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## ForestClim -Bioclimatic variables for microclimate temperatures of European forests

Stef Haesen, Jonas Lembrechts, Pieter de Frenne, Jonathan Lenoir, Juha Aalto, Michael Ashcroft, Martin Kopecký, Miska Luoto, Ilya Maclean, Ivan Nijs, et al.

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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

3 **Stef Haesen<sup>1,2</sup>, Jonas J. Lembrechts<sup>3</sup>, Pieter De Frenne<sup>4</sup>, Jonathan Lenoir<sup>5</sup>, Juha Aalto<sup>6,7</sup>, Michael B.**  
4 **Ashcroft<sup>8</sup>, Martin Kopecký<sup>9,10</sup>, Miska Luoto<sup>7</sup>, Ilya Maclean<sup>11</sup>, Ivan Nijs<sup>3</sup>, Pekka Niittynen<sup>7</sup>, Johan van**  
5 **den Hoogen<sup>12</sup>, Nicola Arriga<sup>13</sup>, Josef Brůna<sup>9</sup>, Nina Buchmann<sup>12</sup>, Marek Čiliak<sup>14</sup>, Alessio Collalti<sup>15</sup>,**  
6 **Emiel De Lombaerde<sup>4</sup>, Patrice Descombes<sup>16,17</sup>, Mana Gharun<sup>12,18</sup>, Ignacio Goded<sup>13</sup>, Sanne Govaert<sup>4</sup>,**  
7 **Caroline Greiser<sup>19</sup>, Achim Grelle<sup>20</sup>, Carsten Gruening<sup>13</sup>, Lucia Hederová<sup>9</sup>, Kristoffer Hylander<sup>21</sup>, Jürgen**  
8 **Kreyling<sup>22</sup>, Bart Kruijt<sup>23</sup>, Martin Macek<sup>9</sup>, František Máliš<sup>24</sup>, Matěj Man<sup>9</sup>, Giovanni Manca<sup>13</sup>, Radim**  
9 **Matula<sup>10</sup>, Camille Meeussen<sup>4</sup>, Sonia Merinero<sup>21,25</sup>, Stefano Minerbi<sup>26</sup>, Leonardo Montagnani<sup>26,27</sup>,**  
10 **Lena Muffler<sup>28</sup>, Romà Ogaya<sup>29,30</sup>, Josep Penuelas<sup>29,30</sup>, Roman Plichta<sup>31</sup>, Miguel Portillo-Estrada<sup>3</sup>,**  
11 **Jonas Schmeddes<sup>22</sup>, Ankit Shekhar<sup>12</sup>, Fabien Spicher<sup>5</sup>, Mariana Ujházyová<sup>14</sup>, Pieter Vangansbeke<sup>4</sup>,**  
12 **Robert Weigel<sup>28</sup>, Jan Wild<sup>9</sup>, Florian Zellweger<sup>32</sup>, Koenraad Van Meerbeek<sup>1,2</sup>**

13 *\*Corresponding author, OrcID = <https://orcid.org/0000-0002-4491-4213>, stef.haesen@kuleuven.be,*  
14 *+32 16 32 24 67*

15 *<sup>1</sup>Department of Earth and Environmental Sciences, Celestijnenlaan 200E, 3001 Leuven, Belgium; <sup>2</sup>KU*  
16 *Leuven Plant Institute, KU Leuven, Leuven, Belgium; <sup>3</sup>Research Group PLECO (Plants and Ecosystems),*  
17 *University of Antwerp, 2610 Wilrijk, Belgium; <sup>4</sup>Forest & Nature Lab, Department of Environment, Ghent*  
18 *University, Geraardsbergsesteenweg 267, 9090 Melle-Gontrode, Belgium; <sup>5</sup>UMR CNRS 7058 ‘Ecologie*  
19 *et Dynamique des Systèmes Anthropisés’ (EDYSAN), Univ. de Picardie Jules Verne, Amiens, France;*  
20 *<sup>6</sup>Finnish Meteorological Inst., P.O. Box 503, FI-00101 Helsinki, Finland; <sup>7</sup>Dept of Geosciences and*  
21 *Geography, Gustaf Hällströmin katu 2a, FIN-00014 Univ. of Helsinki, Finland; <sup>8</sup>Centre for Sustainable*  
22 *Ecosystem Solutions, School of Biological Sciences, University of Wollongong, Wollongong, Australia;*  
23 *<sup>9</sup>Institute of Botany of the Czech Academy of Sciences, Zámek 1, CZ-25243, Průhonice, Czech Republic;*  
24 *<sup>10</sup>Faculty of Forestry and Wood Sciences, Czech University of Life Sciences Prague, Kamýcká 129, CZ-*  
25 *165 21, Prague 6 - Suchbát, Czech Republic; <sup>11</sup>Environment and Sustainability Institute, University of*  
26 *Exeter, Penryn Campus, Penryn, UK, TR10 9FE; <sup>12</sup>Department of Environmental Systems Science, ETH*  
27 *Zurich, Universitaetstrasse 2, 8092 Zurich, Switzerland; <sup>13</sup>European Commission, Joint Research Centre*  
28 *(JRC), Ispra, Italy; <sup>14</sup>Faculty of Ecology and Environmental Sciences, Technical University in Zvolen,*  
29 *T.G.Masaryka 24, 960 01 Zvolen, Slovakia; <sup>15</sup>Institute for Agriculture and Forestry Systems in the*  
30 *Mediterranean, National Research Council of Italy (CNR-ISAFOM), Perugia, Italy; <sup>16</sup>Dept. of Ecology &*  
31 *Evolution, University of Lausanne, 1015 Lausanne, Switzerland; <sup>17</sup>Musée et Jardins botaniques*  
32 *Cantonaux, 1007 Lausanne, Switzerland; <sup>18</sup>Institute of Landscape Ecology, University of Münster,*  
33 *Germany; <sup>19</sup>Department of Physical Geography and Bolin Centre for Climate Research, Stockholm*

34 University, 106 91 Stockholm, Sweden; <sup>20</sup>Department of Ecology, Swedish University of Agricultural  
35 Sciences, Uppsala, Sweden; <sup>21</sup>Department of Ecology, Environment and Plant Sciences and Bolin Centre  
36 for Climate Research, Stockholm University, 106 91 Stockholm, Sweden; <sup>22</sup>Experimental Plant Ecology,  
37 Institute of Botany and Landscape Ecology, University of Greifswald, D-17487 Greifswald, Germany;  
38 <sup>23</sup>Wageningen University and Research, Wageningen, Netherlands; <sup>24</sup>Faculty of Forestry, Technical  
39 University in Zvolen, T.G.Masaryka 24, 960 01 Zvolen, Slovakia; <sup>25</sup>Department of Plant Biology and  
40 Ecology, University of Seville, Apartado 1095, 41080 Seville, Spain; <sup>26</sup>Forest Services, Autonomous  
41 Province of Bolzano, 39100 Bolzano, Italy; <sup>27</sup>Faculty of Science and Technology, Free University of  
42 Bolzano, 39100 Bolzano, Italy; <sup>28</sup>Plant Ecology, Albrecht-von-Haller-Institute for Plant Sciences, Georg-  
43 August University of Goettingen, Untere Karspuele 2, 37073 Goettingen, Germany; <sup>29</sup>CSIC, Global  
44 Ecology Unit CREAM- CSIC-UAB, Bellaterra, 08193, Catalonia, Spain; <sup>30</sup>CREAF, Cerdanyola del Vallès  
45 08193, Catalonia, Spain; <sup>31</sup>Department of Forest Botany, Dendrology and Geobiocoenology, Mendel  
46 University in Brno, Czech Republic; <sup>32</sup>Swiss Federal Institute for Forest, Snow and Landscape Research  
47 WSL, Birmensdorf, Switzerland

#### 48 **OrcIDs**

49 Jonas J. Lembrechts: <https://orcid.org/0000-0002-1933-0750> Jürgen Kreyling: <https://orcid.org/0000-0001-8489-7289>  
50 Pieter De Frenne: <https://orcid.org/0000-0002-8613-0943> Bart Kruijt: <https://orcid.org/0000-0002-6186-1731>  
51 Juha Aalto: <https://orcid.org/0000-0001-6819-4911> Martin Macek: <https://orcid.org/0000-0002-5609-5921>  
52 Martin Kopecký: <https://orcid.org/0000-0002-1018-9316> František Máliš: <https://orcid.org/0000-0003-2760-6988>  
53 Jonathan Lenoir: <https://orcid.org/0000-0003-0638-9582> Matěj Man: <https://orcid.org/0000-0002-4557-8768>  
54 Miska Luoto: <https://orcid.org/0000-0001-6203-5143> Giovanni Manca: <https://orcid.org/0000-0002-9376-0310>  
55 Ilya Maclean: <https://orcid.org/0000-0001-8030-9136> Radim Matula: <https://orcid.org/0000-0002-7460-0100>  
56 Ivan Nijs: <https://orcid.org/0000-0003-3111-680X> Camille Meeussen: <https://orcid.org/0000-0002-5869-4936>  
57 Pekka Niittyinen: <https://orcid.org/0000-0002-7290-029X> Sonia Merinero: <https://orcid.org/0000-0002-1405-6254>  
58 Johan van den Hoogen: <https://orcid.org/0000-0001-6624-8461> Stefano Minerbi: <https://orcid.org/0000-0002-6620-2735>  
59 Nicola Arriga: <https://orcid.org/0000-0001-5321-3497> Leonardo Montagnani: <https://orcid.org/0000-0003-2957-9071>  
60 Josef Brůna: <https://orcid.org/0000-0002-4839-4593> Lena Muffler: <https://orcid.org/0000-0001-8227-7297>  
61 Nina Buchmann: <https://orcid.org/0000-0003-0826-2980> Romà Ogaya: <http://orcid.org/0000-0003-4927-8479>  
62 Marek Čiliak: <https://orcid.org/0000-0002-6720-9365> Josep Penuelas: <https://orcid.org/0000-0002-7215-0150>  
63 Alessio Collalti: <https://orcid.org/0000-0002-4980-8487> Roman Plichta: <https://orcid.org/0000-0003-2442-8522>  
64 Emiel De Lombaerde: <https://orcid.org/0000-0002-0050-2735> Miguel Portillo-Estrada: <https://orcid.org/0000-0002-0348-7446>  
65 Patrice Descombes: <https://orcid.org/0000-0002-3760-9907> Ankit Shekhar: <https://orcid.org/0000-0003-0802-2821>  
66 Mana Gharun: <https://orcid.org/0000-0003-0337-7367> Fabien Spicher: <https://orcid.org/0000-0002-9999-955X>  
67 Ignacio Goded: <https://orcid.org/0000-0002-1912-325X> Mariana Ujházyová: <https://orcid.org/0000-0002-5546-1547>  
68 Sanne Govaert: <https://orcid.org/0000-0002-8939-1305> Pieter Vangansbeke: <https://orcid.org/0000-0002-6356-2858>  
69 Caroline Greiser: <https://orcid.org/0000-0003-4023-4402> Robert Weigel: <https://orcid.org/0000-0001-9685-6783>  
70 Achim Grelle: <https://orcid.org/0000-0003-3468-9419> Wild Jan: <https://orcid.org/0000-0003-3007-4070>  
71 Carsten Gruening: <https://orcid.org/0000-0002-6169-2827> Florian Zellweger: <https://orcid.org/0000-0003-1265-9147>  
72 Lucia Hederová: <https://orcid.org/0000-0003-1283-0952> Koenraad Van Meerbeek: <https://orcid.org/0000-0002-9260-3815>  
73 Kristoffer Hylander: <https://orcid.org/0000-0002-1215-2648>

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-km<sup>2</sup> 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 ( $\Delta T$ ) 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  $\Delta T$  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

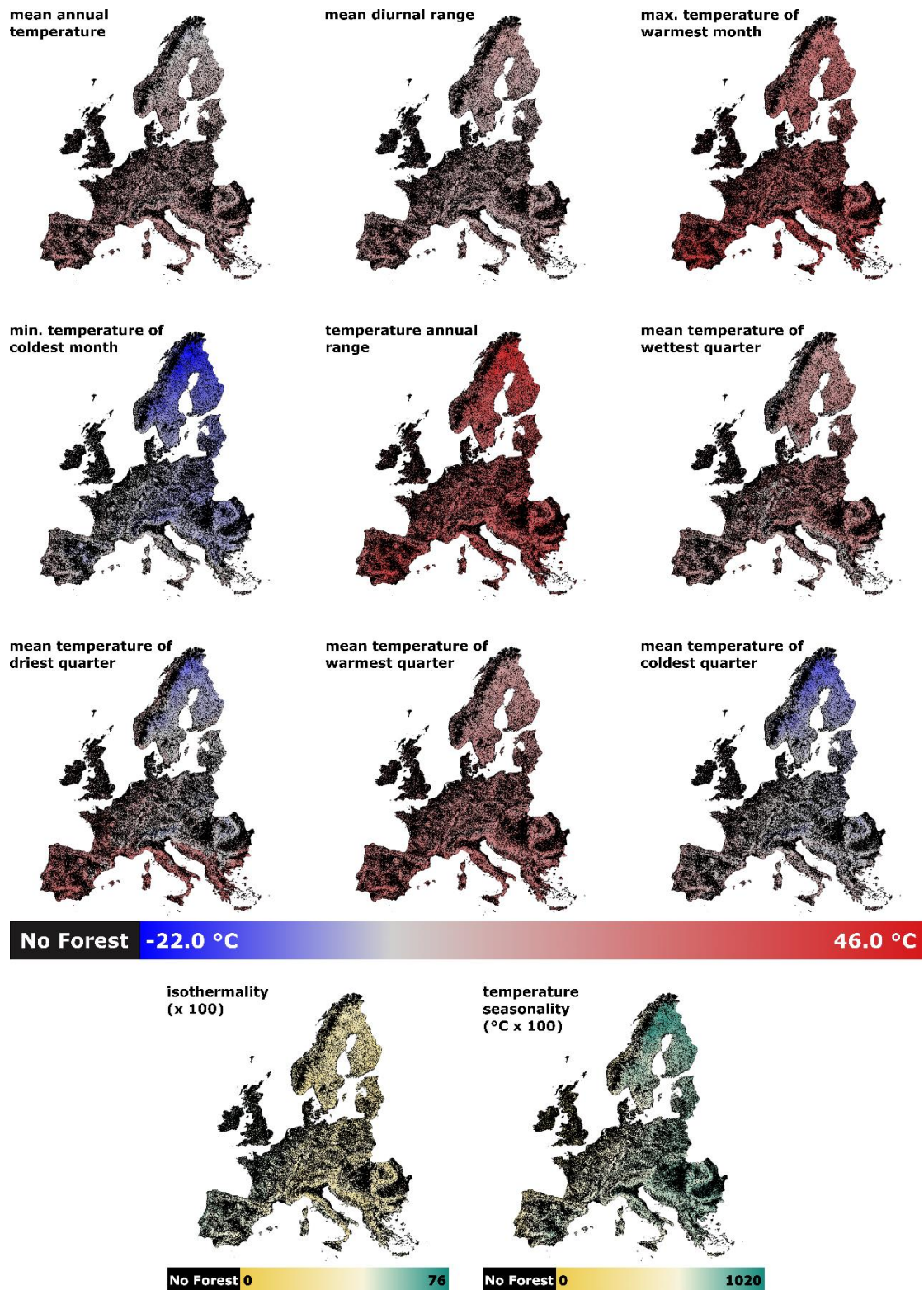
142 forests and across seasons. For more information regarding the different covariates and the  
143 ForestTemp model itself, we refer to Haesen et al. (2021).

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 =  $-3.8^{\circ}\text{C}$ ) in comparison to TerraClimate (mean =  $-4.4^{\circ}\text{C}$ ).  
159 Surprisingly, the maximum temperature of the warmest month was, overall, slightly higher in forests  
160 (ForestClim5; mean =  $24.6^{\circ}\text{C}$ ) compared to its TerraClimate counterpart (mean =  $24.3^{\circ}\text{C}$ ). 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,  $0.9^{\circ}\text{C}$  lower in temperate forests,  
165  $1.6^{\circ}\text{C}$  higher in Mediterranean forests and  $0.7^{\circ}\text{C}$  higher in boreal forests. On the other hand, minimum  
166 temperatures were consistently warmer in temperate ( $0.6^{\circ}\text{C}$ ), Mediterranean ( $0.5^{\circ}\text{C}$ ) and boreal  
167 ( $0.4^{\circ}\text{C}$ ) 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 ( $-2.2^{\circ}\text{C}$ ), Mediterranean ( $-2.1^{\circ}\text{C}$ ) and boreal ( $-0.9^{\circ}\text{C}$ ) forests and minimum temperatures  
173 consistently warmer in temperate ( $0.5^{\circ}\text{C}$ ), Mediterranean ( $0.2^{\circ}\text{C}$ ) and boreal ( $3.5^{\circ}\text{C}$ ) 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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