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1 **ForestClim – Bioclimatic variables for microclimate temperatures of European forests**

2 Running title – 25-m grids of sub-canopy bioclimatic temperature variables

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

79 **1 | ON THE IMPORTANCE OF MICROCLIMATE**

80 Bioclimatic variables are used in a wide range of disciplines, from biogeography over
81 community ecology to the study of ecosystem functioning, to better represent climate conditions
82 relevant for ecological processes. Especially within the field of species distribution modelling, these
83 variables take up a prominent place as they allow us to assess, for example, the effects of climate
84 change on species habitat suitability. To infer a species' climatic niche, species distribution models
85 often use a standard set of bioclimatic variables, mostly available at a coarse spatial resolution of 30
86 arcseconds (c. 1 km), such as CHELSA (Karger et al., 2017) or WorldClim (Fick & Hijmans, 2017).
87 However, a substantial part of life on Earth (e.g., tree seedlings, forest floor herbs, pteridophytes,
88 bryophytes, ground invertebrates and fungi) as well as many key ecological processes (e.g., litter
89 decomposition) respond to climate at much finer scales below tree canopies. Bioclimatic variables
90 currently lack the ability to capture this high spatial variability in microclimatic conditions. For
91 instance, high spatial heterogeneity in vegetation cover, canopy structure and terrain complexity is
92 strongly connected with high temperature variability, up to 6 °C within a single 1-km² pixel of mean
93 annual temperature (Lenoir et al., 2013). Consequently, high-resolution climate data is urgently
94 needed to increase ecological model performance (Ashcroft et al., 2008) and, additionally, should be
95 matched to the biological scale of the organism under study (Potter, Woods, & Pincebourde, 2013).
96 Many studies already downscaled the existing climatic grids using both mechanistic (i.e., physics-
97 based) and correlative (i.e., statistics-based) approaches (Lembrechts, Nijs, & Lenoir, 2018). However,
98 applying these methods on a broad spatial extent is computationally intensive, which has been limiting
99 the development of such microclimate grids up until now.

100 Another key issue arising with long-term climatologies as used in most species distribution
101 models is the fact that climate data are derived from standardized meteorological stations, which
102 poorly capture climate-forcing factors operating near the ground by measuring temperature at 2
103 meters height above short vegetation. In this traditional set-up, the influence of local vegetation or
104 topography is minimized, although it is well-known that these can substantially alter temperature
105 conditions relevant for most species (Geiger, 1950). First, vegetation characteristics (e.g., vegetation
106 height, density or composition) are key drivers in shaping microclimates within the landscape matrix.
107 Especially forests alter the conditions underneath their canopy significantly by means of shading and

108 evapotranspirative cooling. Additionally, forest structure substantially affects wind patterns leading
109 to less turbulent mixing of the air. Second, topographic factors (e.g., aspect or inclination) modulate
110 many physical processes such as air flow and incoming solar radiation, which additionally increases
111 the heterogeneity in temperature conditions within and between habitats composing the landscape.
112 This is especially important for cold-adapted species in the face of climate change, as they might be
113 able to find stable cool spots in the landscape. In these so-called microrefugia, they are able to persist
114 for a longer time as these places can be buffered from contemporary macroclimate warming (Lenoir,
115 Hattab, & Pierre, 2017).

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

121 **2 | FORESTCLIM**

122 Here, we present a set of high-resolution bioclimatic variables of forest microclimate temperature
123 variables based upon the model presented in Haesen et al. (2021), where we provided the proof of
124 concept for the derivation of monthly mean temperature offset (ΔT) values (difference between
125 macro- and microclimate in forest understories) at a spatial resolution of 25 m \times 25 m across Europe.
126 Additionally, we used these offset values to calculate mean annual temperature (ForestClim1). We
127 now derived analogous maps of monthly minimum and maximum temperature offset values and
128 calculated the remaining ForestClim variables (ForestClim2 – ForestClim11; Figure 1). In short, we
129 relied on the SoilTemp database, which provided 1,273 temperature time series from 1,197 distinct
130 logger locations spread across European forests (Lembrechts et al., 2020). We first calculated daily
131 minimum and maximum temperature offsets as the difference between the daily minimum/maximum
132 microclimate temperature, as measured by the sensors, and the corresponding daily
133 minimum/maximum macroclimate air temperature value for exactly the same day, month, year and
134 grid cell from spatially downscaled E-OBS data at 1 km \times 1 km (Moreno & Hasenauer, 2016; Pucher &
135 Neumann, 2022). Note that, prior to calculating the daily offsets, we performed an altitudinal
136 temperature correction using CHELSA v2.1 lapse rates for the corresponding grid cell (Karger et al.,
137 2017; personal communication). Finally, the daily minimum and maximum temperature offset values
138 were aggregated into monthly averages. Second, we used boosted regression trees (BRTs) in order to
139 relate ΔT to explanatory variables describing topography, vegetation characteristics and macroclimate
140 conditions. The model was used to estimate the difference between microclimate (temperature
141 loggers placed within forests) and macroclimate (weather stations outside forests) across European

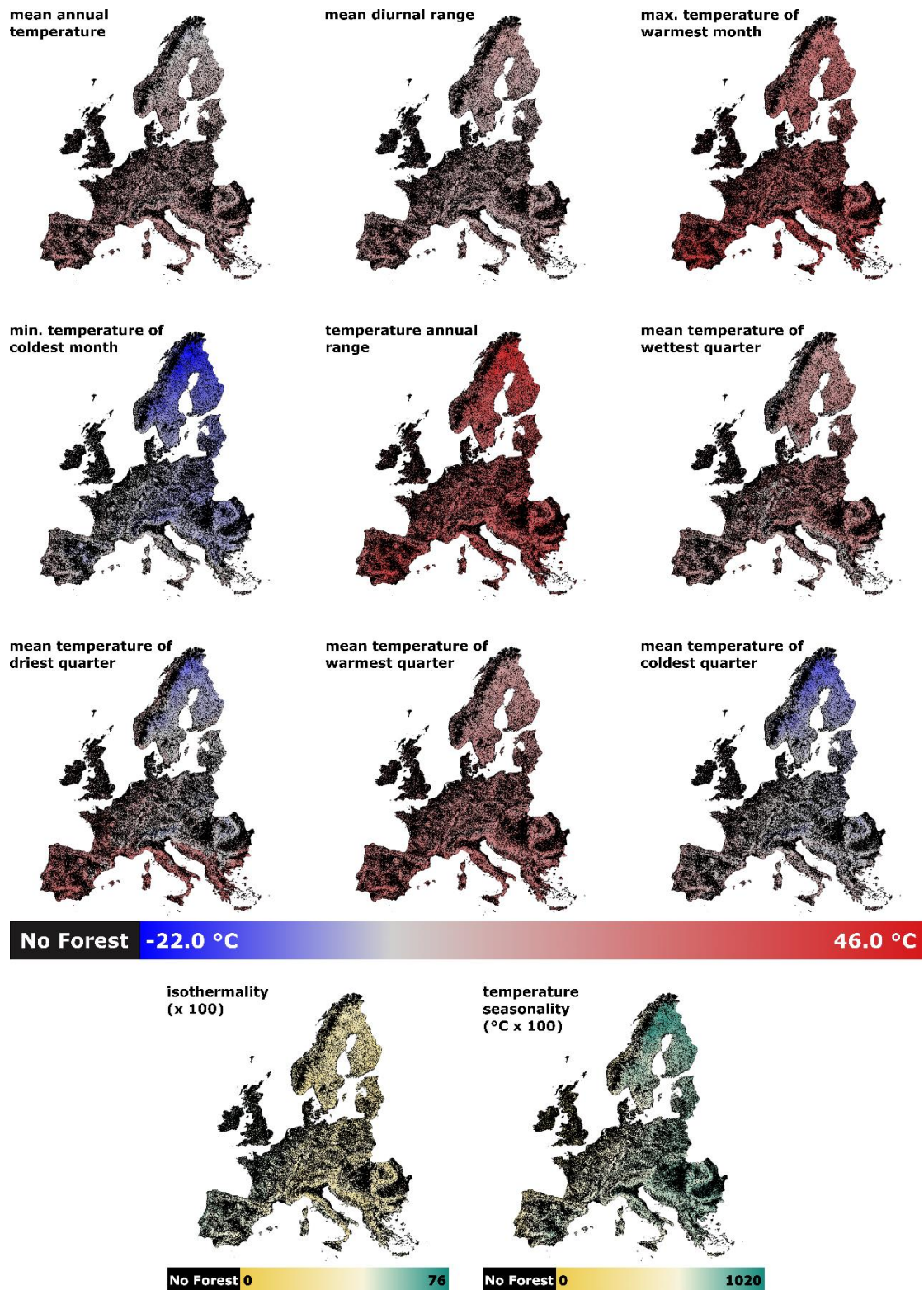
142 forests and across seasons. For more information regarding the different covariates and the
143 ForestTemp model itself, we refer to Haesen et al. (2021).

144 Finally, the resulting maps of the monthly offsets between mean, minimum and maximum
145 sub-canopy and free-air temperature were used to calculate bioclimatic variables following the
146 definition used in WorldClim (Fick & Hijmans, 2017). First, we calculated monthly mean, maximum
147 and minimum sub-canopy temperature by adding monthly temperature offsets to the respective
148 monthly mean, maximum and minimum temperature from TerraClimate (spatial resolution c. 4 km x
149 4 km; Abatzoglou et al., 2018). Next, we used these sub-canopy temperature layers to compute sub-
150 canopy bioclimatic temperature layers, representative of the 2000-2020 period. Wettest and driest
151 quarters were identified for each pixel based on TerraClimate's monthly values. However, note that
152 all temperature offset layers are freely-available meaning that the end-users are able to convert
153 macroclimatic data themselves. All calculations were performed in R version 4.1.1 (R Core Team,
154 2021).

155 We found considerable differences between ForestClim (forest microclimate) and
156 TerraClimate (macroclimate) bioclimatic variables, owing to biome and local forest stand
157 characteristics (e.g., canopy density). As expected, the minimum temperature of the coldest month
158 was higher within forests (ForestClim6; mean = -3.8°C) in comparison to TerraClimate (mean = -4.4°C).
159 Surprisingly, the maximum temperature of the warmest month was, overall, slightly higher in forests
160 (ForestClim5; mean = 24.6°C) compared to its TerraClimate counterpart (mean = 24.3°C). However,
161 ForestClim covers a wide range of different biomes (i.e., boreal, temperate and Mediterranean) and
162 microclimatic conditions in each of them are governed by different processes (De Frenne et al., 2021).
163 Indeed, when we further explored regional patterns in each of these biomes, ForestClim did follow
164 expected patterns with maximum temperatures being, on average, 0.9°C lower in temperate forests,
165 1.6°C higher in Mediterranean forests and 0.7°C higher in boreal forests. On the other hand, minimum
166 temperatures were consistently warmer in temperate (0.6°C), Mediterranean (0.5°C) and boreal
167 (0.4°C) forests, respectively. Furthermore, canopy density plays a crucial role in terms of shading and
168 evapotranspiration and a certain turn-over point in canopy density has been put forward where the
169 buffering effect of forests is converted to an amplifying effect (Gril et al., 2023; von Arx et al., 2013).
170 Indeed, when we only considered forests with a closed canopy ($> 90\%$) in these three biomes,
171 expected patterns were confirmed. Forest maximum temperatures were consistently cooler in
172 temperate (-2.2°C), Mediterranean (-2.1°C) and boreal (-0.9°C) forests and minimum temperatures
173 consistently warmer in temperate (0.5°C), Mediterranean (0.2°C) and boreal (3.5°C) forests. Our
174 results thus underpin an important role for canopy density, with potentially important implications
175 for forest management.

176 **3 | FUTURE PERSPECTIVES**

177 Our European, high-resolution ForestClim bioclimatic temperature products will open a new avenue
178 for future research within a wide range of disciplines. For high-latitudinal and high-elevational regions,
179 it is however important to note that the ForestTemp model is extrapolating beyond the range of the
180 training data and therefore we advise users to cautiously explore the associated extrapolation map.
181 Furthermore, forests are dynamic systems, regularly subjected to natural and anthropogenic
182 disturbances (e.g., pest outbreaks, windstorms, fires and logging). ForestClim is based on the 2015
183 forest type map of the Copernicus project and is thus not valid for pixels that experienced significant
184 forest cover change since then. It is especially this dynamic character of certain variables (e.g., canopy
185 cover) which currently hampers the development of similar products for future scenarios under
186 different shared socioeconomic pathways (De Lombaerde et al., 2022).



187

188 **Figure 1: forest bioclimatic variables below tree canopies at 15 cm above ground in European forests with a**
 189 **spatial resolution of 25 m, representative of the 2000-2020 period. Bioclimatic variables include: mean annual**
 190 **temperature (ForestClim1; °C); mean diurnal range (ForestClim2; °C); isothermality (ForestClim3; x 100);**
 191 **temperature seasonality (ForestClim4; °C x 100); maximum temperature of the warmest month (ForestClim5;**
 192 **°C); minimum temperature of the coldest month (ForestClim6; °C); temperature annual range (ForestClim7; °C);**
 193 **mean temperature of the wettest quarter (ForestClim8; °C); mean temperature of the driest quarter (ForestClim9;**
 194 **°C); mean temperature of the warmest quarter (ForestClim10; °C); and mean temperature of the coldest quarter**
 195 **(ForestClim11; °C). Note that isothermality is a unitless variable.**

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219 **Conflict of Interest:** The authors declare that they have no conflict of interest.

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