

SoilTemp: a global database of near-surface temperature

Running title – SoilTemp: call for data

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1 **Abstract**

2 Current analyses and predictions of spatially-explicit patterns and processes in ecology most often rely
3 on climate data interpolated from standardized weather stations. This interpolated climate data
4 represents long-term average thermal conditions at coarse spatial resolutions only. Hence, many
5 climate-forcing factors that operate at fine spatiotemporal resolutions are overlooked. This is
6 particularly important in relation to effects of observation height (e.g. vegetation, snow and soil
7 characteristics) and in habitats varying in their exposure to radiation, moisture and wind (e.g.
8 topography, radiative forcing, or cold-air pooling). Since organisms living close to the ground relate
9 more strongly to these microclimatic conditions than to free-air temperatures, microclimatic ground
10 and near-surface data are needed to provide realistic forecasts of the fate of such organisms under
11 anthropogenic climate change, as well as of the functioning of the ecosystems they live in.

12 To fill this critical gap, we highlight a call for temperature time series submissions to SoilTemp, a
13 geospatial database initiative compiling soil and near-surface temperature data from all over the
14 world. Currently this database contains time series from 7538 temperature sensors from 51 countries
15 across all key biomes. The database will pave the way towards an improved global understanding of
16 microclimate and bridge the gap between the available climate data and the climate at fine
17 spatiotemporal resolutions relevant to most organisms and ecosystem processes.

18 **Keywords:** microclimate, soil climate, climate change, topoclimate, database, temperature, species
19 distributions, ecosystem processes

20 **Introduction**

21 Current ecological research increasingly deals with large-scale patterns and processes, with global
22 databases of species distributions and traits becoming increasingly available (Bruehlheide *et al.*, 2018,
23 Kissling *et al.*, 2018, Kattge *et al.*, 2019). Analyses of these patterns and processes – and their
24 predictions under anthropogenic climate change – often rely on global climatic grids at coarse spatial
25 resolutions interpolated from standardized weather stations that represent long-term average
26 atmospheric conditions (Lembrechts *et al.*, 2018). Moreover, sensors in these weather stations are
27 shielded from direct solar radiation and located at ~2 meters above a frequently mown lawn (free-air
28 temperature or 'macroclimate', Jarraud, 2008). These climatic grids thus ignore many climate-forcing
29 processes that operate near the ground surface, at fine spatiotemporal resolutions, and in
30 environments that vary in their exposure to winds, radiation and moisture ('microclimate', Daly, 2006,
31 Bramer *et al.*, 2018, Körner & Hiltbrunner, 2018). Importantly, while these microclimatic processes
32 often operate at fine spatiotemporal resolutions, they can affect ecological relations both at the local
33 and the global scale (De Frenne *et al.*, 2013, Ashcroft *et al.*, 2014, Lembrechts *et al.*, 2019). For
34 example, they can potentially protect ground-dwelling biota against long-term climate variability,
35 providing microrefugia for these species to survive in locations deemed unsuitable in models using
36 climate data at coarse spatial resolutions, or buffer organisms against short-term extreme events (De
37 Frenne *et al.*, 2013, Lenoir *et al.*, 2017, Bramer *et al.*, 2018, Suggitt *et al.*, 2018). Microclimates can
38 however also expose organisms to more extreme temperatures, in which case distribution models
39 that ignore such microclimates may erroneously predict species survival instead of extinction
40 (Pincebourde & Casas, 2019). In order to provide realistic forecasts of species distributions and
41 performance, as well as of the functioning of the ecosystems they operate in, climate data that
42 incorporates microclimatic processes, ideally measured *in-situ*, are thus urgently needed (Körner &
43 Hiltbrunner, 2018).

44 **Horizontal and vertical features driving microclimate**

45 The offset between micro- and macroclimate is particularly pronounced around the soil surface, as
46 temperatures measured at 2 m above the ground can differ substantially from those at ground level,
47 or in the layers just above and below it (Geiger, 1950, Lembrechts *et al.*, 2019). This offset can result
48 from both 'horizontal' and 'vertical' features (Fig. 1), and can exceed several degrees centigrade in
49 annual averages. For example, Kearney (2019) modelled coarse-scale soil temperatures at various
50 depths considering the vertical features affecting the radiation balance. These vertical features include
51 the effects of vegetation characteristics (e.g. structure and cover), snow cover and soil characteristics
52 (e.g. moisture content, geological types, texture and bulk density) (Li, 1926, Zhang *et al.*, 2008,

53 Lembrechts *et al.*, 2019). The result of these vertical features is not only an instantaneous temperature
54 offset between air and soil temperatures, but also a buffering effect, i.e. the temporal variability in
55 temperature changes is lower in the soil than in the air (Geiger, 1950, Ashcroft & Gollan, 2013).
56 Horizontal processes on the other hand relate more to the spatial resolution of the climatic data. They
57 can be broken up into those that require only fine-resolution environmental information for specific
58 sites (e.g. effects of slope and aspect on radiation balances; Bennie *et al.*, 2008), and those where
59 temperatures are also affected by neighboring locations (e.g. topographic shading, cold-air drainage
60 and atmospheric temperature inversions, which are landscape context dependent; Whiteman, 1982,
61 Ashcroft & Gollan, 2012).

62 How horizontal and vertical features interact to define differences between soil and air temperature
63 may differ with the biome, season and day time. For example, in grasslands during summer, incoming
64 short-wave solar radiation is usually the dominant factor determining daytime soil surface
65 temperatures, which in turn result in higher air temperatures through convective heating (Geiger,
66 1950). However, during winter, horizontal processes such as cold-air drainage and coastal buffering
67 can have larger effects, especially on overnight air temperatures, when air temperatures may be
68 driving soil temperatures rather than vice-versa (Vitasse *et al.*, 2017). In dense forests, the situation is
69 even more complex: upper canopies block the bulk of short wave solar radiation, such that sub-canopy
70 temperatures are determined by convective heat transfer between the air surrounding the canopy
71 and direct conductance through physical contact of different parts of the canopy layer, in addition to
72 the limited radiation that does permeate the canopy (Körner & Paulsen, 2004, Lenoir *et al.*, 2017,
73 Zellweger *et al.*, 2019). As a result, horizontal processes such as passing fronts, and winds blowing in
74 hotter or colder air from outside the forest, will in large part define the – dampened – temperature
75 patterns under forest canopies (Ashcroft *et al.*, 2008).

76 ***The need for microclimate data across the field of ecology***

77 Many organisms living in the soil and close to the soil surface (e.g. soil micro-organisms like fungi,
78 ground arthropods, herbs, mosses, tree seedlings and small vertebrates) only experience fine-scale
79 soil and/or near-surface temperatures, and thus likely relate less strongly to free-air temperatures
80 (Randin *et al.*, 2009, Niittynen & Luoto, 2017, Lembrechts *et al.*, 2019). This may be reflected in a
81 species' distribution, but also their morphology, physiology and behavior (Körner & Paulsen, 2004,
82 Kearney *et al.*, 2009, Opedal *et al.*, 2015, de Boeck *et al.*, 2016). Many species indeed survive, live and
83 reproduce where average background climate appears unsuitable, and equally may be gone from sites
84 within apparently suitable areas where microclimatic extremes exceed their limits (Suggitt *et al.*,
85 2011). Without microclimate data, we not only lack information on the potential thermal

86 heterogeneity that is available for species to thermoregulate in situ, but also on the true magnitude
87 of climate change that species will be exposed to (Pincebourde *et al.*, 2016, Maclean *et al.*, 2017).
88 Accurately predicting how species' ranges will shift under climate change requires a good
89 understanding of the variety of climate niches truly available to them (Maclean *et al.*, 2015, Lenoir *et*
90 *al.*, 2017). The latter requires both a good understanding of what defines current microclimates, as
91 well of how climate change will interact with the drivers of microclimatic conditions (Maclean, 2019).
92 Additionally, it is the soil temperature rather than the air temperature that defines many ecosystem
93 functions in and close to the soil, like evapotranspiration, decomposition, root growth,
94 biogeochemical cycling and soil respiration (Pleim & Gilliam, 2009, Portillo-Estrada *et al.*, 2016, Hursh
95 *et al.*, 2017, Gottschall *et al.*, 2019, Medinets *et al.*, 2019). Given the repeatedly proven sensitivity of
96 many of these processes to temperatures (Rosenberg *et al.*, 1990, Coûteaux *et al.*, 1995, Schimel *et*
97 *al.*, 1996), here again having accurate measurements will be of utmost importance. The carbon
98 balance in boreal forests, for example, is largely dependent on soil thaw and thus soil rather than air
99 temperatures (Goulden *et al.*, 1998).

100 These realizations highlight the urgency to start using soil and near-surface microclimate data when
101 modelling the ecology and biogeography of surface and soil-dwelling organisms, as well as the
102 functioning of soil ecosystems, instead of readily available coarse-scaled free-air climate data (from
103 e.g. CHELSA (Karger *et al.*, 2017), TerraClimate (Abatzoglou *et al.*, 2018) or WorldClim (Fick & Hijmans,
104 2017)). While a suit of models now exist that produce fine-scale climate data (Bramer *et al.*, 2018,
105 Lembrechts *et al.*, 2018), we do not yet fully understand whether models using data that represent
106 average conditions over large areas provide adequate “mean field approximations” of (i.e. are
107 representative for) more complex spatiotemporal effects driven by the climatic conditions that
108 organisms experience (Bennie *et al.*, 2014). To accomplish the latter, global in-situ data is needed for
109 large-scale fine-resolution calibration and validation of these models. However, while the quality and
110 resolution of free-air temperature data and models at the global scale is rapidly improving (Bramer *et*
111 *al.*, 2018), soil temperature datasets used in biogeography and biogeochemistry are still largely
112 restricted to the landscape or regional scale, at best, and from intensively studied regions only
113 (Ashcroft *et al.*, 2008, Ashcroft *et al.*, 2009, Carter *et al.*, 2015, Aalto *et al.*, 2018), or they are derived
114 from models lacking fine-grained ground-truthing data (e.g. Copernicus Climate Change Service (C3S),
115 2019). Land surface temperatures as obtained from satellite data, on the other hand, are hampered
116 by their inability to measure below the vegetation cover (Bramer *et al.*, 2018).

117 In order to accurately describe and predict the (future) distribution and/or traits of surface and soil-
118 dwelling species at larger scales, we need to improve our general knowledge of the offsets and

119 spatiotemporal changes in variability between soil-level and free-air temperatures (Aalto *et al.*, 2018,
120 Lembrechts *et al.*, 2019). There is an urgent need to work towards globally available soil and near-
121 surface temperature data based on in-situ measurements and at relevant spatiotemporal resolutions
122 (Ashcroft & Gollan, 2012, Pradervand *et al.*, 2014, Slavich *et al.*, 2014, Opedal *et al.*, 2015, Meineri &
123 Hylander, 2017).

124 ***Launch of the SoilTemp database***

125 To tackle these issues, we launch an ambitious database initiative, compiling soil and near-surface
126 temperature data from all over the world into a global geospatial database: SoilTemp. At the time of
127 writing, we brought together temperature data from 7538 sensors placed both below, at and above
128 (up to 2 m) the soil surface (Fig. 2a), which is an accumulation of over 180.000 months of temperature
129 data with measurement intervals between 1 and 240 minutes (>30% every 60 minutes). The database
130 hosts loggers from 51 different countries spread across all continents, with a broad distribution across
131 the world's climatic space (Fig. 2b). There is a dominance of time series from Europe and areas below
132 1500 m a.s.l. (Fig. 2c, d). More than 75% of sensor measurements occurred within the last decade, but
133 the database does contain several time series covering longer time periods as well, with a maximum
134 of 42 years (Fig. 2d).

135 When the remaining critical gaps in our spatial coverage will be filled (see below), this database will
136 allow global assessments of the long-established theories on boundary layer climatology in
137 heterogeneous environments (Geiger, 1950), which has so far been lacking. The growing database
138 provides a unique opportunity to disentangle the role of the different horizontal and vertical features
139 influencing soil and near-surface temperature across all biomes of the world, with high spatial and
140 temporal resolutions. It will allow relating patterns in soil temperature to processes in the lower air
141 layers and calibrate and validate global models of soil temperature and (micro)climate (Kearney *et al.*,
142 2014a, Kearney *et al.*, 2014b, Carter *et al.*, 2015, Maclean *et al.*, 2017). It will also allow us to create
143 global maps of a wide array of general and microclimate-specific bioclimatic variables (e.g. growing
144 degree days, growing season length) at relevant spatiotemporal resolutions (Körner & Hiltbrunner,
145 2018).

146 Ultimately, this joint global effort and the resulting global microclimatic products will enable us to
147 improve analyses of the relationships between species' macroecology and the microclimate they
148 experience, identify microrefugia and stepping stones and improve global models of ecosystem
149 functioning and element cycling. Indeed, replacing the coarse-scaled free-air temperature averages
150 used traditionally in models in all fields of ecology with these more relevant soil-specific data products

151 is likely to increase their descriptive and predictive power, as the countless above-mentioned regional
152 studies exemplify (Lembrechts *et al.*, 2019). Additionally, this first global effort to combine and collect
153 in-situ measurements will help solve long-standing issues regarding sensor comparability and data
154 collection variability (Bramer *et al.*, 2018), as well as the question at what spatial scale microclimate
155 data can prove most informative for ecological modelling (Jucker *et al.*, 2020). The temperature time
156 series in the database, many of which are covering increasingly long time periods of up to a decade or
157 more, will also allow fine-tuning forecasts of microclimate data into the future by deepening our
158 understanding of the link between microclimatic dynamics in the soil and the air (Lenoir *et al.*, 2017,
159 Wason *et al.*, 2017, Bramer *et al.*, 2018, Maclean, 2019), improving our predictions of biodiversity and
160 ecosystem functioning under climate change.

161 ***Dig out your loggers! A call for contributions***

162 To reach these goals, we encourage scientists owning in-situ measured temperature data to submit
163 these to the growing SoilTemp database. All time series spanning one month or more, with
164 temperature measurements a maximum of 4 hours apart, all soil depths, all heights above the ground
165 up till two meters, all biomes, and all sensor types and brands will be accepted. Note that both spatially
166 dense and sparse logger networks, as well as single loggers are accepted. The achieved spatial
167 resolution is dependent on the provision of spatially precise coordinates to achieve a good relationship
168 with potential explanatory variables (e.g. high resolution remotely sensed environmental data). If we
169 have these coordinates and thus the location and distance between loggers, we can effectively obtain
170 the extent and spacing for each logger network (Western *et al.*, 2002).

171 We include data from both observational and experimental plots, yet sensors have to be measuring
172 in-situ and not in pots, and experiments manipulating the local climate (e.g. open-top chambers, rain-
173 out shelters or vegetation-removal experiments) are excluded (Table 1). Given currently less well-
174 represented climate regions, we especially encourage submissions from extreme cold and hot
175 environments to fill the remaining gaps in our global coverage. More specifically, hot tropical climates
176 (both tropical rainforests and tropical seasonal forests and savannas) and cold and hot deserts are
177 currently still largely underrepresented (Fig. 2b), in particular from Africa, Asia, Antarctica and the
178 Americas (Fig. 2a). Data contributors will be invited as co-authors on the main global papers resulting
179 from this database (see Supplementary Materials for details on terms of use and data ownership).

180 By encouraging sampling and submissions from remote areas, we aim to help solve the global sampling
181 bias in soil ecological data (Cameron *et al.*, 2018, Guerra *et al.*, 2019), and we hope to build a truly
182 global network representing – and actively engaging - scientists from a wide diversity of cultural

183 backgrounds (Maestre & Eisenhauer, 2019). More information is available on the SoilTemp website,
184 accessible via Figshare (DOI [10.6084/m9.figshare.12126516](https://doi.org/10.6084/m9.figshare.12126516)).

185 When fully established, the SoilTemp database and its derivative products (e.g. bioclimatic variables)
186 will be made freely available to facilitate the analysis of global patterns in microclimates, increase the
187 comparability between regional studies and simplify the use of accurate microclimatic data in ecology
188 (Bramer *et al.*, 2018). At the moment, critical metadata is already freely accessible via Figshare (DOI
189 [10.6084/m9.figshare.12126516](https://doi.org/10.6084/m9.figshare.12126516)). Given the absence of and the need for globally available soil
190 microclimate data products at relevant spatial resolutions for use in ecological analyses, we believe
191 that SoilTemp has the potential to become a highly important resource that will enable a step change
192 in ecological modelling.

193

194 **Table**

195 *Table 1: Minimal data requirements and obligatory metadata for submission to the database. For*
196 *more details, see Supplementary Material.*

197

Minimum data requirements	Obligatory metadata
Minimum one consecutive month of in-situ measured temperature time series	Accurate (handheld GPS or finer) spatial coordinates of the loggers (+ estimated accuracy)
Maximum time interval between measurements: 4 hours	Height/depth of the sensor relative to the soil surface
No climate manipulation experiments (only control plots of those experiments, or observational studies)	Type or brand of temperature sensor used, and type of shelter (e.g. no shelter, home-made shelter, Stevenson screen...)
No modelling studies (only empirical data)	Temporal resolution of the sensor Habitat classification

198

199

200 **Figures**

201 **Figure 1: the horizontal and vertical drivers of the offset between in-situ soil and free-air**
202 **temperatures.** Conceptually, there are two different sets of features responsible for the offset between
203 coarse-scale free air temperatures (top left, e.g. WorldClim, Fick & Hijmans, 2017) and fine-scale soil
204 temperatures (bottom right, e.g. Ashcroft & Gollan, 2012, Lembrechts et al., 2019),. Firstly, one can
205 incorporate fine-scale horizontal climate-forcing factors like topography and terrain-related features,
206 land cover types and distance to water bodies to go from coarse-scaled to finer resolutions (top right,
207 e.g. Aalto et al., 2017, Macek et al., 2019). Secondly, one can consider observation height, and the
208 effects of vegetation characteristics (like structure and cover), snow cover and soil characteristics (like
209 moisture, geological types, texture and bulk density) on the radiation balance to convert from free-air
210 to soil temperatures (e.g. Kearney, 2019). Both horizontal and vertical features can introduce positive
211 or negative differences (offset values) between soil and air temperatures through their effects on
212 processes related to the radiation balance, like wind, convective heat transfer and surface albedo. The
213 complexities of these horizontal and vertical processes can vary with biome, season and time of day.
214 Temperatures are represented here using an unspecified temperature range from cold (blue) to warm
215 (red).

216 **Figure 2: Overview of the status of the SoilTemp-database as of March 2020.** Spatial (a), climatic (b),
 217 elevational (c) and temporal (d) distribution of sensors in the SoilTemp-database as of March 2020. (a)
 218 Background world map in WGS1984, hexagons with a resolution of approximately 70.000 km² using
 219 the *dggridR*-package in R. (b) Colors of hexagons indicate the number of sensors at each climatic
 220 location, with a 40 × 40 bin resolution. Small dots in the background represent the global variation in
 221 climatic space (obtained by sampling 1.000.000 random locations from the CHLSA world maps at a
 222 spatial resolution of 2.5 arc minutes. Overlay with dotted lines and numbers (from 1 to 9) depict a
 223 delineation of Whittaker biomes (adapted from Whittaker, 1970): (1) tundra and ice, (2) boreal forest,
 224 (3) temperate seasonal forest, (4) temperate rainforest, (5) tropical rainforest, (6) tropical seasonal
 225 forest/savanna, (7) subtropical desert, (8) temperate grassland/desert, (9) woodland/shrubland. (c)
 226 Number of sensors in each elevation class. (d) Time span covered by each sensor in the database,
 227 ranked by starting date. Data showed from 1992 onwards, note that the time period covered by 4
 228 loggers with starting dates in 1976 is truncated.

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