperature (measured in situ) minus the daily median ERA5-Land free-air temperature	°C	Summer	−0.71	2.15	−4.04	3.28
			Winter	0.68	2.87	−2.94	6.84
Soil temperature offset	Daily soil temperature offsets calculated using the daily median plot temperature (measured in situ) minus the daily median ERA5-Land free-air temperature	°C	Summer	−2.34	2.74	−6.59	2.50
			Winter	1.86	3.48	−2.64	9.06

and Figure 2), higher free-air temperature, wind speed and soil moisture led to cooler microclimate temperatures than free-air temperatures. In summer, the negative effects of wind speed and soil moisture on air offsets were slightly more pronounced for forests with lower plant area index (Figure 2). Unlike other weather variables, precipitation and day length in winter and solar radiation in summer had a positive effect on air temperature offsets. Besides, a higher daily range of free-air temperature resulted in a slightly cooler forest microclimate compared to free-air temperature in both summer and winter, and these effects were slightly stronger in forests with high leaf area index.

Regarding the interactive effects of weather variables with distance to the forest edge (Table 3 and Figure 3), in both summer and winter, the impacts of all weather variables (except for precipitation and day length in winter) on air temperature offset values depended on the distance to the edge. These interactive effects were statistically significant but small in magnitude, even for those related to free-air temperature.

3.3 | Effects of Weather Conditions, Forest Structure and Edge Distance on Soil Temperature Offsets

As with air temperature offsets, free-air temperature had the largest effect on soil temperature offsets, while the effects of other variables were small (Table 2 and Figures 4 and 5).

In both summer and winter (Table 2 and Figure 4), higher free-air temperature, daily range of free-air temperature, wind speed, soil moisture led to cooler forest microclimate soil temperature than free-air temperature, which was similar to those for forest microclimate air temperature. Yet the magnitude of the effects of daily range of free-air temperature on soil temperature offsets was greater than on air temperature offsets. Precipitation and solar radiation showed positive relationships with soil temperature offsets in both summer and winter. Soil temperature offsets were negatively correlated with day length in both summer and winter, which was in the opposite direction to air temperature offsets. The interaction effects of all weather variables (except for precipitation in summer) with plant area index on soil temperature offsets were often significant (but still of small magnitude). However, these interaction effects did not always show consistent directions as observed for air temperature offsets (Table 2 and Figure 4).

The interaction effects of weather variables with distance to the forest edge on soil temperature offsets generally mirrored their interactions with the plant area index (Table 3 and Figure 5), showing a consistent direction and similar magnitude in both summer and winter.

4 | Discussion

This study examines temperature buffering at the daily resolution, focusing on the interplay between weather conditions, forest structural complexity and edge effects. By linking weather conditions to in situ measured below-canopy temperatures, we offer a comprehensive analysis of how these elements shape microclimatic dynamics within forests. Understanding these

TABLE 2 | Effects of free-air temperature and its daily range, precipitation, wind speed, soil moisture, solar radiation, day length and snow cover and plant area index (and their interactions) on air (left) and soil (right) temperature offsets across the 45 studied forests across Europe, for both summer (top) and winter (bottom) seasons. Results from linear mixed model results with 'region/transectID/plot' and 'year/month/date' as random effect terms. R^2m = marginal R^2 value and R^2c = conditional R^2 value.

	Air temperature offset					**Soil temperature offset**				
Season	**Variable**	**Relative effect size**	***p***	R^2m	R^2c	**Variable**	**Relative effect size**	***p***	R^2m	R^2c
Summer	Intercept	−0.72	< 0.001	0.30	0.51	Intercept	−2.48	< 0.001	0.72	0.79
	Free-air temperature	−1.16	< 0.001			Free-air temperature	−2.35	< 0.001		
	Daily range of free-air temperature	−0.11	< 0.001			Daily range of free-air temperature	−0.52	< 0.001		
	Precipitation	0.02	0.105			Precipitation	0.15	< 0.001		
	Wind speed	−0.06	< 0.001			Wind speed	−0.04	< 0.001		
	Soil moisture	−0.13	< 0.001			Soil moisture	−0.19	< 0.001		
	Solar radiation	0.13	< 0.001			Solar radiation	0.14	< 0.001		
	Day length	0.01	0.548			Day length	−0.67	< 0.001		
	Plant area index	−0.12	< 0.001			Plant area index	−0.26	< 0.001		
	Daily range of free-air temperature × Plant area index	−0.01	0.027			Free-air temperature × Plant area index	0.05	< 0.001		
	Wind speed × Plant area index	0.02	< 0.001			Daily range of free-air temperature × Plant area index	−0.05	< 0.001		
	Soil moisture × Plant area index	0.04	< 0.001			Wind speed × Plant area index	−0.02	< 0.001		
	Solar radiation × Plant area index	0.03	< 0.001			Soil moisture × Plant area index	0.05	< 0.001		
	Day length × Plant area index	−0.07	< 0.001			Solar radiation × Plant area index	0.03	< 0.001		
						Day length × Plant area index	−0.02	0.004		
Winter	Intercept	0.49	< 0.001	0.43	0.55	Intercept	1.62	< 0.001	0.78	0.87
	Free-air temperature	−1.82	< 0.001			Free-air temperature	−3.80	< 0.001		
	Daily range of free-air temperature	−0.20	< 0.001			Daily range of free-air temperature	−0.08	< 0.001		
	Precipitation	0.15	< 0.001			Precipitation	0.04	0.001		
	Wind speed	0.01	0.445			Wind speed	0.02	0.140		
	Soil moisture	−0.14	< 0.001			Soil moisture	−0.13	< 0.001		
	Solar radiation	0.01	0.652			Solar radiation	0.16	< 0.001		

(Continues)

	Air temperature offset					Soil temperature offset				
Season	**Variable**	**Relative effect size**	***p***	**R^2m**	**R^2c**	**Variable**	**Relative effect size**	***p***	**R^2m**	**R^2c**
	Day length	0.31	< 0.001			Day length	−0.32	< 0.001		
	Snow cover	−0.06	0.055			Snow cover	−0.60	< 0.001		
	Plant area index	−0.01	< 0.001			Plant area index	−0.05	< 0.001		
	Free-air temperature × Plant area index	−0.02	0.004			Free-air temperature × Plant area index	−0.02	0.010		
	Daily range of free-air temperature × Plant area index	−0.03	< 0.001			Daily range of free-air temperature × Plant area index	−0.02	0.001		
	Precipitation× Plant area index	0.01	0.031			Precipitation × Plant area index	−0.03	< 0.001		
	Soil moisture × Plant area index	−0.02	< 0.001			Wind speed × Plant area index	0.02	< 0.001		
	Solar radiation × Plant area index	0.06	< 0.001			Soil moisture × Plant area index	0.05	< 0.001		
	Day length × Plant area index	0.02	0.007			Solar radiation × Plant area index	−0.02	< 0.001		
	Snow cover × Plant area index	−0.03	< 0.001			Day length × Plant area index	0.02	0.005		
						Snow cover × Plant area index	−0.04	< 0.001		

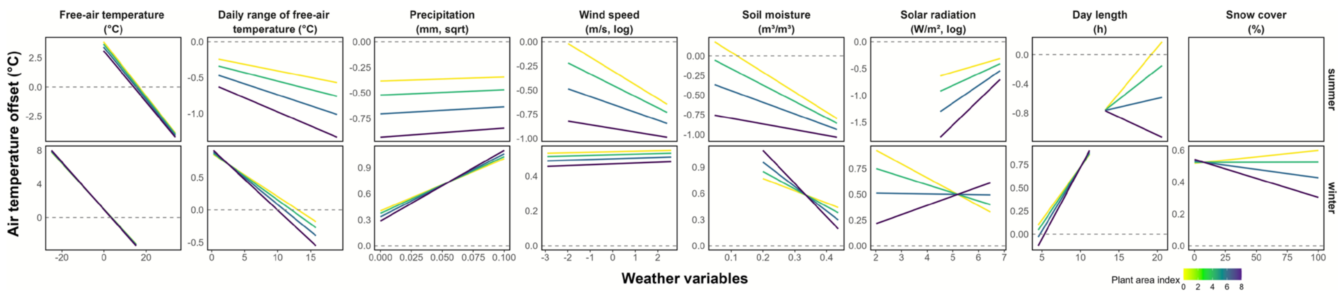


FIGURE 2 | Effects of free-air temperature and its daily range, precipitation, wind speed, soil moisture, solar radiation, day length and snow cover interacted with plant area index on air temperature offset for each region. The lines show the LMMs model predictions with 'region/transectID/plot' and 'year/month/date' as random effects. The colours of the lines represent the plant area index gradient. The same figure with the raw data added is shown in Figure S30 in Supporting Information.

weather variables is essential as they regulate energy exchange within the forest ecosystem– particularly between the forest canopy and the ground surface– which in turn influences key water processes such as evaporation, condensation, and soil moisture fluctuations (Zhang et al. 2014; Wilson et al. 2020; Seneviratne et al. 2010). According to over five years of continuous observations, our findings demonstrate that free-air temperature prevailed over the other weather conditions to determine air and soil temperature offset values. Air and soil temperature offsets became more negative (i.e., cooler forest microclimate temperatures) as free-air temperature increased. In general, higher soil moisture, wind speed, and snow cover also led to more negative air and soil temperature offsets, whereas increases in precipitation and solar radiation were associated with slightly higher offsets. Notably, the effects of weather variables were often modified by forest structural complexity and distance to the forest edge; however, these influences were inconsistent and differed between seasons, making generalizations difficult.

TABLE 3 | Effects of free-air temperature and its daily range, precipitation, wind speed, soil moisture, solar radiation, day length and snow cover and distance to forest edge (and their interactions) on air (left) and soil (right) temperature offsets across the 45 studied forests across Europe, for both summer (top) and winter (bottom) seasons. Results from linear mixed model results with 'region/transectID/plot' and 'year/month/date' as random effect terms. R^2m = marginal R^2 value and R^2c = conditional R^2 value.

	Air temperature offset					**Soil temperature offset**				
Season	**Variable**	**Relative effect size**	***p***	R^2m	R^2c	**Variable**	**Relative effect size**	***p***	R^2m	R^2c
Summer	Intercept	−0.71	< 0.001	0.31	0.51	Intercept	−2.50	< 0.001	0.72	0.79
	Free-air temperature	−1.24	< 0.001			Free-air temperature	−2.46	< 0.001		
	Daily range of free-air temperature	−0.09	< 0.001			Daily range of free-air temperature	−0.48	< 0.001		
	Precipitation	0.02	0.099			Precipitation	0.15	< 0.001		
	Wind speed	−0.08	< 0.001			Wind speed	−0.06	< 0.001		
	Soil moisture	−0.13	< 0.001			Soil moisture	−0.23	< 0.001		
	Solar radiation	0.13	< 0.001			Solar radiation	0.15	< 0.001		
	Day length	−0.01	0.613			Day length	−0.69	< 0.001		
	Distance to edge	−0.06	< 0.001			Distance to edge	−0.15	< 0.001		
	Free-air temperature × Distance to edge	0.01	0.020			Free-air temperature × Distance to edge	0.04	< 0.001		
	Daily range of free-air temperature × Distance to edge	−0.03	< 0.001			Daily range of free-air temperature × Distance to edge	−0.05	< 0.001		
	Precipitation × Distance to edge	−0.02	< 0.001			Wind speed × Distance to edge	−0.03	< 0.001		
	Wind speed × Distance to edge	−0.02	< 0.001			Soil moisture × Distance to edge	0.06	< 0.001		
	Soil moisture × Distance to edge	0.04	< 0.001			Solar radiation × Distance to edge	0.03	< 0.001		
	Solar radiation × Distance to edge	0.03	< 0.001							
	Day length × Distance to edge	−0.02	< 0.001							
Winter	Intercept	0.49	< 0.001	0.44	0.55	Intercept	1.64	< 0.001	0.78	0.87
	Free-air temperature	−1.88	< 0.001			Free-air temperature	−3.80	< 0.001		
	Daily range of free-air temperature	−0.19	< 0.001			Daily range of free-air temperature	−0.08	< 0.001		
	Precipitation	0.15	< 0.001			Precipitation	0.05	< 0.001		
	Wind speed	0.01	0.563			Wind speed	0.02	0.189		
	Soil moisture	−0.14	< 0.001			Soil moisture	−0.17	< 0.001		

(Continues)

	Air temperature offset					Soil temperature offset				
Season	Variable	Relative effect size	p	R^2m	R^2c	Variable	Relative effect size	p	R^2m	R^2c
	Solar radiation	0.00	0.877			Solar radiation	0.17	< 0.001		
	Day length	0.36	< 0.001			Day length	−0.32	< 0.001		
	Snow cover	−0.05	0.091			Snow cover	−0.60	< 0.001		
	Distance to edge	0.01	0.005			Distance to edge	−0.08	< 0.001		
	Free-air temperature × Distance to edge	−0.04	< 0.001			Free-air temperature × Distance to edge	−0.03	< 0.001		
	Daily range of free-air temperature × Distance to edge	0.03	< 0.001			Daily range of free-air temperature × Distance to edge	−0.01	0.036		
	Wind speed × Distance to edge	−0.02	< 0.001			Precipitation × Distance to edge	−0.02	< 0.001		
	Soil moisture × Distance to edge	−0.01	< 0.001			Wind speed × Distance to edge	0.02	< 0.001		
	Solar radiation × Distance to edge	0.01	0.154			Soil moisture × Distance to edge	0.06	< 0.001		
	Snow cover × Distance to edge	−0.03	< 0.001			Solar radiation × Distance to edge	−0.05	< 0.001		
						Day length × Distance to edge	0.02	< 0.001		
						Snow cover × Distance to edge	0.01	0.014		

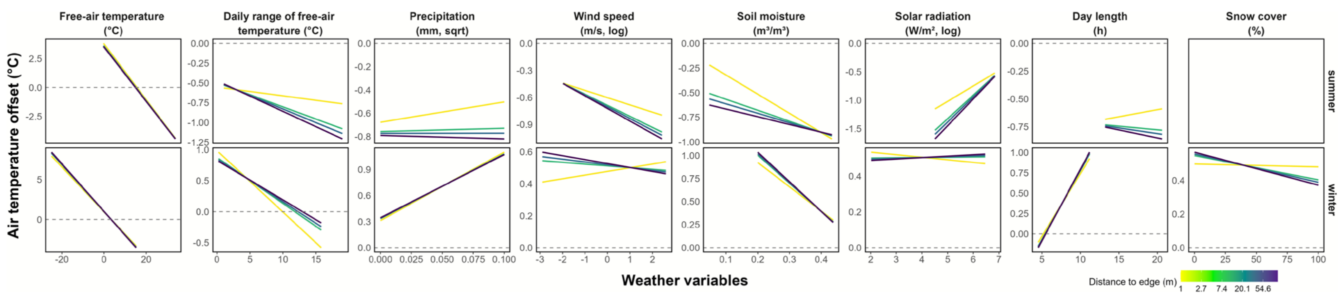


FIGURE 3 | Effects of free-air temperature and its daily range, precipitation, wind speed, soil moisture, solar radiation, day length and snow cover interacted with distance to forest edge on air temperature offset for each region. Free-air temperature, precipitation, wind speed, soil moisture and snow cover were extracted from the ERA5-Land database. The lines show the LMM model predictions with 'region/transectID/plot' and 'year/month/date' as random effects. The colours of the lines represent the edge distance gradient. The uneven spacing along the distance-to-edge legend reflects the back-transformed log(distance) value. The same figure with the raw data is shown in Figure S31 in Supporting Information.

4.1 | Seasonal Patterns of Temperature Offsets

Our study in temperate broadleaved forests revealed a seasonal pattern in daily temperature offsets: mean air and soil temperature offsets were negative in summer and positive in winter. Similarly, Meeussen et al. (2021) reported seasonal-scale air temperature offsets in the same experimental network, with an average summer offset of −2.8°C and a positive winter offset close to zero (0.1°C). This seasonal "offset reversal" is driven by shifts in forest energy balance. While summer canopies buffer solar heating through shading and latent heat flux, winter forests reduce heat loss from the ground, especially at night, with the remaining canopy and insulating leaf litter retaining warmth and limiting longwave radiative cooling and turbulent mixing

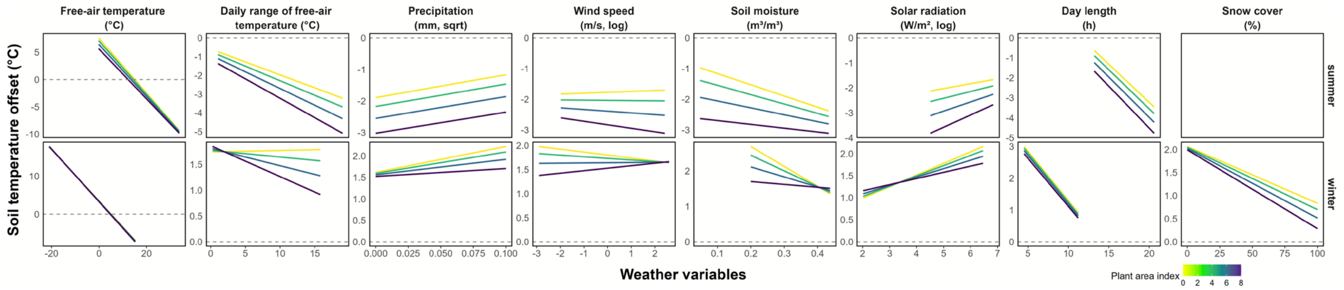


FIGURE 4 | Effects of free-air temperature and its daily range, precipitation, wind speed, soil moisture, solar radiation, day length and snow cover interacted with plant area index on soil temperature offset. Free-air temperature, precipitation, wind speed, soil moisture and snow cover were extracted from the ERA5-Land database. The lines show the LMMs model predictions with 'region/transectID/plot' and 'year/month/date' as random effects. The colours of the lines represent the plant area index gradient. The same figure with the raw data is shown in Figure S32 in Supporting Information.

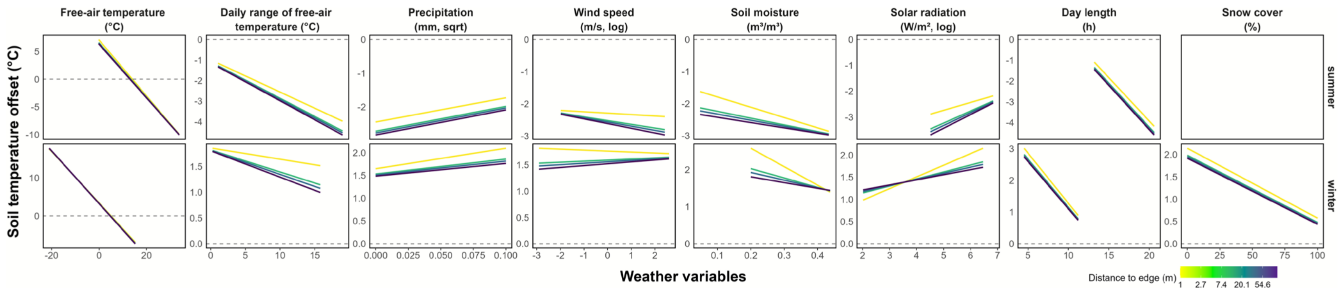


FIGURE 5 | Effects of free-air temperature and its daily range, precipitation, wind speed, soil moisture, solar radiation, day length and snow cover interacted with distance to forest edge on soil temperature offset. Free-air temperature, precipitation, wind speed, soil moisture and snow cover were extracted from the ERA5-Land database. The lines show the LMMs model predictions with 'region/transectID/plot' and 'year/month/date' as random effects. The colours of the lines represent edge distance gradient. The uneven spacing along the distance-to-edge legend reflects the back-transformed log(distance) value. The same figure with the raw data is shown in Figure S33 in Supporting Information.

(Zellweger et al. 2019; De Frenne et al. 2021). Nevertheless, we assumed that positive winter offsets would be more characteristic of boreal coniferous forests, where persistent foliage provides continuous canopy insulation. In addition, other factors, including snow cover dynamics and species-specific tree thermal regulating capacity, likely play important roles with canopy dynamics in shaping winter temperature offsets, especially at the daily scale. Yet, we also found a study by Zellweger et al. (2019) based on short-term logger data that reported negative daily temperature offsets in broadleaved forests during both summer and winter: −0.5°C (range: −1.4 to 0.4) and −0.03°C (range: −0.8 to 0.8), respectively. This suggests that the results are not always consistent, even at a similar daily temporal resolution.

4.2 | Interactive Effects of Free-Air Temperature and Its Daily Range With Forest Structure and Edge Distance

Despite the mean temperature offsets in summer and winter being opposite, these offsets respond similarly and consistently to weather variables across seasons, with only a few exceptions or differences in their interaction with plant area index or distance to edge. This suggests that while the baseline offset differs fundamentally between summer and winter, the mechanisms driving variation in offsets in response to weather remain largely consistent.

Among the weather variables studied, free-air temperature emerged as the dominant factor influencing both air and soil temperature offsets, indicating its primary role in controlling forest near-surface thermal conditions. Free-air temperature, which reflects the atmospheric temperature unaffected by immediate surface influences, acts as a boundary condition by setting the ambient thermal state of the air column above the surface (Oke 2002; Geiger et al. 2009). This boundary condition largely determines the baseline thermal environment that near-surface air and soil temperatures respond to. In contrast, other weather variables such as wind, precipitation, solar radiation, and humidity function primarily as fluxes or dynamic inputs rather than boundary conditions. Wind influences momentum transfer and heat transport, precipitation adds moisture to the system, and solar radiation provides energy input—all of which dynamically modify surface temperatures and microclimate conditions on shorter temporal and spatial scales (Oke 2002; Monteith and Unsworth 2013). Soil moisture and snow cover, meanwhile, act as surface state variables that further affect energy and water exchanges but do not serve as atmospheric boundary conditions (Seneviratne et al. 2010; Edwards et al. 2007). While these fluxes and surface conditions can significantly influence local thermal environments, their effects are often more variable and site-specific compared to the more consistent and systematic influence of free-air temperature. Consequently, fluctuations in free-air temperature tend to be more strongly reflected in surface temperature patterns, explaining its predominant role in driving air temperature offsets.

Recent in situ microclimate studies covering continental extents usually cover relatively short-term periods and are based on aggregated data at the seasonal or monthly resolution (Zellweger et al. 2019; Haesen et al. 2021). Our study addresses these gaps by analyzing microclimatic fluctuations at a daily resolution over more than five years. We observed that as free-air temperature increased, forest air and soil temperatures became increasingly cooler relative to free-air, indicating a strengthening of the microclimate buffering capacity. These findings align with previous studies conducted at global and regional scales with monthly resolution, encompassing temperate, tropical, and boreal forest ecosystems (De Frenne et al. 2019; De Lombaerde et al. 2022; Hes et al. 2024). Higher free-air temperatures are typically accompanied by elevated vapor pressure deficit, which enhances plant transpiration and soil evaporation, amplifying microclimatic temperature offsets through evaporative cooling (e.g., Breshears et al. 1998; Fang and Leung 2022). Forests generally exhibit higher evapotranspiration rates than non-forested open areas due to greater soil moisture availability and active vegetation transpiration. This process consumes energy as latent heat, effectively cooling both air and soil (e.g., Breil et al. 2020). On the other hand, forest canopies provide shading that reduces direct solar radiation reaching the ground, thereby limiting surface heating during warmer periods (De Frenne et al. 2021). This pattern is evident in the negative effects of plant area index and distance to edge on both air and soil temperature offsets in our study. In addition, we found statistically significant—though not easily visualized—interaction effects between free-air temperature and plant area index, as well as between free-air temperature and distance to edge. However, in our observational study we cannot mechanistically unravel the specific contribution of shading vs. evapotranspiration on microclimate cooling during the day. In conclusion, while free-air temperature appears to be the dominant predictor of offset values, the underlying mechanisms remain complex and likely involve interactions among multiple physical and biological processes (De Frenne et al. 2019, 2021).

Daily range of free-air temperature reflects the combined effects of daytime heating and nighttime cooling and therefore serves as a proxy for atmospheric and radiative conditions, such as sky clarity, humidity, and radiation balance, that influence the strength of forest microclimate buffering. By incorporating this variable, we aimed to disentangle the influence of overall temperature levels from that of daily thermal variability, providing deeper insight into how forest characteristics interact with macroclimatic conditions to stabilize local thermal environments. The negative effect of daily range of free-air temperature was obvious on soil temperature offsets and was slightly stronger in denser forests or in the forest interior in our study. This pattern suggests that larger diurnal temperature range—typically occurring under clear-sky conditions with minimal cloud cover (Fischer and Schär 2009; Dessler 2010)–amplify differences between forest and free-air temperatures. On clear days, increased solar radiation raises daytime soil temperatures more strongly in open areas than under the canopy, while at night, enhanced radiative cooling in forests leads to a sharper temperature drop. Such day-night asymmetry in cloud-radiation interactions amplifies overall temperature contrasts between below-canopy and free-air temperatures (Yin et al. 2020; Luo et al. 2024). In summer, this results in net heat loss and cooler soil temperatures. This finding contrasts with some global-scale analyzes suggesting that cloudy days, often associated with a narrower daily free-air temperature range, have an overall cooling effect (Zelinka et al. 2017). In winter, the same mechanism of enhanced nighttime cooling under clear skies prevents the soil from retaining warmth, making it colder than under cloudier conditions with smaller diurnal temperature ranges.

4.3 | Interactive Effects of Soil Moisture With Forest Structure and Edge Distance

During summer, higher soil moisture in our study was also associated with cooler microclimatic air and soil temperatures in the forest understory compared to free-air thermal conditions, though with a smaller magnitude than the effect of free-air temperature. Similar patterns of cooler microclimate temperature under higher soil moisture were also found by several studies (Von Arx et al. 2013; Davis et al. 2019; Horváth et al. 2023; Greiser et al. 2024). Increased soil moisture can enhance latent heat fluxes through both soil evaporation and transpiration from understory vegetation, contributing to local cooling and thus slightly promoting microclimate buffering (Dai et al. 1999). However, higher soil moisture can also enhance the cooling capacity of canopy trees by increasing transpiration, which may reduce above-canopy temperatures more than below-canopy temperatures (Richter et al. 2022), leading to a narrower temperature offset between the forest understory and the free-air temperatures. This pattern was not observed in our results, suggesting that, at the daily scale, soil moisture in our study may primarily contribute to sub-canopy cooling mediated by soil evaporation and transpiration from understory vegetation, consistent with findings from Stickley and Fraterrigo (2021) and related indirect evidence reported by several studies (Gilliam 2007; Williams and Ward 2010; Kovács et al. 2020; Prévosto et al. 2020; Van Gestel et al. 2022; Horváth et al. 2023). Our results indicate the complex impacts of soil moisture on above- and below-canopy temperatures, which may vary depending on local conditions, forest structure, and temporal resolution.

We also found that, in summer, the negative relationship between soil moisture and both air and soil temperature offsets was slightly more pronounced in forests with a lower plant area index or smaller distance from the forest edge in summer. A similar finding– that the cooling effect of soil moisture on the understory was stronger when canopies were more open – was also reported by Greiser et al. (2024), though their results could vary depending on the specific observation year. Yet, more studies have shown higher efficient water absorption and enhanced evaporative cooling with higher soil moisture in dense forests compared to more open forests (Von Arx et al. 2013; Seneviratne et al. 2010; Greiser et al. 2024). While we observed a similar pattern in winter, with a slightly stronger negative relationship between air temperature offsets and soil moisture in denser forests, the underlying explanation of reduced water uptake and evaporation in deciduous forests during winter is unlikely to apply. Those inconsistent findings suggest that the relationship between soil moisture, canopy density, and microclimatic cooling is complex and context-dependent. Similarly, Davis et al. (2019) summarized that shifts in water balance, combined with accelerating canopy loss due to increased disturbance frequency and severity, could lead to significant changes in the microclimate.

4.4 | Interactive Effects of Wind Speed With Forest Structure and Edge Distance

Our study found that forest microclimate air and soil temperatures were noticeably cooler than free-air temperature with increasing wind speed. This effect was slightly more pronounced in forests with a lower plant area index during the summer, particularly for air temperature offsets. Strong winds are often assumed to reduce forest microclimatic offsets by mixing cooler canopy air into the atmosphere, slightly lowering free-air temperatures (De Frenne et al. 2021). Since wind penetration into forests is limited, below-canopy temperatures remain relatively unchanged, leading to less negative offsets (Renaud et al. 2011; Schmidt et al. 2017). However, our results revealed an opposite trend: both air and soil temperatures within forests became cooler than free-air temperatures as wind speed increased—that is, forests were relatively cooler under windier conditions. One plausible explanation is that increased wind may enhance evaporative cooling from canopy foliage, particularly in forests with more open canopies, where air movement is less obstructed (Davarzani et al. 2014; Konrad et al. 2021). In such conditions, the cooling induced by enhanced evapotranspiration may outweigh the warming effects of vertical mixing. This may explain why in our study the wind-induced cooling effect was slightly more pronounced in stands with a lower plant area index during the summer, especially for air temperature.

In contrast, when comparing forest edges to the interior, the negative effect of wind speed on air temperature offset was slightly more pronounced within the forest interior in summer. This may be because higher wind speeds near the forest edge enhance the mixing of warm above-canopy air into the understory, thereby diminishing the cooling effect of shading and evapotranspiration close to the edge and resulting in a slightly warmer microclimate compared to the deeper interior (Davis et al. 2019), leading to a slightly less cool microclimate compared to the deeper forest interior. Greater distance from the forest edge is often associated with more complex forest structure, as wind enters the forest, turbulence decreases sharply in the lower canopy (Irvine et al. 1997; Wuyts et al. 2008). In winter, although a similar negative effect of wind on air temperature was observed in the forest interior, the pattern at the forest edge was reversed: wind speed was slightly associated with warmer understory air temperature, possibly because turbulence disrupted nocturnal cold-air pooling and transported relatively warmer air from adjacent open areas into the forest edge. Taken together, these findings highlight the dual role of edge-driven air mixing– dampening cooling in summer and potentially enhancing warming in winter– depending on seasonal background conditions.

4.5 | Interactive Effects of Solar Radiation With Forest Structure and Edge Distance

Our study found that both air and soil temperature buffering weakens as solar radiation increases. That is, under higher solar radiation, the forest microclimate becomes less buffered and closer in temperature to open-air conditions, even though it remains cooler overall. This indicates that higher solar radiation penetrates canopy gaps and directly warms understory air and soil (Promis et al. 2009). Meanwhile, the rapidly increasing solar radiation reduces the effectiveness of shading and evapotranspiration (e.g., stomatal closure), narrowing the temperature difference between forested and open areas (Esperon-Rodriguez et al. 2021; Yu et al. 2024). Unlike free-air temperature, increased solar radiation acts as an internal heat source (Oke 2002), warming the forest and reducing the temperature offset. In addition, clear and sunny conditions, which are often closely associated with higher solar radiation, can also lead to lower precipitation and soil moisture, suppressing evapotranspiration and weakening cooling in both vegetation and soil (Rowlands et al. 2002). This was also reflected in our correlation analysis, which showed strong negative correlations between solar radiation and both precipitation and soil moisture, especially during the summer (Figure S5).

During summer, the weakening of air or soil temperature buffering with increasing solar radiation was slightly more pronounced in forests with a high plant area index or increasing distance to the edge during summer. On the contrary, for soil temperature offsets in winter, solar radiation exhibited slightly less positive effects in denser forests or the forest interior, which might link to the limited amount of solar radiation reaching the soil during winter. As a result, temperature offsets increase less under high solar radiation in dense stands than in open forests or the forest edge, where sunlight penetrates more easily. It might also result from the influence of solar radiation on snow melting (Ellis and Pomeroy 2007; Pomeroy et al. 2009). A negative correlation between snow cover and solar radiation was detected (Figure S5). However, the underlying mechanism requires further investigation.

4.6 | Interactive Effects of Precipitation With Forest Structure and Edge Distance

Our results showed less air or soil cooling with higher precipitation in both summer and winter, which might be due to the reduced evaporative cooling because wetter surfaces are closer to saturation, leaving less capacity for additional evaporation at a daily resolution. For example, Diószegi et al. (2023) demonstrated that throughfall during longer and more intensive precipitation dampens forest buffering. Higher precipitation might also homogenize moisture and energy conditions across the forest, diminishing the variability that often drives stronger cooling effects in drier conditions. Moreover, in summer, less dense forests experienced slightly more noticeable cooling from precipitation. This suggests that the open canopy allows precipitation to interact more effectively with the environment, amplified by greater solar exposure, enhanced evaporation, and better air circulation, which collectively contribute to a more pronounced cooling effect.

4.7 | Interactive Effects of Snow Cover With Forest Structure and Edge Distance

The snow cover effect was more pronounced on soil temperature than on air temperature offsets. The similar results of the important regulation of snowpack on soil temperature dynamics in a hardwood forest were also found by Wilson et al. (2020).

Snow has been shown to act as an insulating layer for soil and vegetation, creating a warmer microclimate that buffers against sub-zero temperatures (Edwards et al. 2007; Graae et al. 2012). However, in our study with daily-resolution observations, we found that as snow cover increased, soil temperatures in forests became relatively colder than free-air temperatures, though this effect was minor. One possible explanation is that extensive snow cover often coincides with prolonged cold winter conditions (Diro et al. 2018). When sub-zero air temperatures persist for extended periods, frozen ground alters subsurface hydrology by reducing soil permeability, limiting infiltration, and promoting surface runoff, which may influence the potential insulating effect of snow (Rush and Rajaram 2022). Yet studies such as those by Wilson et al. (2020) and Maurer and Bowling (2014) suggest that winter soil moisture may not always be sensitive to snowpack size. This indicates the need for further in situ studies and observations on snow cover to gain a more precise and comprehensive understanding. While Era5-Land provides high-resolution daily weather information, their inherent uncertainties, especially at localized sites, could influence the observed microclimatic offsets, highlighting the need for future studies to address these uncertainties through comparisons with localized observations or higher-resolution datasets (Meyer et al. 2023).

4.8 | Interactive Effects of Day Length With Forest Structure and Edge Distance

The effect of day length on air temperature offsets was significant only in winter, showing a slight increase with longer days. This positive effect was somewhat stronger in forests with a higher plant area index. Longer winter days provide more solar input, warming the canopy and near-surface air. In dense forests, a higher plant area index helps absorb and retain this energy, moderating sub-canopy air temperatures and reducing overnight cooling (Rajendran and Smith 2016). In contrast, day length negatively affects soil temperature offsets in both seasons—enhancing cooling in summer and reducing warming in winter. In summer, longer days increase solar radiation but also boost vegetation growth and evapotranspiration, which together reduce soil heating and increase cooling. In winter, although day length slightly raises solar input, snow cover and low sun angles limit soil warming, resulting in a less positive offset (Bender et al. 2020; Friesen et al. 2021). These patterns suggest that while sub-canopy air temperatures respond to longer days via canopy-mediated warming, soil temperatures remain constrained by insulation and limited energy transfer, producing opposite trends.

5 | Conclusions

In the past decade, significant advancements have been made in understanding microclimate patterns, related drivers, and their effects on forest biodiversity and ecosystem functioning. However, as the field evolves, there is an increasing demand for more accurate and high-resolution microclimate models and predictions. Drawing on over five years of continuous in situ observations collected across the continent, this study addressed a critical research gap by examining daily-resolution microclimate buffering in European temperate forests. We investigated how microclimatic temperatures respond to the interactive effects of multiple weather conditions with forest structural complexity and edge distance. We found significant effects of weather conditions in driving soil and air temperature offsets, with free-air temperature being the dominant factor. Higher soil moisture and wind speed had a smaller but still notable effect on microclimate temperature buffering, generally related to cooler air and soil microclimatic temperatures. Conversely, higher precipitation and solar radiation reduced the effectiveness of soil cooling buffering. Our findings underscore that the microclimate conditions are determined by complex interaction paths among multiple weather variables, forest structure, and edge distance. We offer valuable insights, and data, for refining future microclimate models and understanding forest ecosystem responses to changing environmental conditions.

While previous studies based on monthly or seasonal averages have provided important insights, our daily-resolution study offers a deeper and more dynamic understanding of microclimatic variation. First, although greater variability in weather variables such as precipitation, wind speed, soil moisture, solar radiation, snow cover is expected to be captured at the daily scale, free-air temperature consistently emerges as the dominant driver of both air and soil temperature offset dynamics. This emphasizes the overriding influence of macroclimate even amid short-term fluctuations. Second, our findings emphasize that the choice of weather variables and their modeled relationships should be explicitly tailored to the temporal resolution of analysis. Certain weather variables– such as precipitation and soil moisture– exhibit patterns that are counterintuitive or even opposite to those reported in lower-resolution studies, indicating the complexity of microclimatic responses on short timescales. This highlights the importance of incorporating temporal-scale sensitivity into microclimate modeling frameworks to ensure accurate interpretation and prediction of local temperature dynamics. Third, the interactive effects of plant area index and distance to forest edge are not always consistent at the daily scale. For instance, the positive effect of solar radiation on air temperature offsets in summer was weaker in denser forests and forest interiors. In contrast, for wind speed, the negative effect on air temperature offsets during summer was stronger in open forests and forest interiors. Moreover, in winter, the interaction patterns can differ from those in summer, indicating clear seasonal variability in these relationships. This implies that previously hidden mechanisms involving vegetation structure and edge influence become more detectable at finer temporal resolutions. This also points to the potential for lagged responses in how soil and sub-canopy air adjust to atmospheric conditions.

Altogether, our findings underscore the importance of high-frequency, long-term monitoring to fully understand the drivers of temperature offsets and the dynamic nature of microclimate processes. Our findings represent typical patterns for broadleaved forests across temperate Europe, ranging from cold to warm regions. These results can serve as useful references or models for similar forest types. However, for boreal forests, tropical forests, and high-elevation mountainous areas, further studies are recommended to determine whether similar or consistent patterns can be detected.

Author Contributions

Liping Wei: conceptualization, data curation, formal analysis, funding acquisition, methodology, writing – original draft, writing – review and editing. **Pieter Sanczuk:** conceptualization, data curation, formal analysis, funding acquisition, methodology, writing – review and editing. **Pieter Vangansbeke:** conceptualization, data curation, formal analysis, funding acquisition, methodology, writing – review and editing. **Karen De Pauw:** conceptualization, data curation, formal analysis, funding acquisition, methodology, writing – review and editing. **Thomas Vanneste:** conceptualization, data curation, formal analysis, funding acquisition, methodology, writing – review and editing. **Kurt Bollmann:** data curation, writing – review and editing. **Jörg Brunet:** data curation, writing – review and editing. **Kim Calders:** conceptualization, writing – review and editing. **Sara A. O. Cousins:** data curation, writing – review and editing. **Martin Diekmann:** data curation, writing – review and editing. **Cristina Gasperini:** data curation, writing – review and editing. **Bente J. Graae:** data curation, writing – review and editing. **Per-Ola Hedwall:** data curation, writing – review and editing. **Giovanni Iacopetti:** data curation, writing – review and editing. **Jonathan Lenoir:** conceptualization, data curation, writing – review and editing. **Anna Orczewska:** data curation, writing – review and editing. **Quentin Ponette:** data curation, writing – review and editing. **Jan Plue:** data curation, writing – review and editing. **Ilaria Santi:** data curation, writing – review and editing. **Federico Selvi:** data curation, writing – review and editing. **Fabien Spicher:** data curation, writing – review and editing. **Hans Verbeeck:** data curation, writing – review and editing. **Florian Zellweger:** data curation, writing – review and editing. **Pieter De Frenne:** conceptualization, data curation, formal analysis, funding acquisition, methodology, writing – review and editing.

Acknowledgements

L.W., P.S., P.V., K.D.P., T.V. and P.D.F. received funding through the ERC Starting grant (FORMICA 757833). P.D.F. and P.S. received funding from the European Research Council (ERC) under the European Union's Horizon 2020 research and innovation program (ERC Consolidator Grant CanopyChange 101124948). L.W. and P.D.F. were funded by the international mobility project of the National Natural Science Foundation of China—Research Foundation Flanders (NSFC-FWO, No. 32211530482). K.D.P. was additionally supported by the Research Foundation—Flanders (FWO, grant number 12A0L25N). T.V. was supported by the Special Research Fund (BOF) of Ghent University (No. 01P09722). This work was also supported by the Research Foundation—Flanders (FWO) by funding the scientific research network FLEUR (W000322N, www.fleur.ugent.be). We thank the anonymous reviewers for their constructive comments.

Funding

This work was supported by National Natural Science Foundation of China—Research Foundation Flanders: NSFC-FWO (Grant 32211530482), Fonds Wetenschappelijk Onderzoek (Grant 12A0L25N), FLEUR (Grant W000322N), European Research Council (Grants FORMICA 757833 and CanopyChange 101124948) and Universiteit Gent (Grant 01P09722).

Conflicts of Interest

The authors declare no conflicts of interest.

Data Availability Statement

Temperature offset data are accessible on Figshare at https://doi.org/10.6084/m9.figshare.30579236 (Wei et al. 2025). The raw microclimate data are deposited in the SoilTemp database at https://doi.org/10.1111/gcb.15123 (Lembrechts et al. 2020). ERA5 data were obtained from the Copernicus Climate Change Service (C3S) Climate Data Store (CDS) at https://doi.org/10.24381/cds.adbb2d47 (Muñoz-Sabater et al. 2021). Plan area index data are available on Figshare at https://doi.org/10.6084/m9.figshare.11662794.v1 (Meeussen et al. 2020).

References

Aalto, J., V. Tyystjärvi, P. Niittynen, et al. 2022. "Microclimate Temperature Variations From Boreal Forests to the Tundra." *Agricultural and Forest Meteorology* 323: 109037. https://doi.org/10.1016/j.agrformet.2022.109037.

Ashcroft, M. B., and J. R. Gollan. 2013. "Moisture, Thermal Inertia, and the Spatial Distributions of Near-Surface Soil and Air Temperatures: Understanding Factors That Promote Microrefugia." *Agricultural and Forest Meteorology* 176: 77–89. https://doi.org/10.1016/j.agrformet.2013.03.008.

Bender, E., M. Lehning, and J. Fiddes. 2020. "Changes in Climatology, Snow Cover, and Ground Temperatures at High Alpine Locations." *Frontiers in Earth Science* 8: 100. https://doi.org/10.3389/feart.2020.00100.

Beugnon, R., N. Le Guyader, A. Milcu, et al. 2024. "Microclimate Modulation: An Overlooked Mechanism Influencing the Impact of Plant Diversity on Ecosystem Functioning." *Global Change Biology* 30, no. 3: e17214. https://doi.org/10.1111/gcb.17214.

Bramer, I., B. J. Anderson, J. Bennie, et al. 2018. "Advances in Monitoring and Modelling Climate at Ecologically Relevant Scales." In *Advances in Ecological Research*, vol. 58, 101–161. Academic Press. https://doi.org/10.1016/bs.aecr.2017.12.005.

Breil, M., D. Rechid, E. L. Davin, et al. 2020. "The Opposing Effects of Reforestation and Afforestation on the Diurnal Temperature Cycle at the Surface and in the Lowest Atmospheric Model Level in the European Summer." *Journal of Climate* 33, no. 21: 9159–9179. https://doi.org/10.1175/JCLI-D-19-0624.1.

Breshears, D. D., J. W. Nyhan, C. E. Heil, and B. P. Wilcox. 1998. "Effects of Woody Plants on Microclimate in a Semiarid Woodland: Soil Temperature and Evaporation in Canopy and Intercanopy Patches." *International Journal of Plant Sciences* 159, no. 6: 1010–1017.

Chen, J. Q., J. F. Franklin, and T. A. Spies. 1993. "Contrasting Microclimates Among Clear-Cut, Edge, and Interior of Old-Growth Douglas-Fir Forest." *Agricultural and Forest Meteorology* 63: 219–237. https://doi.org/10.1016/0168-1923(93)90061-L.

Dai, A., K. E. Trenberth, and T. R. Karl. 1999. "Effects of Clouds, Soil Moisture, Precipitation, and Water Vapor on Diurnal Temperature Range." *Journal of Climate* 12, no. 8: 2451–2473. https://doi.org/10.1175/1520-0442(1999)012<2451:eocsmp>2.0.co;2.

Davarzani, H., K. Smits, R. M. Tolene, and T. Illangasekare. 2014. "Study of the Effect of Wind Speed on Evaporation From Soil Through Integrated Modeling of the Atmospheric Boundary Layer and Shallow Subsurface." *Water Resources Research* 50, no. 1: 661–680. https://doi.org/10.1002/2013WR013952.

Davies-Colley, R. J., G. W. Payne, and M. Van Elswijk. 2000. "Microclimate Gradients Across a Forest Edge." *New Zealand Journal of Ecology* 24, no. 2: 111–121. https://www.jstor.org/stable/24054666.

Davis, K. T., S. Z. Dobrowski, Z. A. Holden, P. E. Higuera, and J. T. Abatzoglou. 2019. "Microclimatic Buffering in Forests of the Future: The Role of Local Water Balance." *Ecography* 42, no. 1: 1–11. https://doi.org/10.1111/ecog.03836.

De Frenne, P., R. Beugnon, D. Klinges, et al. 2025. "Ten Practical Guidelines for Microclimate Research in Terrestrial Ecosystems." *Methods in Ecology and Evolution* 16, no. 2: 269–294. https://doi.org/10.1111/2041-210X.14476.

De Frenne, P., J. Lenoir, M. Luoto, et al. 2021. "Forest Microclimates and Climate Change: Importance, Drivers and Future Research Agenda." *Global Change Biology* 27, no. 11: 2279–2297. https://doi.org/10.1111/gcb.15569.

De Frenne, P., F. Zellweger, F. Rodríguez-Sánchez, et al. 2019. "Global Buffering of Temperatures Under Forest Canopies." *Nature Ecology & Evolution* 3, no. 5: 744–749. https://doi.org/10.1038/s41559-019-0842-1.

De Lombaerde, E., P. Vangansbeke, J. Lenoir, et al. 2022. "Maintaining Forest Cover to Enhance Temperature Buffering Under Future Climate Change." *Science of the Total Environment* 810: 151338. https://doi.org/10.1016/j.scitotenv.2021.151338.

Decker, K. L. M., D. Wang, C. Waite, and T. Scherbatskoy. 2003. "Snow Removal and Ambient Air Temperature Effects on Forest Soil Temperatures in Northern Vermont." *Soil Science Society of America Journal* 67, no. 4: 1234–1242. https://doi.org/10.2136/sssaj2003.1234.

Dessler, A. E. 2010. "A Determination of the Cloud Feedback From Climate Variations Over the Past Decade." *Science* 330, no. 6010: 1523–1527. https://doi.org/10.1126/science.1192546.

Díaz-Calafat, J., J. Uria-Diez, J. Brunet, et al. 2023. "From Broadleaves to Conifers: The Effect of Tree Composition and Density on Understory Microclimate Across Latitudes." *Agricultural and Forest Meteorology* 341: 109684. https://doi.org/10.1016/j.agrformet.2023.109684.

Diószegi, G., M. Immitzer, M. M. Müller, and H. Vacik. 2023. "Effects of Interaction Between Forest Structure and Precipitation Event Characteristics on Fuel Moisture Conditions." *Agricultural and Forest Meteorology* 342: 109681. https://doi.org/10.1016/j.agrformet.2023.109681.

Diro, G. T., L. Sushama, and O. Huziy. 2018. "Snow-Atmosphere Coupling and Its Impact on Temperature Variability and Extremes Over North America." *Climate Dynamics* 50, no. 7–8: 2993–3007. https://doi.org/10.1007/s00382-017-3788-5.

Edwards, A. C., R. Scalenghe, and M. Freppaz. 2007. "Changes in the Seasonal Snow Cover of Alpine Regions and Its Effect on Soil Processes: A Review." *Quaternary International* 162: 172–181. https://doi.org/10.1016/j.quaint.2006.10.027.

Ellis, C. R., and J. W. Pomeroy. 2007. "Estimating Sub-Canopy Shortwave Irradiance to Melting Snow on Forested Slopes." *Hydrological Processes* 21, no. 19: 2581–2593. https://doi.org/10.1002/hyp.6794.

Esperon-Rodriguez, M., S. A. Power, M. G. Tjoelker, R. M. Marchin, and P. D. Rymer. 2021. "Contrasting Heat Tolerance of Urban Trees to Extreme Temperatures During Heatwaves." *Urban Forestry & Urban Greening* 66: 127387. https://doi.org/10.1016/j.ufug.2021.127387.

Fang, Y., and L. R. Leung. 2022. "Relative Controls of Vapor Pressure Deficit and Soil Water Stress on Canopy Conductance in Global Simulations by an Earth System Model." *Earth's Future* 10, no. 9: e2022EF002810. https://doi.org/10.1029/2022EF002810.

Fischer, E. M., and C. Schär. 2009. "Future Changes in Daily Summer Temperature Variability: Driving Processes and Role for Temperature Extremes." *Climate Dynamics* 33, no. 7–8: 917–935. https://doi.org/10.1007/s00382-008-0473-8.

Frey, S. J., A. S. Hadley, S. L. Johnson, M. Schulze, J. A. Jones, and M. G. Betts. 2016. "Spatial Models Reveal the Microclimatic Buffering Capacity of Old-Growth Forests." *Science Advances* 2, no. 4: e1501392. https://doi.org/10.1126/sciadv.1501392.

Friesen, H. C., R. A. Slesak, D. L. Karwan, and R. K. Kolka. 2021. "Effects of Snow and Climate on Soil Temperature and Frost Development in Forested Peatlands in Minnesota, USA." *Geoderma* 394: 115015. https://doi.org/10.1016/j.geoderma.2021.115015.

Geiger, R., R. H. Aron, and P. Todhunter. 2009. *The Climate Near the Ground*. Rowman & Littlefield.

Gilliam, F. S. 2007. "The Ecological Significance of the Herbaceous Layer in Temperate Forest Ecosystems." *Bioscience* 57, no. 10: 845–858. https://doi.org/10.1641/B571007.

Govaert, S., C. Meeussen, T. Vanneste, et al. 2020. "Edge Influence on Understorey Plant Communities Depends on Forest Management." *Journal of Vegetation Science* 31, no. 2: 281–292. https://doi.org/10.1111/jvs.12844.

Graae, B. J., P. de Frenne, A. Kolb, et al. 2012. "On the Use of Weather Data in Ecological Studies Along Altitudinal and Latitudinal Gradients." *Oikos* 121, no. 1: 3–19. https://doi.org/10.1111/j.1600-0706.2011.19694.x.

Greiser, C., L. Hederová, G. Vico, J. Wild, M. Macek, and M. Kopecký. 2024. "Higher Soil Moisture Increases Microclimate Temperature Buffering in Temperate Broadleaf Forests." *Agricultural and Forest Meteorology* 345: 109828. https://doi.org/10.1016/j.agrformet.2023.109828.

Greiser, C., E. Meineri, M. Luoto, J. Ehrlén, and K. Hylander. 2018. "Monthly Microclimate Models in a Managed Boreal Forest Landscape." *Agricultural and Forest Meteorology* 250: 147–158. https://doi.org/10.1016/j.agrformet.2017.12.252.

Gril, E., F. Spicher, C. Greiser, et al. 2023. "Slope and Equilibrium: A Parsimonious and Flexible Approach to Model Microclimate." *Methods in Ecology and Evolution* 14, no. 3: 885–897. https://doi.org/10.1111/2041-210X.14048.

Haesen, S., J. J. Lembrechts, P. de Frenne, et al. 2021. "ForestTemp – Sub-Canopy Microclimate Temperatures of European Forests." *Global Change Biology* 27, no. 23: 6307–6319. https://doi.org/10.1111/gcb.15892.

Hardy, J. P., P. M. Groffman, R. D. Fitzhugh, et al. 2001. "Snow Depth Manipulation and Its Influence on Soil Frost and Water Dynamics in a Northern Hardwood Forest." *Biogeochemistry* 56, no. 2: 151–174. https://doi.org/10.1023/A:1013036803050.

Harper, K. A., S. E. Macdonald, P. J. Burton, et al. 2005. "Edge Influence on Forest Structure and Composition in Fragmented Landscapes." *Conservation Biology* 19, no. 3: 768–782. https://doi.org/10.1111/j.1523-1739.2005.00045.x.

Hes, G., I. Vanderkelen, R. Fisher, J. Chave, J. Ogée, and E. L Davin. 2024. "Projecting Future Forest Microclimate Using a Land Surface Model." *Environmental Research Letters* 19, no. 2: 024030. https://doi.org/10.1088/1748-9326/ad1f04.

Hijmans, R. J., E. Williams, C. Vennes, and M. R. J. Hijmans. 2024. *Introduction to the "Geosphere" Package*. Comprehensive R Archive Network (CRAN). https://doi.org/10.32614/CRAN.package.geosphere.

Honnay, O., K. Verheyen, J. Butaye, H. Jacquemyn, B. Bossuyt, and M. Hermy. 2002. "Possible Effects of Habitat Fragmentation and Climate Change on the Range of Forest Plant Species." *Ecology Letters* 5, no. 4: 525–530. https://doi.org/10.1046/j.1461-0248.2002.00346.x.

Horváth, C. V., B. Kovács, F. Tinya, et al. 2023. "A Matter of Size and Shape: Microclimatic Changes Induced by Experimental Gap Openings in a Sessile Oak–Hornbeam Forest." *Science of the Total Environment* 873: 162302. https://doi.org/10.1016/j.scitotenv.2023.162302.

IPCC. 2021. "Climate Change 2021: The Physical Science Basis." In *Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*, edited by V. Masson-Delmotte, P. Zhai, A. Pirani et al. Cambridge University Press. https://doi.org/10.1017/9781009157896.

Irvine, M. R., B. A. Gardiner, and M. K. Hill. 1997. "The Evolution of Turbulence Across a Forest Edge." *Boundary-Layer Meteorology* 84, no. 3: 467–496. https://doi.org/10.1023/A:1000453031036.

John, A., J. D. Olden, M. F. Oldfather, M. M. Kling, and D. D. Ackerly. 2024. "Topography Influences Diurnal and Seasonal Microclimate Fluctuations in Hilly Terrain Environments of Coastal California." *PLoS One* 19, no. 3: e0300378. https://doi.org/10.1371/journal.pone.0300378.

Jucker, T., S. R. Hardwick, S. Both, et al. 2018. "Canopy Structure and Topography Jointly Constrain the Microclimate of Human-Modified Tropical Landscapes." *Global Change Biology* 24, no. 11: 5243–5258. https://doi.org/10.1111/gcb.14415.

Karger, D. N., O. Conrad, J. Böhner, et al. 2017. "Climatologies at High Resolution for the Earth's Land Surface Areas." *Scientific Data* 4, no. 1: 1–20. https://doi.org/10.1038/sdata.2017.122.

Koenig, W. D., and A. M. Liebhold. 2016. "Temporally Increasing Spatial Synchrony of North American Temperature and Bird Populations." *Nature Climate Change* 6, no. 6: 614–617. https://doi.org/10.1038/nclimate2933.

Konrad, W., G. Katul, and A. Roth-Nebelsick. 2021. "Leaf Temperature and Its Dependence on Atmospheric CO_2 and Leaf Size." *Geological Journal* 56, no. 2: 866–885. https://doi.org/10.1002/gj.3757.

Kovács, B., F. Tinya, C. Németh, and P. Ódor. 2020. "Unfolding the Effects of Different Forestry Treatments on Microclimate in Oak Forests: Results of a 4-Yr Experiment." *Ecological Applications* 30, no. 2: e02043. https://doi.org/10.1002/eap.2043.

Lembrechts, J. J., J. Aalto, M. B. Ashcroft, et al. 2020. "SoilTemp: A Global Database of Near-Surface Temperature." *Global Change Biology* 26, no. 11: 6616–6629. https://doi.org/10.1111/gcb.15123.

Lenoir, J., T. Hattab, and G. Pierre. 2017. "Climatic Microrefugia Under Anthropogenic Climate Change: Implications for Species Redistribution." *Ecography* 40, no. 2: 253–266. https://doi.org/10.1111/ecog.02788.

Luo, H., J. Quaas, and Y. Han. 2024. "Diurnally Asymmetric Cloud Cover Trends Amplify Greenhouse Warming." *Science Advances* 10, no. 25: eado5179.

Matlack, G. R. 1993. "Microenvironment Variation Within and Among Forest Edge Sites in the Eastern United States." *Biological Conservation* 66, no. 3: 185–194. https://doi.org/10.1016/0006-3207(93)90004-K.

Maurer, G. E., and D. R. Bowling. 2014. "Seasonal Snowpack Characteristics Influence Soil Temperature and Water Content at Multiple Scales in Interior Western U.S. Mountain Ecosystems." *Water Resources Research* 50, no. 6: 5216–5234. https://doi.org/10.1002/2013WR014452.

Meeussen, C., S. Govaert, T. Vanneste, et al. 2020. "Structural Variation of Forest Edges Across Europe." *Forest Ecology and Management* 462: 117929. https://doi.org/10.1016/j.foreco.2020.117929.

Meeussen, C., S. Govaert, T. Vanneste, et al. 2021. "Microclimatic Edge-To-Interior Gradients of European Deciduous Forests." *Agricultural and Forest Meteorology* 311: 108699. https://doi.org/10.1016/j.agrformet.2021.108699.

Menge, J. H., P. Magdon, S. Wöllauer, and M. Ehbrecht. 2023. "Impacts of Forest Management on Stand and Landscape-Level Microclimate Heterogeneity of European Beech Forests." *Landscape Ecology* 38, no. 4: 903–917. https://doi.org/10.1007/s10980-023-01596-z.

Meyer, A. V., Y. Sakairi, M. R. Kearney, and L. B. Buckley. 2023. "A Guide and Tools for Selecting and Accessing Microclimate Data for Mechanistic Niche Modeling." *Ecosphere* 14, no. 4: e4506. https://doi.org/10.1002/ecs2.4506.

Monteith, J., and M. Unsworth. 2013. *Principles of Environmental Physics: Plants, Animals, and the Atmosphere*. Academic Press.

Muñoz-Sabater, J., E. Dutra, A. Agustí-Panareda, et al. 2021. "ERA5-Land: A State-Of-The-Art Global Reanalysis Dataset for Land Applications." *Earth System Science Data* 13, no. 9: 4349–4383. https://doi.org/10.5194/essd-13-4349-2021.

Nakagawa, S., and H. Schielzeth. 2013. "A General and Simple Method for Obtaining R2 From Generalized Linear Mixed-Effects Models." *Methods in Ecology and Evolution* 4, no. 2: 133–142. https://doi.org/10.1111/j.2041-210x.2012.00261.x.

Oke, T. R. 2002. *Boundary Layer Climates*. 2nd ed. Routledge.

Orczewska, A., and A. Glista. 2005. "Floristic Analysis of the Two Woodland-Meadow Ecotones Differing in Orientation of the Forest Edge." *Polish Journal of Ecology* 53, no. 3: 365–382.

Pinheiro, J., D. Bates, S. DebRoy, D. Sarkar, and Team, R. C. 2023. *nlme: Linear and Nonlinear Mixed Effects Models. v. 3.1-164*. R-project.

Pomeroy, J. W., D. Marks, T. Link, et al. 2009. "The Impact of Coniferous Forest Temperature on Incoming Longwave Radiation to Melting Snow." *Hydrological Processes* 23, no. 17: 2513–2525. https://doi.org/10.1002/hyp.7325.

Prévosto, B., M. Helluy, J. Gavinet, C. Fernandez, and P. Balandier. 2020. "Microclimate in Mediterranean Pine Forests: What Is the Influence of the Shrub Layer?" *Agricultural and Forest Meteorology* 282: 107856. https://doi.org/10.1016/j.agrformet.2019.107856.

Promis, A., D. Schindler, A. Reif, and G. Cruz. 2009. "Solar Radiation Transmission in and Around Canopy Gaps in an Uneven-Aged Nothofagus Betuloides Forest." *International Journal of Biometeorology* 53, no. 4: 355–367. https://doi.org/10.1111/j.1469-185X.1964.tb01164.x.

Rajendran, P., and H. Smith. 2016. "Modelling of Solar Irradiance and Daylight Duration for Solar-Powered UAV Sizing." *Energy Exploration & Exploitation* 34, no. 2: 235–243. https://www.jstor.org/stable/90007395.

Renaud, V., J. L. Innes, M. Dobbertin, and M. Rebetez. 2011. "Comparison Between Open-Site and Below-Canopy Climatic Conditions in Switzerland for Different Types of Forests Over 10 Years (1998–2007)." *Theoretical and Applied Climatology* 105, no. 1: 119–127. https://doi.org/10.1007/s00704-010-0361-0.

Richard, B., J. L. Dupouey, E. Corcket, et al. 2021. "The Climatic Debt Is Growing in the Understorey of Temperate Forests: Stand Characteristics Matter." *Global Ecology and Biogeography* 30, no. 7: 1474–1487. https://doi.org/10.1111/geb.13312.

Richter, R., H. Ballasus, R. A. Engelmann, C. Zielhofer, A. Sanaei, and C. Wirth. 2022. "Tree Species Matter for Forest Microclimate Regulation During the Drought Year 2018: Disentangling Environmental Drivers and Biotic Drivers." *Scientific Reports* 12, no. 1: 17559. https://doi.org/10.1038/s41598-022-22582-6.

Riutta, T., E. M. Slade, D. P. Bebber, et al. 2012. "Experimental Evidence for the Interacting Effects of Forest Edge, Moisture and Soil Macrofauna on Leaf Litter Decomposition." *Soil Biology and Biochemistry* 49: 124–131. https://doi.org/10.1016/j.soilbio.2012.02.028.

Rowlands, A. L. E. D., J. Pomeroy, J. Hardy, D. Marks, K. Elder, and R. Melloh. 2002. "Small-Scale Spatial Variability of Radiant Energy for Snowmelt in a Mid-Latitude Sub-Alpine Forest." In *Proceedings of the 59th Eastern Snow Conference*, vol. 9. Eastern Snow Conference.

Ruel, J. J., and M. P. Ayres. 1999. "Jensen's Inequality Predicts Effects of Environmental Variation." *Trends in Ecology & Evolution* 14, no. 9: 361–366. https://doi.org/10.1016/S0169-5347(99)01664-X.

Rush, M. J., and H. Rajaram. 2022. "Influence of Snowpack Cold Content on Seasonally Frozen Ground and Its Hydrologic Consequences: A Case Study From Niwot Ridge, CO." *Water Resources Research* 58, no. 9: e2021WR031911. https://doi.org/10.1029/2021WR031911.

Sanczuk, P., K. de Pauw, E. de Lombaerde, et al. 2023. "Microclimate and Forest Density Drive Plant Population Dynamics Under Climate Change." *Nature Climate Change* 13, no. 8: 840–847. https://doi.org/10.1038/s41558-023-01744-y.

Schmidt, M., H. Jochheim, K. C. Kersebaum, G. Lischeid, and C. Nendel. 2017. "Gradients of Microclimate, Carbon and Nitrogen in Transition Zones of Fragmented Landscapes – A Review." *Agricultural and Forest Meteorology* 232: 659–671. https://doi.org/10.1016/j.agrformet.2016.10.022.

Seneviratne, S. I., T. Corti, E. L. Davin, et al. 2010. "Investigating Soil Moisture–Climate Interactions in a Changing Climate: A Review." *Earth-Science Reviews* 99, no. 3–4: 125–161. https://doi.org/10.1016/j.earscirev.2010.02.004.

Stickley, S. F., and J. M. Fraterrigo. 2021. "Understory Vegetation Contributes to Microclimatic Buffering of Near-Surface Temperatures in Temperate Deciduous Forests." *Landscape Ecology* 36, no. 4: 1197–1213. https://doi.org/10.1007/s10980-021-01195-w.

Van Gestel, M., E. Matthysen, D. Heylen, and K. Verheyen. 2022. "Survival in the Understorey: Testing Direct and Indirect Effects of

Microclimatological Changes on Ixodes ricinus." *Ticks and Tick-borne Diseases* 13, no. 6: 102035. https://doi.org/10.1016/j.ttbdis.2022.102035.

Vanneste, T., L. Depauw, E. de Lombaerde, et al. 2024. "Trade-Offs in Biodiversity and Ecosystem Services Between Edges and Interiors in European Forests." *Nature Ecology & Evolution* 8, no. 5: 880–887. https://doi.org/10.1038/s41559-024-02335-6.

Von Arx, G., E. Graf Pannatier, A. Thimonier, and M. Rebetez. 2013. "Microclimate in Forests With Varying Leaf Area Index and Soil Moisture: Potential Implications for Seedling Establishment in a Changing Climate." *Journal of Ecology* 101, no. 5: 1201–1213. https://doi.org/10.1111/1365-2745.12121.

Wei, L., P. Sanczuk, K. De Pauw, et al. 2024. "Using Warming Tolerances to Predict Understory Plant Responses to Climate Change." *Global Change Biology* 30, no. 1: e17064. https://doi.org/10.1111/gcb.17064.

Wei, L., P. Sanczuk, P. Vangansbeke, et al. 2025. "Data From: Interactive Effects of Weather and Forest Structure on Microclimate Buffering in European Deciduous Forests." *Figshare*. https://doi.org/10.6084/m9.figshare.30579236.

Williams, S. C., and J. S. Ward. 2010. "Effects of Japanese Barberry (Ranunculales: Berberidaceae) Removal and Resulting Microclimatic Changes on Ixodes scapularis (Acari: Ixodidae) Abundances in Connecticut, USA." *Environmental Entomology* 39, no. 6: 1911–1921. https://doi.org/10.1603/EN10131.

Wilson, G., M. Green, J. Brown, et al. 2020. "Snowpack Affects Soil Microclimate Throughout the Year." *Climatic Change* 163, no. 2: 705–722. https://doi.org/10.1007/s10584-020-02943-8.

Wood, S. N. 2017. *Generalized Additive Models: An Introduction With R*. 2nd ed. Chapman and Hall/CRC. https://doi.org/10.1201/9781315370279.

Wuyts, K., K. Verheyen, A. de Schrijver, W. M. Cornelis, and D. Gabriels. 2008. "The Impact of Forest Edge Structure on Longitudinal Patterns of Deposition, Wind Speed, and Turbulence." *Atmospheric Environment* 42, no. 37: 8651–8660. https://doi.org/10.1016/j.atmosenv.2008.08.010.

Yin, J., A. Molini, and A. Porporato. 2020. "Impacts of Solar Intermittency on Future Photovoltaic Reliability." *Nature Communications* 11, no. 1: 4781. https://doi.org/10.1038/s41467-020-18602-6.

Young, A., and N. Mitchell. 1994. "Microclimate and Vegetation Edge Effects in a Fragmented Podocarp-Broadleaf Forest in New Zealand." *Biological Conservation* 67, no. 1: 63–72. https://doi.org/10.1016/0006-3207(94)90010-8.

Yu, Z., J. Chen, J. Chen, et al. 2024. "Enhanced Observations From an Optimized Soil-Canopy-Photosynthesis and Energy Flux Model Revealed Evapotranspiration-Shading Cooling Dynamics of Urban Vegetation During Extreme Heat." *Remote Sensing of Environment* 305: 114098. https://doi.org/10.1016/j.rse.2024.114098.

Zelinka, M. D., D. A. Randall, M. J. Webb, and S. A. Klein. 2017. "Clearing Clouds of Uncertainty." *Nature Climate Change* 7, no. 10: 674–678. https://doi.org/10.1038/nclimate3402.

Zellweger, F., D. Coomes, J. Lenoir, et al. 2019. "Seasonal Drivers of Understorey Temperature Buffering in Temperate Deciduous Forests Across Europe." *Global Ecology and Biogeography* 28, no. 12: 1774–1786. https://doi.org/10.1111/geb.12991.

Zellweger, F., E. Sulmoni, J. T. Malle, et al. 2024. "Microclimate Mapping Using Novel Radiative Transfer Modelling." *Biogeosciences* 21, no. 2: 605–623. https://doi.org/10.5194/bg-21-605-2024.

Zhang, K., Y. Li, J. D. Schwartz, and M. S. O'Neill. 2014. "What Weather Variables Are Important in Predicting Heat-Related Mortality? A New Application of Statistical Learning Methods." *Environmental Research* 132: 350–359. https://doi.org/10.1016/j.envres.2014.04.004.

Zhang, Y., S. Wang, A. G. Barr, and T. A. Black. 2008. "Impact of Snow Cover on Soil Temperature and Its Simulation in a Boreal Aspen Forest." *Cold Regions Science and Technology* 52, no. 3: 355–370. https://doi.org/10.1016/j.coldregions.2007.07.001.

Zuur, A. F., E. N. Ieno, and G. M. Smith. 2007. *Analysing Ecological Data*. Springer New York. https://doi.org/10.1016/B978-0-12-387667-6.00013-0.

Supporting Information

Additional supporting information can be found online in the Supporting Information section. **Data S1:** gcb70634-sup-0001-Supinfo.docx.