Mapping spatial microclimate patterns in mountain forests from LiDAR

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Abstract: Forests create unique microclimates that have the potential to serve as microrefugia for species under climate change. Yet, our understanding of the heterogenous thermal patterns at the forest floor of complex landscapes (e.g., in mountain forests) remains incomplete. We here used Light Detection and Ranging (LiDAR) for predicting summer temperature offsets in a mountain forest landscape in the European Alps. We calibrated models on a network of 150 microclimate loggers that were combined with data from 15 meteorological stations to estimate the maximum, mean, and minimum temperature offsets, using LiDAR-derived metrics of forest structure and topography as predictors. Models predicted summer temperature offsets with an R^2/RMSE of 0.50/3.15 °C for maximum temperature, 0.51/0.41 °C for mean temperature and 0.55/0.57 °C for minimum temperature. Forest canopy openness and elevation were most important for predicting temperature offsets. The mean offset ranged from – 1.9 °C to 2.7 °C (mean of - 0.3 °C), but both minimum and maximum offsets varied considerably, with some forests even having warmer maximum and colder minimum temperatures than open areas. This was particularly prominent in forests of the subalpine zone, which are characterized by open canopies and a considerable presence of coniferous shrubs. In contrast, submontane forests with largely closed canopies had mostly colder maximum and warmer minimum temperatures within forests compared to open areas. Analysing the development of temperature offsets with time since disturbance, we found that recently disturbed forests had higher maximum temperatures compared to open areas, but they recovered to closed forest conditions within two decades. We conclude that mountain forests exhibit complex microclimate patterns that vary strongly with forest type and canopy openness. We further highlight that disturbances are an important driver of spatiotemporal dynamics in forest microclimate. Finally, temperature offset maps such as the ones generated here have strong potential to improve the robustness of species distribution models and to assess climate risks for biodiversity.

Keywords: Temperature offset, forest floor climate, climate extremes, remote sensing, forest disturbance

Introduction

Climate change has profound impacts on terrestrial ecosystems globally (Sheridan and Bickford 2011; Roulin 2014; Visser and Both 2005; Walther et al. 2002; Scheffers et al. 2016). One possible response of many mobile species is to shift their locations towards the poles and higher elevations to stay within their climatic niche (Lenoir et al. 2020; Chen et al. 2011; Chen et al. 2009). Climate change will thus likely lead to a redistribution of life on Earth and the emergence of novel biological communities (Lenoir et al. 2020; Pecl et al. 2017). Yet, not all taxa shift their distribution proportionally to climatic change, with some taxa – particularly endothermic organisms and plants – lagging behind macroclimatic warming trends, while others respond more strongly than what can be expected from changes in temperature alone (Bässler et al. 2013; Lenoir et al. 2020). Consequently, the transformation of species assemblages towards thermophile taxa, as well as the general shift of species towards the poles and higher elevations is often more complex than changes in temperature predict (Devictor et al. 2012; Bertrand et al. 2011; Dullinger et al. 2012; Scheffers et al. 2014; Ash, Givnish, and Waller 2017). One of the potential reasons for this divergence is the local climate regulating function of vegetation, which is particularly pronounced in forest ecosystems, creating distinct local microclimates that determine the climatic conditions perceived by many species (De Frenne et al. 2021; Lembrechts, Nijs, and Lenoir 2019).

Forests cover nearly one third of the global terrestrial land surface and play a crucial role in modulating species' responses to climate warming (FAO 2020; De Frenne et al. 2021). For instance, forests buffer temperature maxima on average by 4 °C compared to open lands (De Frenne et al. 2019). The microclimate in forests thus differs from macroclimate, mainly due to vegetation increasing evapotranspiration and air mixing, as well as intercepting solar radiation (Geiger, Aron, and Todhunter 2009; De Frenne et al. 2021). In addition, many forested areas have complex structural (e.g., downed deadwood, snags) and micro-topographical features (e.g., pit-and-mound structures) that further can modulate microclimatic conditions (Jucker et al. 2018; Dobrowski 2011). The distinct thermal environments in forests can further serve as microrefugia under climate change, because microclimates in forests tend to change at a slower rate than in open lands (De Frenne et al. 2013; De Frenne et al. 2019; Scheffers, Phillips, and Shoo 2014). The absolute difference between within-stand and open-land temperatures is termed temperature offset, and serves as a measure of how well forests buffer open-land temperatures and especially macroscale climate extremes (De Frenne et al. 2021; De Frenne et al. 2019; Zellweger, Coomes, et al. 2019). While other measures of microclimatic buffering exist (Gril et al. 2022), we here adopt this simple definition and refer to temperature offset in the following when addressing the absolute difference between within-stand and open-land temperatures.

Despite the growing body of research supporting the significance of forests for offsetting temperature extremes, ecological research assessing biotic responses to increasing temperatures has largely relied on low-resolution climate data representing open conditions (Bramer et al. 2018). This data is typically derived from standardized meteorological weather stations, which record temperatures in open areas at 1.2 m to 2 m above ground in order to represent macroclimatic conditions (WMO 2008). However, these conditions differ from the microclimatic conditions in forests; they are thus often not representative for the thermal environment that forest-dwelling species experience (Potter, Arthur Woods, and Pincebourde 2013; De Frenne et al. 2021). This discrepancy might partly explain why the observed response of many biotic systems differs from expectations derived from models driven with macroclimate data (Abbass et al. 2022; De Frenne et al. 2019; Willis and Bhagwat 2009; Lembrechts, Nijs, and Lenoir 2019; Moritz and Agudo 2013). Hence, to better understand biotic responses to increasing temperatures and to improve projections of climate change effects, a better understanding of the spatial variability in forest microclimate is needed.

Forest structure, that is the horizontal and vertical distribution of vegetation, plays a crucial role for modulating forest microclimate. Numerous studies have shown that a decrease in canopy cover causes temperature offsets to decrease, which highlights the importance of canopy cover in modulating forest microclimate (De Lombaerde et al. 2022; Frey et al. 2016;

De Frenne et al. 2019; Zellweger, Coomes, et al. 2019). Similarly, other structural features – such as multiple tree layers or downed and standing deadwood – might influence forest microclimates, but their effects are less well understood (Thom et al. 2020; Kovács, Tinya, and Ódor 2017; De Frenne et al. 2021). Forest structure is often contingent on the prevailing forest type, which can thus serve as proxy of forest microclimatic temperature offsets. A study by Renaud et al. (2011), for instance, found that the temperature offsets of mountain forests were lowest for pine forests, which are open in structure, and highest for deciduous forests with closed canopies. Furthermore, forest disturbances can temporally alter forest structure by opening up the canopy and altering the prevalence of open and closed forest developmental stages at the landscape scale (Senf et al. 2020; Senf, Sebald, and Seidl 2021). Yet, both the effects of forest type and disturbance on microclimate are not fully understood (Schwartz et al. 2022; Ewers and Banks-Leite 2013; Gavito et al. 2021; Sánchez-Reyes et al. 2021; Thom et al. 2020; Aragón et al. 2015; Renaud et al. 2011). Focusing on the effects of forest type and disturbance is important, as climate change could cause substantial shifts in both tree species distribution and disturbance regimes (Thom et al. 2022; Thom and Seidl 2022; Albrich et al. 2022). If disturbances increase under climate change, for instance, this could create negative feedbacks between climate change and temperature offsets in forests, potentially rendering future forests unsuitable as microclimate refugia (De Frenne et al. 2021). Those negative feedbacks might include the loss of intact tree canopy following stand-replacing disturbances (Senf and Seidl 2021) or more subtle changes in forest structure such as shorter and more open forests under increasing disturbances (Stritih et al. 2023). Understanding the feedback processes between microclimates, changing forest types and disturbance regimes requires the consideration of spatial and temporal variability in forest microclimates at the landscape scale. However, there is still a lack of microclimate studies that go beyond the plot or stand scale, considering variability in microclimate in relation to landscape-scale variation in forest type and disturbance.

Remote sensing offers a way forward in understanding landscape-level variation in microclimate by means of upscaling local in-situ measurements to the landscape scale (Senf 2022; Zellweger, De Frenne, et al. 2019). While measurements from in-situ microclimate loggers are the gold standard for capturing microclimatic conditions on the ground, they only record conditions for a single point in space and – depending on the sampling design – their measurements might not be representative of the full landscape (e.g., when plot locations were stratified along an elevation gradient). Observations from microclimate loggers alone might thus give biased estimates of the thermal characteristics of a full landscape. Remote sensing provides spatially continuous information on vegetation properties that can be used to infer microclimatic conditions in a spatially explicit manner, thus complementing networks of microclimate loggers (Zellweger, De Frenne, et al. 2019). Light detection and ranging (LiDAR) is of particular use for quantifying temperature offsets across forest landscapes, due to its ability to represent vertical and horizontal forest structure as well as local topographic features (Jucker et al. 2018). In fact, several studies have shown great potential for mapping forest microclimate from LiDAR (Zellweger, Coomes, et al. 2019; Frey et al. 2016; Kašpar et al. 2021; Lenoir, Hattab, and Pierre 2017; Davis et al. 2019), but those studies either used drone-based data with limited spatial extent or limited the analysis to relatively few simple metrics of canopy cover. Furthermore, most previous works have focused on topographically simple landscapes. It thus remains unclear whether using LiDAR data to map temperature offsets in topographically more complex forest landscapes, such as found in the European Alps, is also feasible.

The aim of this study is to quantify the spatial patterns of temperature offsets in mountain forests using airborne LiDAR data in combination with a large network of microclimate loggers and weather stations, focussing in particular on temperature offsets during summer. We approach this aim by addressing four specific objectives: (1) Testing whether summer temperature offsets in mountain forests can be mapped from airborne LiDAR data. (2) Quantifying the relative importance of forest structural and topographic variables for predicting summer temperature offsets. (3) Characterizing the effect of forest types on summer temperature offsets at the landscape scale. (4) Assessing the effect of past forest disturbances on summer temperature offsets at the landscape scale. We expect high resolution LiDAR data to be well-suited for mapping temperature offsets in complex terrain, with forest structure being more important than topography, because forest structure is the main determinant of how much incoming solar radiation reaches the forest floor. Yet, topographic variability in mountain forests is high, which might increase the importance of local topographic features. We further expect that the temperature offsets are most pronounced in submontane forests characterized by high canopy cover and less pronounced in subalpine forests that are naturally open (Renaud et al. 2011). Finally, we anticipate that temperature offsets are reduced in recently disturbed sites and increase with forest development due to increasing canopy closure over the successional trajectory (Zenner et al. 2016).

Methods

Study area

The study was carried out at Berchtesgaden National Park, a 20’808 ha landscape in the German Alps with 8’645 ha of forests. The area has a long history of intense forest management, which ceased in 1978 with the establishment of the national park. Since then, there has been no forest management in 75 % of the area, allowing for the analysis of natural forest dynamics without human influence. The study area is topographically complex, spanning an elevation gradient from 603 m a.s.l. (Lake Königssee) to 2713 m a.s.l. (mount Watzmann). In the submontane zone (below 850 m a.s.l.) natural vegetation is dominated by European beech (*Fagus sylvatica* L.). The montane zone between 850 m and 1400 m a.s.l. is naturally covered by mixed forests, which typically contain Norway spruce (*Picea abies* (L.) Karst.), European beech and silver fir (*Abies alba* Mill.). Due to the long history of forest use in the area, Norway spruce is currently dominating large parts of the submontane and montane zones. In the subalpine zone between 1400 m a.s.l. and the treeline at approximately 1700 m a.s.l., Norway spruce forests as well as European larch (*Larix decidua* Mill.) and Swiss stone pine (*Pinus cembra* L.) forests prevail. Finally, the timberline ecotone is dominated by dwarf mountain pine (*Pinus mugo ssp. mugo* Turra) (Thom et al. 2022; Thom and Seidl 2022) (Figure 1).

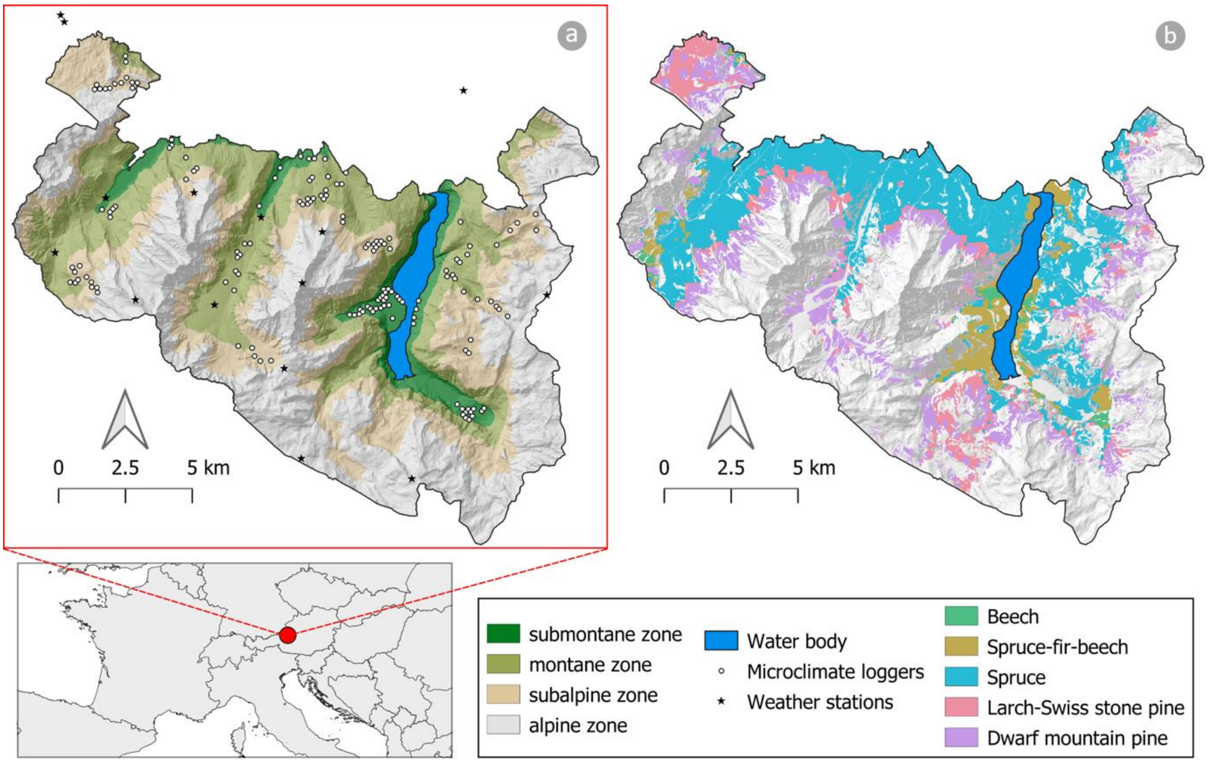

Figure 1: The location of Berchtesgaden National Park with (a) the locations of microclimate loggers (white dots with black circles) and weather stations (black stars), and (b) the current distribution of forest types according to Thom et al. (2022).

Temperature measurements and offset estimation

We calculated temperature offsets from a network of microclimate loggers and macroclimate weather stations distributed throughout Berchtesgaden National Park (Figure 1a). Microclimatic temperature was recorded from July 8th until August 31st 2021 using 150 Tomst TMS-4 loggers. The loggers recorded the temperature at -6, 2 and 15 cm height above ground every 15 minutes (Wild et al. 2019). Here, we used the temperature measured at 15 cm above ground to characterize forest microclimate (Haesen et al. 2021). Microclimate loggers were installed at the centre of 500 m^2 circular forest inventory plots stratified along three elevation zones (submontane, montane, subalpine) and five forest developmental stages, with ten replica per combination (resulting in 150 loggers in total). Forest development stages were classified according to Zenner et al. (2016), distinguishing gap/regeneration, establishment, optimum, plenter, and terminal/decay stages. This stratification allowed for a broad representation of all forest types and forest development stages in the landscape. Macroclimate temperature at a minimum of 2 m height above ground was recorded in 10-minute intervals at 15 weather stations operated by the national park and the Bavarian Avalanche Service. These weather stations cover the entire elevation gradient of the landscape and are evenly distributed over the national park area (including nearby locations outside of the national park boundaries, Figure 1a).

To calculate temperature offsets, we first averaged the temperature data from microclimate loggers and weather stations to hourly values as the arithmetic mean. Second, to obtain macroclimatic temperatures for the location of each microclimate logger, we interpolated hourly macroclimatic temperatures using adiabatic lapse rates. This was achieved with linear regression models based on elevation and temperature records from the 15 macroclimate weather stations (Figure 1). We calculated individual lapse rates for each hour of the observation period (a total of 99'000 models). These models were robust, except for a few points in time, with a median R^2 of 0.93 (range: 0.11 – 1.00) and an average root mean square error (RMSE) of 0.95 °C (range: 0.26 – 3.79 °C). The average adiabatic lapse rate was 0.56 °C/100 m with a standard deviation of 0.16 °C/100 m. From these models the we interpolated macroclimatic temperatures for each microclimate sensor location based on its elevation. Third, we calculated the minimum, mean and maximum temperature for both the micro- and macroclimate record over the full observation period (July 8^{th} until August 31^{st} 2021). We finally calculated the temperature offset as the difference between the minimum, mean, and maximum microclimatic and interpolated macroclimatic temperature, respectively. Negative temperature offset values signify colder within-stand than open-land temperatures.

LiDAR-based predictor variables

Two groups of predictor variables – one representing forest structure and the other representing topography – were derived from airborne LiDAR data. The data were acquired during early September 2021 using a helicopter-mounted Riegel VQ-780i sensor with average point density of ~50 points m^{-2}. Forest structure predictors were calculated from the LiDAR point cloud, which was extracted around the location of each microclimate logger using a 12.6 m buffer, corresponding to a 500 m^2 plot area. We calculated a set of 36 potential metrics summarizing the distribution and intensity of LiDAR returns using the *lidR* package in R version 4.2.2 (Roussel et al. 2020; R Core Team 2019). From those 36 potential predictors, we selected three candidate predictors based on a-priori ecological hypotheses and bivariate correlation analysis (Table 1): the percent of lidar returns reaching the ground (hereafter referred to as *canopy openness*), the average height of returns (hereafter referred to as *height*), and the cumulative percentage of returns from the ground layer (i.e., the first of ten equally spaced horizontal layers; see Table 1 and Roussel et al. 2020; hereafter referred to as *ground vegetation density*). *Canopy openness* quantifies the amount of light reaching the forest floor, and we hypothesize it to be positively correlated with mean and maximum temperature offsets and negatively with minimum temperature offsets (Zellweger et al. 2019). *Height* indicates the average height of trees and thus serves as a proxy for forest age and potential structural complexity (with taller stands having a higher variability in individual tree heights; Atkins et al. 2021). We expected this variable to correlate negatively with mean and maximum temperature offsets and positively with minimum temperature offsets. *Ground vegetation density* indicates the density and cover of forest floor vegetation. Here we had contrasting expectations, with dense ground vegetation providing additional shadowing and evaporative cooling (Stickley and Fraterigo 2021), but open layers of coniferous shrubs still allowing high solar radiation to reach the ground while simultaneously reducing wind speeds. We thus did not have a clear hypothesis on the direction of the correlation with temperature offsets.

We used a digital elevation model with 1 m spatial resolution derived from LiDAR data for topography predictors. Potential topography predictors included seven metrics defined by Frey et al. (2016) for estimating microclimatic temperatures in mountainous regions. However, we found substantial multi-collinearity between those predictors and decided to only include the average slope and topographic index into our final model (see Table 1 for details). We calculated both metrics for each logger location using a 50 m circular extraction buffer. We used a larger buffer to account for surrounding topography features, such as local depressions. We tested different buffers in a preliminary analysis and found 50 m to be best suited to capture local topographic conditions. We further obtained two additional predictor variables characterizing potential solar irradiance from the solar irradiance and irradiation model *r.sun* implemented in Grass GIS (Geographic Resources Analysis and Support System) (Hofierka and Suri 2002; Neteler et al. 2012). We ran the model on the same LiDAR-based DEM, but with a coarser resolution of 10 m x 10 m, to derive solar irradiation patterns for 12:00 and 16:00 on the 15th of July 2021, representing north-south and east-west gradients. As global, direct and diffuse incoming solar radiation were highly correlated, we decided to only use diffuse incoming solar radiation in the final model based on higher correlations with temperature offsets in a-priori bivariate correlation analyses. Finally, elevation was used as a control variable to account for its influence on overall climatic conditions that could modulate microclimate in mountainous terrain, such as wind speeds, but are unrelated to local factors (Dobrowski 2011; Meineri and Hylander 2017). We further included elevation as cofounder for both the structure and topographic variables, which show strong elevational patterns (i.e., shorter and more open forests in higher elevation areas; steeper and more rugged terrain in higher elevation areas).

For creating temperature-offset maps for the entire forested landscape of Berchtesgaden National Park, we calculated the same predictors outlined above not only for the individual plots, but also for a regular 20 m x 20 m grid. While the size of the grid cells is slightly below the plot size, we assume this difference to be negligible. We only predicted offset values for forested grid cells, which we identified with an existing forest mask at 10 m x 10 m resolution provided by the national park administration (see Figure 1 and Mandl (2020)).

Table 1: Overview of the forest structure and the topographic predictor variables used to model temperature offsets.

Predictor	Definition
Structure	
Height	Mean absolute height of all LiDAR returns.
Canopy openness	Proportion of LiDAR returns classified as ground. Higher values thus indicate a sparser canopy with more returns reaching the forest floor.
Ground vegetation density	Cumulative percentage of returns in the 1st of ten equally spaced horizontal layers. Higher values thus means a higher proportion of all returns returned by the lowest vegetation layer.
Topography	
Elevation	Elevation at the centre point of a plot
Topographic index	Difference between the elevation of the centre point and the average elevation of a plot (negative values: local low point/ positive values: local high point)
Slope	Average slope of a plot

Diffuse incoming solar radiation at 12:00	Amount of solar energy falling on a surface that is scattered by atmospheric particles; representing conditions at 12:00.
Diffuse incoming solar radiation at 16:00	Amount of solar energy falling on a surface that is scattered by atmospheric particles; representing conditions at 16:00.

Modelling temperature offset

We modelled the average (TO_{mean}), minimum (TO_{min}), and maximum (TO_{max}) temperature offsets based on the forest structure and topography predictors described above using linear models in the R software environment (R Core Team 2019). We specifically used the following packages: *lidR*, *raster*, *rgdal*, *exactextractr*, *sf*, *and ggplot2* (Hijmans 2020; Keitt 2010; Baston 2020; Pebesma 2018; Wickham 2009). We also tested more complex models that can deal with non-linearities and potential interactions between variables (i.e., boosted regression trees, generalized additive models), but found linear models to outperform those more complex models. That said, we included elevation as second-order polynomial due to some non-linear patterns in the residuals. We assessed model performance by means of RMSE and R^2 using spatial block cross validation with plots clustered into ten spatial clusters based on their location (Valavi et al. 2019). Additionally, we extracted the standardized regression coefficient for each predictor variable as well as partial eta-squared values to assess the importance of each variable for predicting temperature offsets. We note here that our intention was to build a robust and accurate predictive model of temperature offsets and not to perform causal inference of underlying drivers. We thus recommend being cautious in applying causal interpretation to our model estimates. Finally, we used the calibrated linear models to make spatial predictions of the temperature offsets for the forested area of the national park.

Influence of disturbance and forest type

We compared the mapped temperature offset across past disturbances and forest types. Specifically, we analysed our spatial predictions of temperature offset by overlaying a forest disturbance map created by Senf and Seidl (2021), who used satellite data to map forest disturbance for all of continental Europe at 30 m spatial resolution. The map contains the year of the most severe forest disturbance from 1986 until 2020, which we extracted for all 20 m grid cells where the centre point intersected a disturbance patch. We reclassified the disturbance years from year of disturbance to time since disturbance (i.e., 2021 minus the disturbance year) to obtain a chronosequence of temperature offset over post-disturbance development (i.e. one to 35 years after disturbance). For statistical analyses, we grouped the chronosequence in five-year bins. Similarly, we assessed the influence of forest type on the temperature offset using a forest type map with a resolution of 1 ha created by Thom et al. (2022) (Figure 1b). To exclude interacting effects between forest type and disturbance, we only considered areas with restored forest canopies (i.e. without disturbance for the last 25 years) in the analysis of forest type effects (Senf, Müller, and Seidl 2019). Finally, we tested what proportion of the overall spatial variation in temperate offsets can be explained by forest type and time since disturbance, respectively, using analysis of variance.

Results

Temperature offset models and predictions

The linear models predicted temperature offset with an R^2/RSME of 0.50/3.15 °C for maximum temperature, 0.51/0.41 °C for mean temperature and 0.55/0.57 °C for minimum temperature (Figure 2). The temperature offset maps predicted by the models revealed a high spatial variability in forest microclimate (Figure 3). Mean and maximum temperature offsets were smaller or even reversed (warmer temperatures in forests compared to open lands) in the subalpine zone, whereas forests in the montane and submontane zone showed overall negative offsets for mean and maximum temperature (i.e., colder temperatures within stands compared to macroclimatic temperatures). For the offset of minimum temperature, we found that minimum temperatures were warmer in submontane forests and colder in sub-alpine forests compared to open lands. Overall, landscape-scale maximum temperature offset ranged from - 7.5 to + 16.6 °C with a median of + 1.4 °C and a mean of + 1.6 °C. Mean temperature offsets ranged from - 1.9 to + 2.7 °C with a median of - 0.3 °C and a mean of - 0.3 °C. Minimum temperature offsets ranged from - 2.6 to + 1.2 °C with a median of - 0.5 °C and a mean of - 0.5 °C. Less than half of the forests in our study landscape showed negative summer maximum temperature offsets (36%) (i.e., colder temperatures in forests than in open land), whereas three quarters did show negative mean temperature offsets (75%). For minimum temperatures, 76 % of temperature offsets were negative (i.e., colder minimum temperatures in forests than in open lands), with 24% of the forests showing warmer minimum temperatures in forests than open lands.

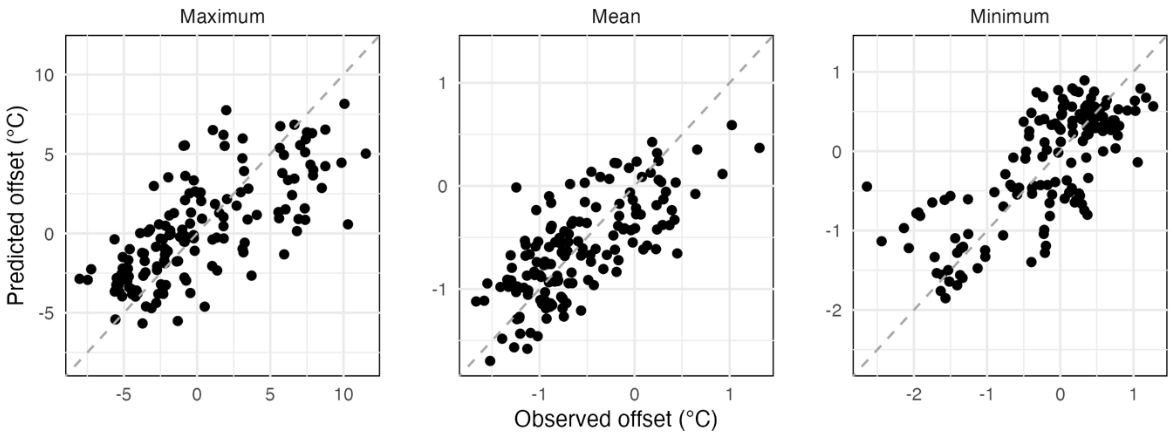

Figure 2: Observed versus predicted daytime temperature offsets for maximum, mean and minimum summer temperatures. The grey lines represent the 1:1 lines.

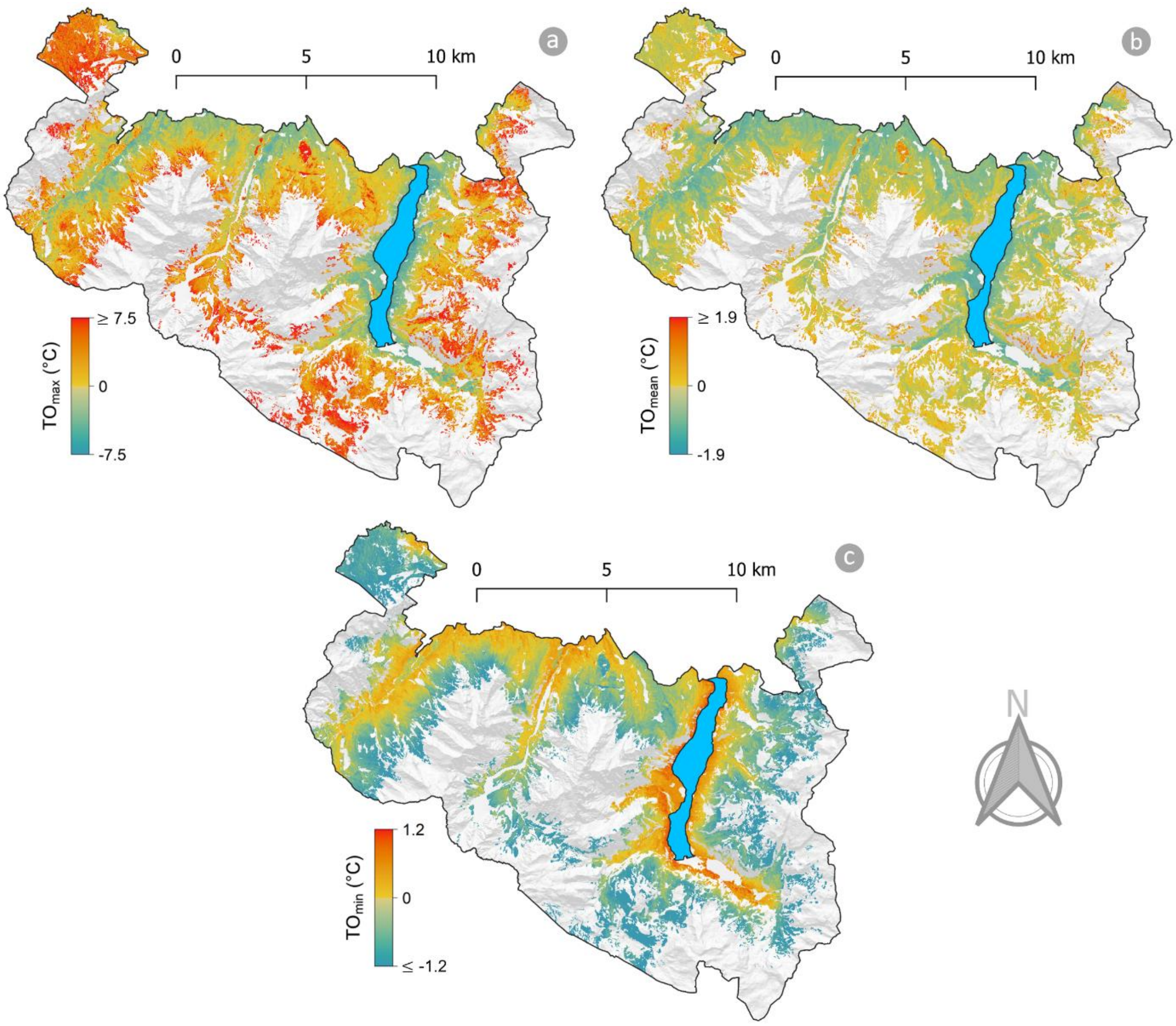

Figure 3: Maps of the maximum (a), the mean (b), and the minimum (c) of temperature offset for Berchtesgaden national park. For improved visualisation we cantered the colour gradient and left out the ~1.2 % of the most extreme values.

Canopy openness and elevation were the two most important variables for predicting temperature offsets in our landscape, with higher importance of elevation for the extremes (minimum and maximum) but higher importance of openness for the mean offset (Figure 4). Canopy openness was positively correlated with maximum and mean temperature offset, but negatively correlated with minimum temperature offset. It explained 13.6%, 29.1% and 6.3% of the variance in the maximum, mean and minimum temperature offsets, respectively.

Ground vegetation density and canopy height did not have a measurable influence on maximum and minimum temperature offsets, and only a weak positive association with mean temperature offset. Besides elevation, which explained 24.6%, 9.1% and 42.7% of the variance in maximum, mean and minimum temperature offsets, the influences of topographic effects were less clear. Diffuse incoming solar radiation at 16:00 correlated positively with the maximum and mean offsets, whereas diffuse incoming solar radiation at 12:00 correlated negatively with mean and minimum offsets. The topographic index had only a weak positive correlation with mean temperature offset.

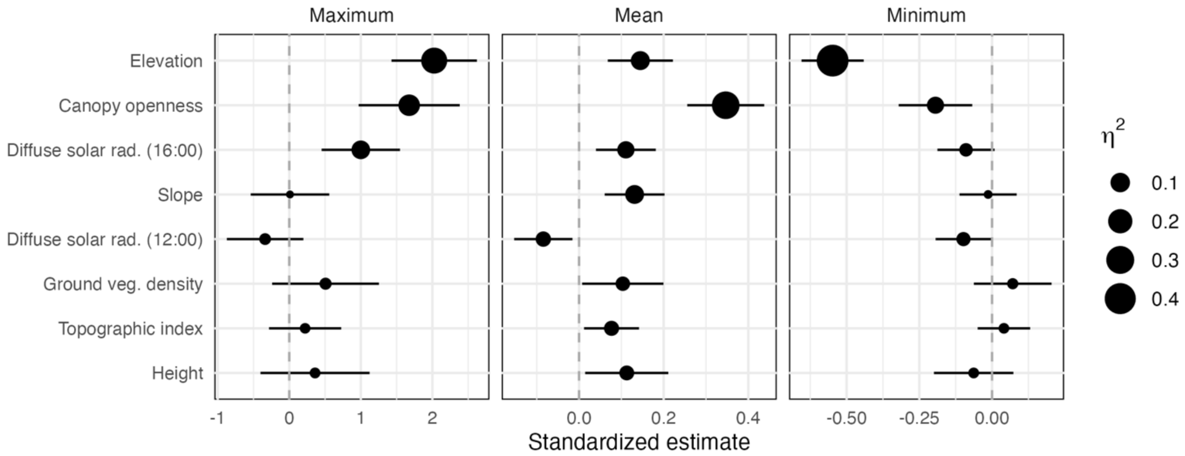

Figure 4: Model coefficients with 95% confidence intervals (standardized estimate) and relative influence, measured in terms of partial eta^2 values (the proportion of the total variance that is attributed to an individual predictor).

Influence of forest type and disturbance on temperature offsets

There was considerable variation in temperature offsets between – but also within – forest types (Figure 5). Beech forests – found mostly in submontane areas – had the lowest maximum and mean temperature offsets and the highest minimum temperature offsets. Nevertheless, beech forests also had a considerable fraction of forests with positive mean (11 %) and maximum (24 %) temperature offsets and negative minimum temperature offsets (30%). Spruce-fir-beech and spruce forests – which span a wide range of elevations – also showed high variability, with largely negative mean temperature offsets (84% and 89%, respectively), but more variable maximum temperature offsets (30% and 45% of spruce-fir-beech and spruce forests had positive maximum temperature offsets; Figure 5). Larch-Swiss stone pine and dwarf mountain pine forests showed overall mixed mean temperature offsets, with mostly warmer maximum temperatures and colder minimum temperatures within forests than in open lands. Overall, our results show that forest type is an important proxy of local forest microclimate, with forest type explaining 24% of the spatial variability in mean temperature offset and 45% and 46% of maximum and minimum temperature offsets (all for recently undisturbed forests).

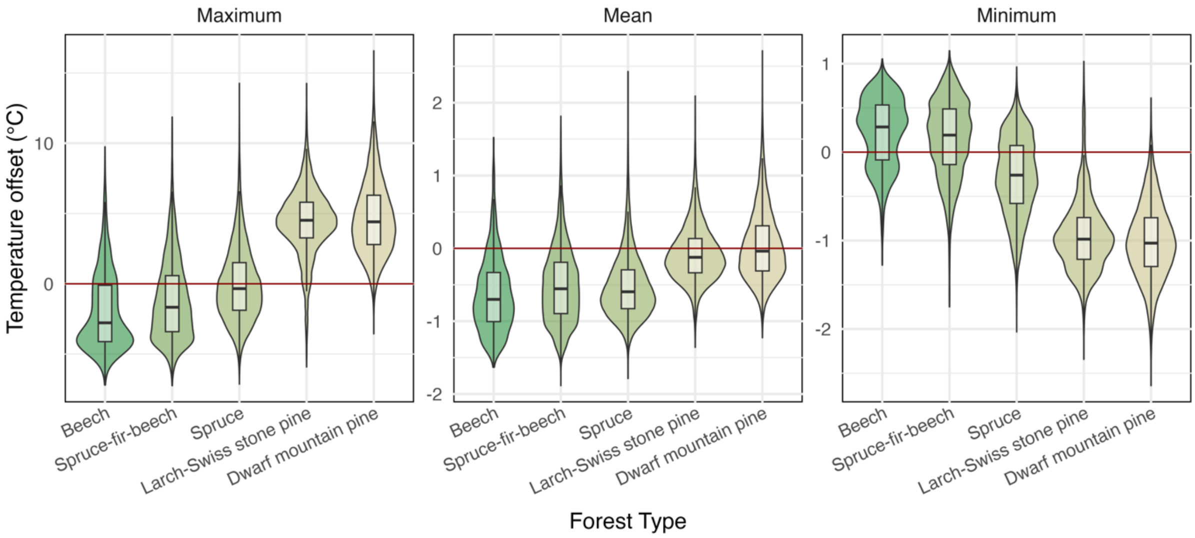

Figure 5: Distribution of maximum, mean and minimum temperature offsets across forest types. We only show forest cells without disturbance in the past 25 years. The red horizontal line shows where temperature offset is 0.

Forest disturbances and subsequent post-disturbance forest development also had substantial influence on the variability in forest temperature offsets (Figure 5). While average temperature offsets stayed rather consistent over post-disturbance development, maximum temperature offset increased > 5 years after disturbance, whereas minimum temperature offset decreased. That is, between 6 and 20 years after disturbance, forests tend to have warmer maximum and cooler minimum temperatures compared to open lands. During canopy closure

(21-25 years after disturbance), both maximum and minimum temperature offsets shifted back towards negative/positive offset values. Overall, disturbance and post-disturbance recovery was an important driver of temperate offsets. In disturbed sites, time since disturbance explained 12% of the variance in maximum and mean temperate offsets and 6 % of minimum temperature offset. Across all forests, however, disturbances explained less than 2% of the spatial variation in temperature offsets.

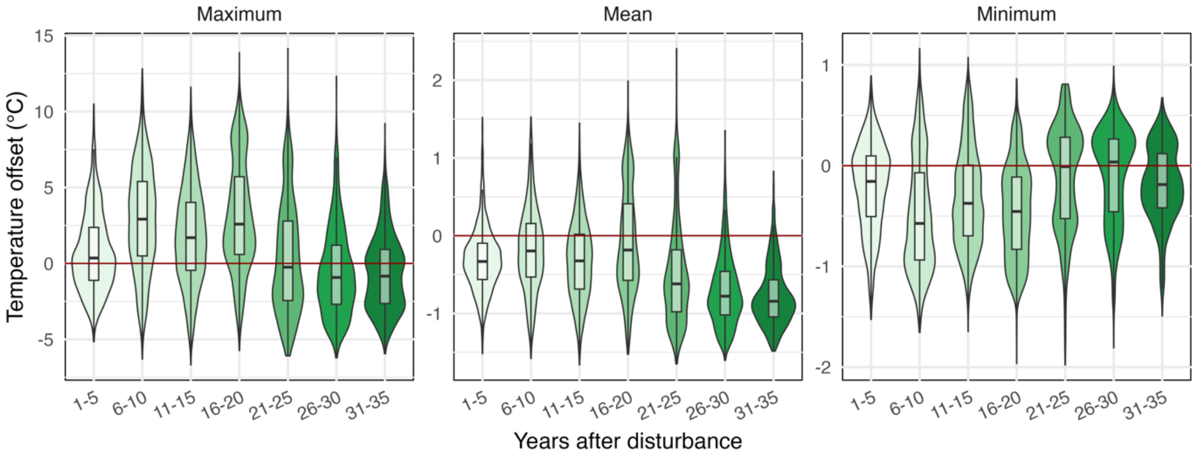

Figure 6: Distribution of maximum, mean and minimum temperature offsets over time since disturbance. The red horizontal line shows where temperature offset is 0.

Discussion

We here present an application of LiDAR data for mapping temperature offsets across a topographically complex landscape with more than 8,000 ha of forest area. Overall, we show that summer temperature offsets were highly variable, with both colder and warmer temperatures within forests compared to open lands. Canopy openness and a second-order polynomial term of elevation were the most important predictors of temperature offsets. Canopy openness determines the amount of incoming solar radiation that reaches the forest floor and thus the direct energy available at the forest floor. The strong influence of canopy openness is in line with previous studies (De Frenne et al. 2021; Zellweger et al. 2019). Elevation does not directly influence temperature offsets, but serves as proxy for climatic conditions, which affect local microclimates, such as wind speeds (Dobrowski 2011; Meineri and Hylander 2017). Elevation further serves as a proxy for turnover in forest composition and thus different temperature offsets we observed for the different forest types in our study landscape (Figure 5). Yet, by controlling for elevation in our model, we also show that even within the same forest type (i.e., the same elevation zone) canopy density plays a crucial role for determining temperature offsets, highlighting the overall important role of the forest canopy in regulating microclimate. Local topography played only a minor role for temperature offsets in our study, except for the potential solar radiation in the afternoon. Comparing our models to those of previous studies, e.g., of Haesen et al. (2021) and Davis et al. (2019), revealed that the performance of our models in terms of R^2 was slightly lower. However, important differences in study design make a direct comparison challenging: Davis et al. (2019), modelled daily variation in absolute microclimatic temperature, and Haesen et al. (2021) included additional predictors such as mean annual cloud cover and long-term average macroclimatic conditions. Considering the high topographic complexity and high variability in forest types in our landscape, it can be concluded that the performance of our models was overall satisfactory, and that LiDAR data is well suited for consistently predicting temperature offsets, even in topographically complex terrain.

Average and maximum temperature offset predictions reported in our study tended to be low but within range of previous studies (De Frenne et al. 2019; Haesen et al. 2021). De Frenne et al. (2019) reported temperature offsets to vary substantially within and among biomes, with boreal biomes exhibiting lower offsets than temperate and tropical biomes. In terms of microclimatic buffering our conifer-dominated temperate mountain forests thus behave similarly to boreal forests. Our results also highlight that forests not always cool temperatures in summer, but that the influence of structure, composition and disturbance history can also lead to warmer microclimates compared to open lands. This might be especially true for mountain forests in high elevations close to the timber line, which are often open in structure and are generally underrepresented in continental-scale assessments of microclimate (e.g., Haesen et al. 2021). We found that less than half of the forests in our mountain landscape did, in fact, not buffer temperature extremes (i.e., positive maximum and negative minimum offsets). While counterintuitive, the low or even reversed temperature offsets found in our study are plausible and can be explained by at least two factors: First, the difference in height of measurement between microclimate loggers and weather stations. Microclimate measurements were taken near the ground surface, which tends to be warmer than air temperatures on summer days (García-García et al. 2019) and likely colder than air temperatures during the night. Macroclimatic readings, on the other hand, were taken at a minimum height of two meters above ground. The temperature offset metrics derived here thus reflect the difference between air temperatures, which are widely used when assessing the biotic response to climate change, and the microclimatic temperatures that forest dwelling species experience at the forest floor (e.g., forest floor plants, ground-dwelling insects). Second, in open forests such as the sub-alpine forests in our landscape, microclimate loggers might be directly exposed to the sun. The temperature recorded at the loggers might thus be influenced by relatively short periods of time with direct incoming solar radiation heating up the logger (Maclean et al. 2021). The absolute temperature offsets found in our study landscape thus need to be interpreted with caution. Future work should study temperatures inside and outside of forests at comparable heights to isolate the effects of forest structure, forest type and disturbance on microclimatic temperatures more stringently. Recoding additional climate parameters (i.e., humidity, incoming solar radiation and wind speed) might further aid the interpretation of the offsets recorded in our study.

The observed influence of forest type on temperature offset was in line with our expectations. Subalpine larch-Swiss stone pine and dwarf mountain pine forests had considerably warmer maximum and mean temperatures as well as colder minimum temperatures compared to open lands, which are likely caused by a high abundance of coniferous shrubs at the forest floor and sparse forest cover typical for subalpine forests. These particular structures cause the forest floor to be exposed to high incoming solar irradiation and stronger outgoing longwave radiation, while the sparse tree cover still shields from wind. This results in microclimates that have warmer maximum and colder minimum temperatures than open lands, as has already been reported in previous studies (von Arx, Dobbertin, and Rebetez 2012; Renaud et al. 2011). The often shallow soils in sub-alpine forests might further lead to low evaporative cooling in the summer, which can further contribute to the high maximum temperatures in those systems reported in our study. Mountain forests are also more complex in spatial configuration, with more openings and edges allowing solar radiation to reach the forest floor even in closed canopy stands (Meeussen et al. 2021). In general, the open forest structures leading to positive temperature offsets can be seen as an adaptation of plants to the harsh conditions at the tree line, where plant life is mostly limited by low temperatures (Körner 2012). In contrast, mostly closed canopy conditions with fewer openings and edges are likely responsible for the generally cooler maximum temperatures and warmer minimum temperatures found in beech, spruce, and spruce-fir-beech forests. Yet, we observed significant variation within each group (Figure 4). This effect can partly result from a decrease in canopy cover with increasing elevation even within the same forest type (Gómez-Hernández et al. 2012; Ehbrecht et al. 2019; von Arx, Dobbertin, and Rebetez 2012).

The influence of disturbance on temperature offset largely supported our hypothesis, with disturbances generally decreasing minimum temperatures and increasing maximum temperatures in the short term, but microclimatic temperatures recover as the canopy closes. After a high severity disturbance, large parts of the forest canopy are lost, leading to temporarily open forest stands with an increased amount of solar radiation reaching the forest floor (Hardwick et al. 2015; Jucker et al. 2018; Smith-Tripp et al. 2022; Thom et al. 2020). Interestingly, the most positive maximum offset was found more than five years after disturbances, which might be explained by more gradual disturbances typical for mountain landscapes (interacting wind and bark beetle disturbances; Seidl and Rammer (2017); Stritih, Seidl, and Senf (2023)). Further, residual structures, such as surviving trees, standing deadwood and snags likely contribute to a complex thermal regime shortly after the disturbance. We note, however, that there is also uncertainty in the attribution of the onset of disturbance in the disturbance map used herein (Senf and Seidl 2021). Interestingly, the temperature offset values after disturbance were similar to those found in the subalpine zone, confirming the importance of forest structure and especially canopy openness in determining microclimates. Furthermore, our findings highlight the potential of forest disturbances to significantly alter microclimatic conditions in closed canopy forests. After disturbance, forests close their canopy in the course of forest development. The resultant reduction in solar irradiation causes temperature offsets to recover towards closed canopy conditions (Schwartz et al. 2022; Zenner et al. 2016). We here show that it takes up to two decades for temperature offsets to recover to values similar to closed canopy conditions, underlining that disturbances can have a long-lasting impact on the climate regulating function of forests.

Conclusion and outlook

We here present a novel approach for the landscape-scale mapping of microclimatic temperature from airborne LiDAR data. Our results demonstrate the ability of LiDAR to capture forest structure and topographic features relevant for predicting microclimatic conditions, even in a complex mountain landscapes. Given the growing availability of LiDAR data, our approach can be readily applied to other regions where similar datasets are available. Our results highlight the importance of forest structure – in particular canopy openness – for microclimate regulation, and demonstrate that forest disturbances can significantly alter those structures and thus microclimate for several decades. This finding has potential implications for the future distribution of microrefugia under climate change, as the frequency and severity of disturbances is likely to increase in the Alps under climate change (Thom, Rammer, and Seidl 2017; Seidl et al. 2017; Albrich et al. 2022). Future research should therefore assess how the interaction between climate-driven shifts in forest types and amplified disturbances influences microclimate in mountain forests. The spatially explicit maps of temperature offsets provided here can be used to improve the assessment of climate risks for biodiversity, i.e., through incorporating microclimatic temperature offsets into species distribution models. A better quantification of forest microclimate will allow for a more process-based understanding of the effects of climate change on forest-dependent communities.

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Data availability

All data and code created/used in this study are publicly available under https://doi.org/10.5281/zenodo.8163612

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