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PERSPECTIVE

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Abstract
Microclimate research gained renewed interest over the last decade and its importance for many ecological processes is increasingly being recognized. Consequently, the call for high-resolution microclimatic temperature grids across broad spatial extents is becoming more pressing to improve ecological models. Here, we provide a new set of open-access bioclimatic variables for microclimate temperatures of European forests at $25 \times 25\,m^2$ resolution.

KEYWORDS
biodiversity, boosted regression trees, climate change, ecosystem processes, forest microclimate, SoilTemp, ForestTemp, species distributions

1 | ON THE IMPORTANCE OF MICROCLIMATE

Bioclimatic variables are used in a wide range of disciplines, from biogeography over community ecology to the study of ecosystem functioning, to better represent climate conditions relevant to ecological processes. Especially within the field of species distribution modelling, these variables take up a prominent place as they allow us to assess, for example, the effects of climate change on species habitat suitability. To infer a species' climatic niche, species distribution models often use a standard set of bioclimatic variables, mostly available at a coarse spatial resolution of 30 arcseconds (ca. 1 km), such as CHELSA (Karger et al., 2017) or WorldClim (Fick & Hijmans, 2017). However, a substantial part of life on Earth (e.g., tree seedlings, forest floor herbs, pteridophytes, bryophytes, ground invertebrates, and fungi) as well as many key ecological processes (e.g., litter decomposition) respond to climate at much finer scales below tree canopies. Bioclimatic variables currently lack the ability to capture this high spatial variability in microclimatic conditions. For instance, high spatial heterogeneity in vegetation cover, canopy structure, and terrain complexity is strongly connected with high temperature variability, up to 6°C within a single 1-km^2 pixel of mean annual temperature (Lenoir et al., 2013). Consequently, high-resolution climate data are urgently needed to increase ecological model performance (Ashcroft et al., 2008) and, additionally, should be matched to the biological scale of the organism under study (Potter et al., 2013). Many studies already downscaled the existing climatic grids using both mechanistic (i.e., physics-based) and correlative (i.e., statistics-based) approaches (Lembrechts et al., 2018). However, applying these methods on a broad spatial extent is computationally intensive, which has been limiting the development of such microclimate grids up until now.

Another key issue arising with long-term climatologies as used in most species distribution models is the fact that climate data are derived from standardized meteorological stations, which poorly capture climate-forcing factors operating near the ground by measuring the temperature at 2 m height above short vegetation. In this traditional set-up, the influence of local vegetation or topography is minimized, although it is well-known that these can substantially alter temperature conditions relevant for most species (Geiger, 1950). First, vegetation characteristics (e.g., vegetation height, density, or composition) are key drivers in shaping microclimates within the landscape matrix. Especially forests alter the conditions underneath their canopy significantly by means of shading and evapotranspirative cooling. Additionally, forest structure substantially affects wind patterns leading to less turbulent mixing of the air. Second, topographic factors (e.g., aspect or inclination) modulate many physical processes such as airflow and incoming solar radiation, which additionally increases the heterogeneity in temperature conditions within and between habitats composing the landscape. This is especially important for cold-adapted species in the face of climate change, as they might be able to find stable cool spots in the landscape. In these so-called microrefugia, they are able to persist for a longer time as these places can be buffered from contemporary macroclimate warming (Lenoir et al., 2017).

It is, thus, clear that accounting for sub-canopy temperature differences and increasing the spatial resolution of conventional bioclimatic variables to capture fine-scale microclimate variability would be a major step forward for global change biology. Solving this mismatch between the climate data currently available for ecological modelling and the climate experienced by organisms should be seen as a crucial step toward better ecological models and predictions.

2 | FORESTCLIM

Here, we present a set of high-resolution bioclimatic variables of forest microclimate temperature variables based upon the model presented in Haesen et al. (2021), where we provided the proof of concept for the derivation of monthly mean temperature offset (ΔT) values (difference between macro- and microclimate in forest understories) at a spatial resolution of 25 m × 25 m across Europe. Additionally, we used these offset values to calculate mean annual temperature (ForestClim1). We now derived analogous maps of monthly minimum and maximum temperature offset values and calculated the remaining ForestClim variables (ForestClim2–ForestClim11; Figure 1). In short, we relied on the SoilTemp database, which provided 1273 temperature time series from 1197 distinct logger locations spread across European forests (Lembrechts et al., 2020). We first calculated daily minimum and maximum temperature offsets as the difference between the daily minimum/maximum microclimate temperature, as measured by the sensors, and the corresponding daily minimum/maximum macroclimate air temperature value for exactly the same day, month, year, and grid cell from spatially downscaled E-OBS data at 1 km × 1 km (Moreno & Hasenauer, 2016; Pucher & Neumann, 2022). Note that, prior to calculating the daily offsets, we performed an altitudinal temperature correction using CHELSA v2.1 lapse rates for the corresponding grid cell (Karger et al., 2017; personal communication). Next, the daily minimum and maximum temperature offset values were aggregated into monthly averages. Second, we used boosted regression trees to relate ΔT to explanatory variables describing topography, vegetation characteristics and macroclimate conditions. The model was used to estimate the difference between microclimate (temperature loggers placed within forests) and macroclimate (weather stations outside forests) across European forests and across seasons. For more information regarding the different covariates and the ForestTemp model itself, we refer to Haesen et al. (2021).

Finally, the resulting maps of the monthly offsets between mean, minimum and maximum sub-canopy and free-air temperature were used to calculate bioclimatic variables following the definition used in WorldClim (Fick & Hijmans, 2017). First, we calculated the monthly mean, maximum and minimum sub-canopy temperature by adding monthly temperature offsets to the respective monthly mean, maximum and minimum temperature from TerraClimate (spatial resolution ca. 4 km × 4 km; Abatzoglou et al., 2018). Next, we used these sub-canopy temperature layers to compute sub-canopy bioclimatic temperature layers, representative of the 2000–2020 period. Wettest and driest quarters were identified for each pixel based on TerraClimate's monthly values. However, note that all temperature offset layers are freely available, meaning that the end-users are able to convert macroclimatic data themselves. All calculations were performed in R version 4.1.1 (R Core Team, 2021).

We found considerable differences between ForestClim (forest microclimate) and TerraClimate (macroclimate) bioclimatic variables, owing to biome and local forest stand characteristics (e.g., canopy density). As expected, the minimum temperature of the coldest month was higher within European forests (ForestClim6; mean = −3.8°C) in comparison with TerraClimate (mean = −4.4°C). Surprisingly, the maximum temperature of the warmest month was, overall, slightly higher in forests (ForestClim5; mean = 24.6°C) compared with its TerraClimate counterpart (mean = 24.3°C). However, ForestClim covers a wide range of different biomes (i.e., boreal, temperate, and Mediterranean) and microclimatic conditions in each of them are governed by different processes (De Frenne et al., 2021). Indeed, when we further explored regional patterns in each of these biomes, ForestClim did follow expected patterns with maximum temperatures being, on average, 0.9°C lower in temperate forests,

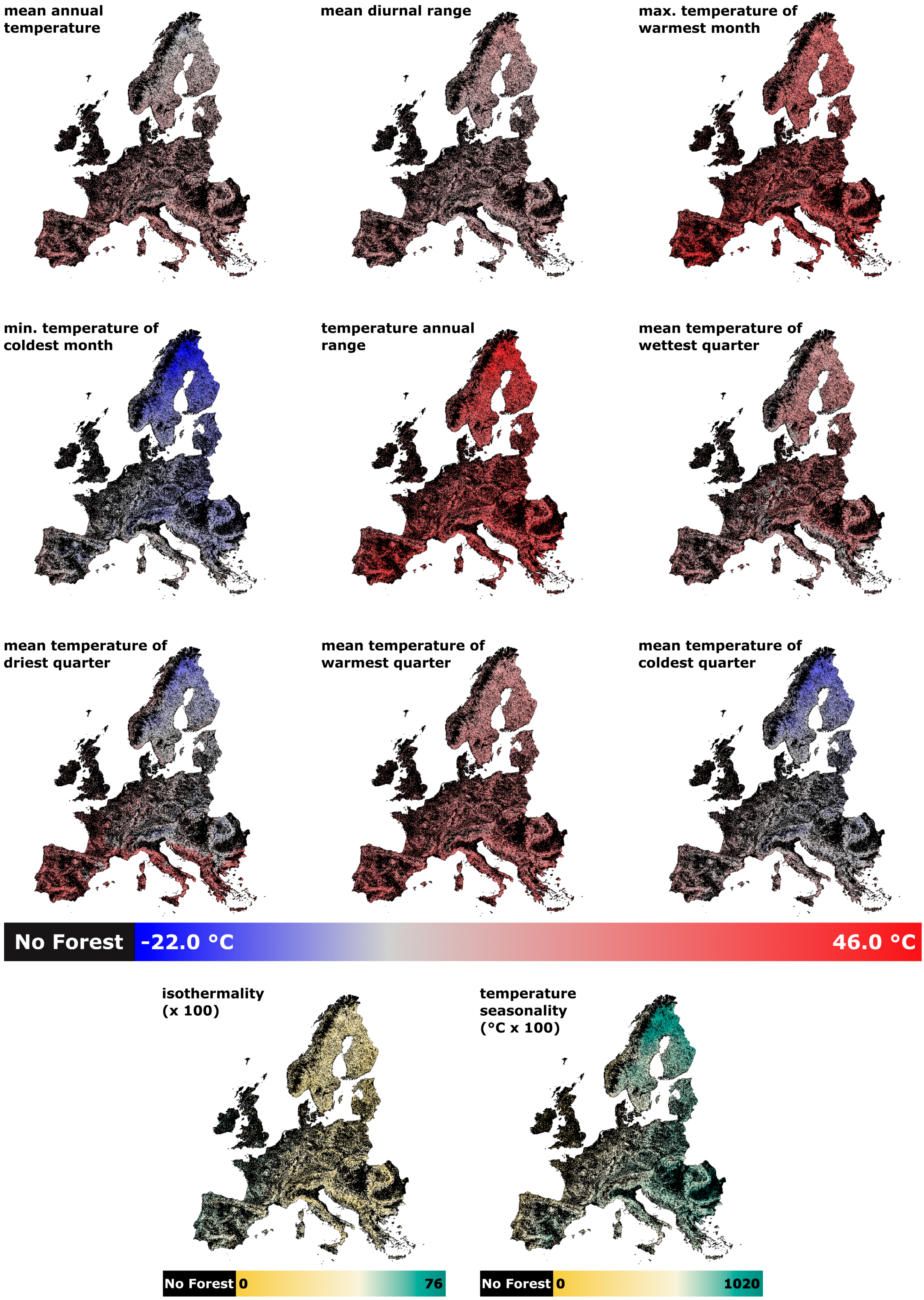

FIGURE 1 Forest bioclimatic variables below tree canopies at 15 cm above ground in European forests with a spatial resolution of 25 × 25 m^2, representative of the 2000–2020 period. Bioclimatic variables include mean annual temperature (ForestClim1; °C); mean diurnal range (ForestClim2; °C); maximum temperature of the warmest month (ForestClim5; °C); minimum temperature of the coldest month (ForestClim6; °C); temperature annual range (ForestClim7; °C); mean temperature of the wettest quarter (ForestClim8; °C); mean temperature of the driest quarter (ForestClim9; °C); mean temperature of the warmest quarter (ForestClim10; °C); mean temperature of the coldest quarter (ForestClim11; °C); isothermality (ForestClim3; ×100); and temperature seasonality (ForestClim4; °C × 100). Note that isothermality is a unitless variable. [Colour figure can be viewed at wileyonlinelibrary.com]

1.6°C higher in Mediterranean forests, and 0.7°C higher in boreal forests. On the other hand, minimum temperatures were consistently warmer in temperate (0.6°C), Mediterranean (0.5°C) and boreal (0.4°C) forests. Furthermore, canopy density plays a crucial role in terms of shading and evapotranspiration, and a certain turn-over point in canopy density has been put forward where the buffering effect of forests is converted to an amplifying effect (Gril et al., 2023; von Arx et al., 2013). Indeed, when we only considered forests with a closed canopy (> 90%) in these three biomes, expected patterns were confirmed. Forest maximum temperatures were consistently cooler in temperate (−2.2°C), Mediterranean (−2.1°C) and boreal (−0.9°C) forests, and minimum temperatures consistently warmer in temperate (0.5°C), Mediterranean (0.2°C) and boreal (3.5°C) forests. Our results thus underpin an important role for canopy density, with potentially important implications for forest management.

3 | FUTURE PERSPECTIVES

Our European, high-resolution ForestClim bioclimatic temperature products will open a new avenue for future research within a wide range of disciplines. For high-latitudinal and high-elevational regions, it is, however, important to note that the ForestTemp model is extrapolating beyond the range of the training data, and, therefore, we advise users to cautiously explore the associated extrapolation map. Furthermore, forests are dynamic systems, regularly subjected to natural and anthropogenic disturbances (e.g., pest outbreaks, windstorms, fires, and logging). ForestClim is based on the 2015 forest-type map of the Copernicus project and is thus not valid for pixels that experienced significant forest cover change since then. However, annual remote sensing-derived products (e.g. Hansen et al., 2013) or data on local management can be used to mask out areas with substantial changes in forest cover. Yet, it is especially this dynamic character of certain variables (e.g., canopy cover), which currently hampers the development of similar products for future scenarios under different shared socioeconomic pathways (De Lombaerde et al., 2022).

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CONFLICT OF INTEREST STATEMENT

The authors declare that they have no conflict of interest.

DATA AVAILABILITY STATEMENT

The processed input data (i.e., monthly temperature offset values) that support the findings of this study as well as all raster layers (GeoTIFFs) produced in this study are openly available on figshare at https://doi.org/10.6084/m9.figshare.14618235 (offset layers for minimum, mean and maximum temperature) and https://doi.org/10.6084/m9.figshare.22059125 (ForestClim) while the raw temperature time series necessary to process monthly temperature offset values are available from SoilTemp, a global database of soil and near-surface air temperature measurements data. Restrictions apply to the availability of raw SoilTemp data, which were used under license for this study. The raw temperature time series data are available from Jonas Lembrechts and Stef Haesen with the permission of SoilTemp data contributors of this study.

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