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This article has been accepted for publication and undergone full peer review but has not been through the copyediting, typesetting, pagination and proofreading process, which may lead to differences between this version and the [Version of Record](#). Please cite this article as [doi: 10.1111/GCB.15123](https://doi.org/10.1111/GCB.15123)

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Article type : Report

## SoilTemp: a global database of near-surface temperature

*Running title – SoilTemp: call for data*

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**Author contributions:** JLL performed the analyses and wrote the manuscript , JLL, JA, MBA, PDF, MK, JL, ML, IMDM and IN lead the consortium and contributed to the writing; all authors contribute to the consortium and provided editorial advice.

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1 **Abstract**

2 Current analyses and predictions of spatially-explicit patterns and processes in ecology most often rely on  
3 climate data interpolated from standardized weather stations. This interpolated climate data represents  
4 long-term average thermal conditions at coarse spatial resolutions only. Hence, many climate-forcing  
5 factors that operate at fine spatiotemporal resolutions are overlooked. This is particularly important in  
6 relation to effects of observation height (e.g. vegetation, snow and soil characteristics) and in habitats  
7 varying in their exposure to radiation, moisture and wind (e.g. topography, radiative forcing, or cold-air  
8 pooling). Since organisms living close to the ground relate more strongly to these microclimatic conditions  
9 than to free-air temperatures, microclimatic ground and near-surface data are needed to provide realistic  
10 forecasts of the fate of such organisms under anthropogenic climate change, as well as of the functioning  
11 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 world.  
14 Currently this database contains time series from 7538 temperature sensors from 51 countries across all  
15 key biomes. The database will pave the way towards an improved global understanding of microclimate  
16 and bridge the gap between the available climate data and the climate at fine spatiotemporal resolutions  
17 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 predictions  
24 under anthropogenic climate change – often rely on global climatic grids at coarse spatial resolutions  
25 interpolated from standardized weather stations that represent long-term average atmospheric  
26 conditions (Lembrechts *et al.*, 2018). Moreover, sensors in these weather stations are shielded from direct  
27 solar radiation and located at ~2 meters above a frequently mown lawn (free-air temperature or  
28 'macroclimate', Jarraud, 2008). These climatic grids thus ignore many climate-forcing processes that  
29 operate near the ground surface, at fine spatiotemporal resolutions, and in environments that vary in  
30 their exposure to winds, radiation and moisture ('microclimate', Daly, 2006, Bramer *et al.*, 2018, Körner &  
31 Hiltbrunner, 2018). Importantly, while these microclimatic processes often operate at fine spatiotemporal  
32 resolutions, they can affect ecological relations both at the local and the global scale (De Frenne *et al.*,  
33 2013, Ashcroft *et al.*, 2014, Lembrechts *et al.*, 2019). For example, they can potentially protect ground-  
34 dwelling biota against long-term climate variability, providing microrefugia for these species to survive in  
35 locations deemed unsuitable in models using climate data at coarse spatial resolutions, or buffer  
36 organisms against short-term extreme events (De Frenne *et al.*, 2013, Lenoir *et al.*, 2017, Bramer *et al.*,  
37 2018, Suggitt *et al.*, 2018). Microclimates can however also expose organisms to more extreme  
38 temperatures, in which case distribution models that ignore such microclimates may erroneously predict  
39 species survival instead of extinction (Pincebourde & Casas, 2019). In order to provide realistic forecasts  
40 of species distributions and performance, as well as of the functioning of the ecosystems they operate in,  
41 climate data that incorporates microclimatic processes, ideally measured *in-situ*, are thus urgently needed  
42 (Körner & Hiltbrunner, 2018).

### 43 **Horizontal and vertical features driving microclimate**

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

51 geological types, texture and bulk density) (Li, 1926, Zhang *et al.*, 2008, Lembrechts *et al.*, 2019). The  
52 result of these vertical features is not only an instantaneous temperature offset between air and soil  
53 temperatures, but also a buffering effect, i.e. the temporal variability in temperature changes is lower in  
54 the soil than in the air (Geiger, 1950, Ashcroft & Gollan, 2013). Horizontal processes on the other hand  
55 relate more to the spatial resolution of the climatic data. They can be broken up into those that require  
56 only fine-resolution environmental information for specific sites (e.g. effects of slope and aspect on  
57 radiation balances; Bennie *et al.*, 2008), and those where temperatures are also affected by neighboring  
58 locations (e.g. topographic shading, cold-air drainage and atmospheric temperature inversions, which are  
59 landscape context dependent; Whiteman, 1982, Ashcroft & Gollan, 2012).

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

#### 74 ***The need for microclimate data across the field of ecology***

75 Many organisms living in the soil and close to the soil surface (e.g. soil micro-organisms like fungi, ground  
76 arthropods, herbs, mosses, tree seedlings and small vertebrates) only experience fine-scale soil and/or  
77 near-surface temperatures, and thus likely relate less strongly to free-air temperatures (Randin *et al.*,  
78 2009, Niittynen & Luoto, 2017, Lembrechts *et al.*, 2019). This may be reflected in a species' distribution,  
79 but also their morphology, physiology and behavior (Körner & Paulsen, 2004, Kearney *et al.*, 2009, Opedal  
80 *et al.*, 2015, de Boeck *et al.*, 2016). Many species indeed survive, live and reproduce where average  
81 background climate appears unsuitable, and equally may be gone from sites within apparently suitable

82 areas where microclimatic extremes exceed their limits (Suggitt *et al.*, 2011). Without microclimate data,  
83 we not only lack information on the potential thermal heterogeneity that is available for species to  
84 thermoregulate in situ, but also on the true magnitude of climate change that species will be exposed to  
85 (Pincebourde *et al.*, 2016, Maclean *et al.*, 2017). Accurately predicting how species' ranges will shift under  
86 climate change requires a good understanding of the variety of climate niches truly available to them  
87 (Maclean *et al.*, 2015, Lenoir *et al.*, 2017). The latter requires both a good understanding of what defines  
88 current microclimates, as well of how climate change will interact with the drivers of microclimatic  
89 conditions (Maclean, 2019). Additionally, it is the soil temperature rather than the air temperature that  
90 defines many ecosystem functions in and close to the soil, like evapotranspiration, decomposition, root  
91 growth, biogeochemical cycling and soil respiration (Pleim & Gilliam, 2009, Portillo-Estrada *et al.*, 2016,  
92 Hursh *et al.*, 2017, Gottschall *et al.*, 2019, Medinets *et al.*, 2019). Given the repeatedly proven sensitivity  
93 of many of these processes to temperatures (Rosenberg *et al.*, 1990, Coûteaux *et al.*, 1995, Schimel *et al.*,  
94 1996), here again having accurate measurements will be of utmost importance. The carbon balance in  
95 boreal forests, for example, is largely dependent on soil thaw and thus soil rather than air temperatures  
96 (Goulden *et al.*, 1998).

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

114 In order to accurately describe and predict the (future) distribution and/or traits of surface and soil-  
115 dwelling species at larger scales, we need to improve our general knowledge of the offsets and  
116 spatiotemporal changes in variability between soil-level and free-air temperatures (Aalto *et al.*, 2018,  
117 Lembrechts *et al.*, 2019). There is an urgent need to work towards globally available soil and near-surface  
118 temperature data based on in-situ measurements and at relevant spatiotemporal resolutions (Ashcroft &  
119 Gollan, 2012, Pradervand *et al.*, 2014, Slavich *et al.*, 2014, Opedal *et al.*, 2015, Meineri & Hylander, 2017).

#### 120 ***Launch of the SoilTemp database***

121 To tackle these issues, we launch an ambitious database initiative, compiling soil and near-surface  
122 temperature data from all over the world into a global geospatial database: SoilTemp. At the time of  
123 writing, we brought together temperature data from 7538 sensors placed both below, at and above (up to  
124 2 m) the soil surface (Fig. 2a), which is an accumulation of over 180.000 months of temperature data with  
125 measurement intervals between 1 and 240 minutes (>30% every 60 minutes). The database hosts loggers  
126 from 51 different countries spread across all continents, with a broad distribution across the world's  
127 climatic space (Fig. 2b). There is a dominance of time series from Europe and areas below 1500 m a.s.l.  
128 (Fig. 2c, d). More than 75% of sensor measurements occurred within the last decade, but the database  
129 does contain several time series covering longer time periods as well, with a maximum of 42 years (Fig.  
130 2d).

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

141 Ultimately, this joint global effort and the resulting global microclimatic products will enable us to  
142 improve analyses of the relationships between species' macroecology and the microclimate they  
143 experience, identify microrefugia and stepping stones and improve global models of ecosystem  
144 functioning and element cycling. Indeed, replacing the coarse-scaled free-air temperature averages used

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

### 156 ***Dig out your loggers! A call for contributions***

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

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

175 By encouraging sampling and submissions from remote areas, we aim to help solve the global sampling  
176 bias in soil ecological data (Cameron *et al.*, 2018, Guerra *et al.*, 2019), and we hope to build a truly global  
177 network representing – and actively engaging - scientists from a wide diversity of cultural backgrounds  
178 (Maestre & Eisenhauer, 2019). More information is available on the SoilTemp website, accessible via  
179 Figshare (DOI 10.6084/m9.figshare.12126516).

180 When fully established, the SoilTemp database and its derivative products (e.g. bioclimatic variables) will  
181 be made freely available to facilitate the analysis of global patterns in microclimates, increase the  
182 comparability between regional studies and simplify the use of accurate microclimatic data in ecology  
183 (Bramer *et al.*, 2018). At the moment, critical metadata is already freely accessible via Figshare (DOI  
184 10.6084/m9.figshare.12126516). Given the absence of and the need for globally available soil  
185 microclimate data products at relevant spatial resolutions for use in ecological analyses, we believe that  
186 SoilTemp has the potential to become a highly important resource that will enable a step change in  
187 ecological modelling.

188



189 **Table**

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

192

<b>Minimum data requirements</b>	<b>Obligatory metadata</b>
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

193

194

196 **Figure 1: The horizontal and vertical drivers of the offset between in-situ soil and free-air temperatures.**

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

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

## 222 Acknowledgments

223 We thank Sylvain Pincebourde and an anonymous reviewer for their critical evaluation of our manuscript. This work was supported by  
224 the Research Foundation Flanders (FWO) through a postdoctoral fellowship to Jonas J. Lembrechts (12P1819N) and a Research  
225 Network Grant (WOG W001919N). We gratefully acknowledge all data contributors, all staff of the author institutions engaged in field  
226 measurements and equipment maintenance (namely Erik Herberg, Iris Hamersveld, Ida Westman, Fredrik Brounes, Pernille Eidsen,  
227 Eleanor Walker and the teachers participating in the *Tepåseförsöket 2015*) and the ILTER-network, and thank local peoples for  
228 permission to collect data on their lands. Temperature data collection on European GLORIA summits was funded by European Union  
229 FP-5 project GLORIA-Europe (EVK2-CT-2000-0006) and the Swiss MAVA Foundation project 'Climate change impacts in protected  
230 areas of the Alps and high mountains of Eastern Europe and the Mediterranean region', on the Eastern Swiss GLORIA summits by  
231 the Swiss Federal Office for the Environment (FOEn), the Research Commission and staff of the Swiss National Park, and the  
232 Foundation Dr. Joachim de Giacomini, on Tenerife in the framework of the Flexible Pool project (W47014118) of Sylvia Haider funded  
233 by the German Centre for Integrative Biodiversity Research (iDiv) Halle-Jena-Leipzig, on Livingston Island, Antarctica by different  
234 research projects of the Govern of Spain (PERMAPLANET CTM2009-10165-E; ANTARPERMA CTM2011-15565-E; PERMASNOW  
235 CTM2014-52021-R), and the PERMATHERMAL arrangement between the University of Alcalá and the Spanish Polar Committee and  
236 on the Western Swiss GLORIA summits by Département de la culture et des sports du Valais, Fondation Mariétan, Société  
237 académique de Genève, Swiss Federal Office of Education and Science and Swiss Federal Office for the Environment. Jan Wild,  
238 Martin Macek, Martin Kopecký, Lucia Hederová, Matěj Man and Josef Brůna were supported by the Czech Science Foundation  
239 (project 17-13998S) and the Czech Academy of Sciences (project RVO 67985939), Meelis Pärtel by an Estonian Research Council  
240 grant (PRG609) and by the European Regional Development Fund (Centre of Excellence EcolChange), Lena Muffler, Juergen  
241 Kreyling, Robert Weigel, Mario Trouillier, Martin Wilmking and Jonas Schmeddes by DFG GraKo 2010 Response, Juha M. Alatalo by  
242 Qatar Petroleum (QUEX-CAS-QP-RD-18/19), the authors from Odesa National I. I. Mechnikov University (Sergiy Medinets and  
243 Volodymyr Medinets) by EU FP6 The nitrogen cycle and its influence on the European greenhouse gas balance (NitroEurope), EU  
244 FP7 Effects of Climate Change on Air Pollution Impacts and Response Strategies for European Ecosystems (ÉCLAIRE), Ukrainian  
245 national research projects (No. 505, 550, 574) funded by Ministry of Education and Science of Ukraine and GEF-UNEP funded  
246 'Towards INMS' project, see [www.inms.international](http://www.inms.international) for more details. Florian Zellweger was supported by the Swiss National Science  
247 Foundation (grant no. 172198), Peter Barančok, Róbert Kanka, Jozef Kollár and Andrej Palaj by the Slovak Scientific Grant Agency  
248 (project VEGA 2/0132/18), Jonas Ardö by a infrastructure grant from faculty of Science, Lund University, Julia Kempinen by the  
249 Doctoral Programme in Geosciences at the University of Helsinki, Jan Altman by the Czech Science Foundation (projects 17-07378S

250 and 20-05840Y), the Czech Academy of Sciences (project RVO 67985939) and Ministry of Education, Youth and Sport of the Czech  
251 Republic, program Inter-Excellence, subprogram Inter-Action (project LTAUSA19137), Toke Thomas Høye by the Carlsberg  
252 Foundation (grant no. CF16-0896) and the Villum Foundation (grant no. 17523), Jiri Dolezal by the Czech Science Foundation  
253 (projects 17-19376S), and Ministry of Education, Youth and Sport of the Czech Republic, program Inter-Excellence, subprogram Inter-  
254 Action (project LTAUSA18007), Nico Eisenhauer, Felix Gottschall and Simone Cesarz by the German Centre for Integrative  
255 Biodiversity Research (iDiv) Halle-Jena-Leipzig, funded by the German Research Foundation (FZT 118), Stuart W. Smith by  
256 AfricanBioServices project funded by the EU Horizon 2020 grant number 641918, Haydn Thomas by a K Natural Environmental  
257 Research Council doctoral training partnership grant NE/L002558/1, Isla H. Myers-Smith by the UK Natural Environmental Research  
258 Council ShrubTundra Project NE/M016323/1, Anibal Pauchard, Rafael Garcia and Eduardo Fuentes-Lillo by the projects Fondecyt  
259 1180205, Fondecyt 11170516 and CONICYT PIA APOYO CCTE AFB170008, Rafaella Canessa, Maaiké Y. Bader, Liesbeth van den  
260 Brink, and Katja Tielbörger by the DFG Priority Programme 1803 EarthShape (projects 1 (BA 3843/6-1) and 11 (TI 338/14-1&2)),  
261 Martin Svátek by a grant from the Ministry of Education, Youth and Sports of the Czech Republic (grant number: INTER-TRANSFER  
262 LTT17017), Mihai Pușcaș by ODYSSEE project (ANR-13-ISV7-0004 France, PN-II-ID-JRP-RO-FR-2012 UEFISCDI Romania), Pavel  
263 Dan Turtureanu by UEFISCDI in Romania, MEMOIRE grant no. PN-III-P1-1.1-PD2016-0925, Jonathan Lenoir by the Agence  
264 Nationale de la Recherche (ANR) within the framework of the IMPRINT project "IMpacts des PRocessus microclimatiques sur la  
265 redistributioN de la biodiversité forestière en contexte de réchauffement du macroclimat" (grant number: ANR-19-CE32-0005-01),  
266 Radim Matula and Roman Plichta by a grant Inter-Excellence (project: INTER-TRANSFER LTT17033) from the Ministry of Education,  
267 Youth and Sports of the Czech Republic, Lisa Rew by the National Institute of Food and Agriculture, U.S. Department of Agriculture  
268 Hatch MONB00363, Tim Seipel and Christian Larson by a grant from the United States National Institute of Food and Agriculture grant  
269 2017-70006-27272, Nina Buchmann by the SNF (projects M4P 40FA40\_154245, ICOS-CH 20FI21\_148992, 20FI20\_173691,  
270 InnoFarm 407340\_172433) and the EU (SUPER-G contract no. 774124) for the Swiss FluxNet, Mana Gharun by the SNF project  
271 ICOS-CH Phase 2 20FI20\_173691, Sanne Govaert by the Research Foundation Flanders (FWO) (project GOH1517N Pieter De  
272 Frenne, Camille Meeussen. and Pieter Van Gansbeke by the European Research Council (ERC) under the European Union's Horizon  
273 2020 research and innovation programme (ERC Starting Grant FORMICA 757833), Olivier Roupsard by EU-LEAP-Agri (RAMSES II),  
274 Agropolis and Total Foundation (DSCATT), CGIAR (GLDC) and EU-DESIRA (CASSECS), Zuzana Sitková by the Slovak Research  
275 and Development Agency under the project No. APVV-16-0325 and project ITMS 26220220066 co-funded by the ERDF, Brett Ryan  
276 Scheffers by National Geographic Society (grant no. 9480-14 and WW-240R-17), James D. M. Speed by the Research Council of  
277 Norway (262064), William D. Pearse and the Pearse Lab by National Science Foundation ABI-1759965, NSF EF-1802605 and United  
278 States Department of Agriculture Forest Service agreement 18-CS-11046000-041, Isla H. Myers-Smith by the UK Natural  
279 Environmental Research Council ShrubTundra Project NE/M016323/1, Andrew D Thomas by a Leverhulme Trust Research  
280 Fellowship under Government of Botswana permit EWT8/ 36/4 VIII(4), Shengwei Zong by National Natural Science Foundation of  
281 China (No. 41971124), Roman Plichta by the post-doc project 7.3 of Institutional plan of Mendel University in Brno 2019–2020,  
282 František Máliš by the Slovak Research and Development Agency project APVV-15-0270, Filip Hrbacek and Kamil Laska by the  
283 projects LM2015078 and CZ.02.01/0.0/0.0/16\_013/0001708 of Ministry of Youth and Sports of the Czech Republic, T-M. Ursu was  
284 supported by the Ministry of Research and Innovation through Projects for Excellence Financing in RDI: Contract no. 22 PFE/2018  
285 and PN2019-2022/19270201 – Ctr. 25N BIODIVERS 3-BIOSERV and Andrej Varlagin by RFBR project number 19-04-01234-a. Lore  
286 T. Verryck is funded by a PhD fellowship from the Research Foundation Flanders (FWO) and acknowledges support from the  
287 European Research Council Synergy Grant; ERC-2562013-SyG-610028 IMBALANCE-P and Pallieter De Smedt holds a postdoctoral  
288 fellowship of the Research Foundation-Flanders (FWO) and The Kreinitz Experiment is a cooperative research project initiated by the  
289 Helmholtz Centre for Environmental Research - UFZ. We also acknowledge project 18-74-10048 from the Russian Science  
290 Foundation, the Dirección General de Cambio Climático del Gobierno de Aragón, the Ordesa y Monte Perdido National Park and the  
291 Servicio de Medio Ambiente de Soria de la Junta de Castilla y León, the National Swiss Fund for research (SNSF, project "Lif3web",  
292 n°162604).

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

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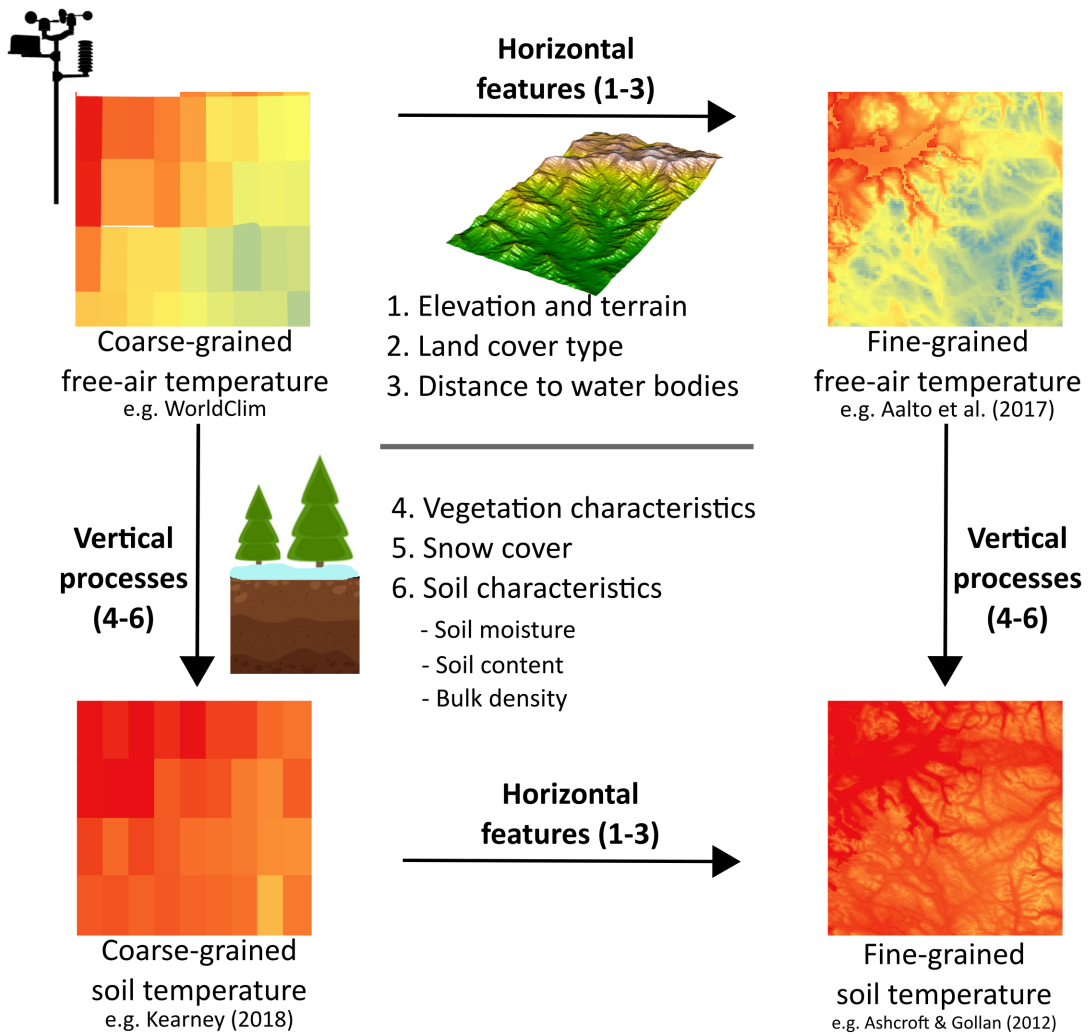
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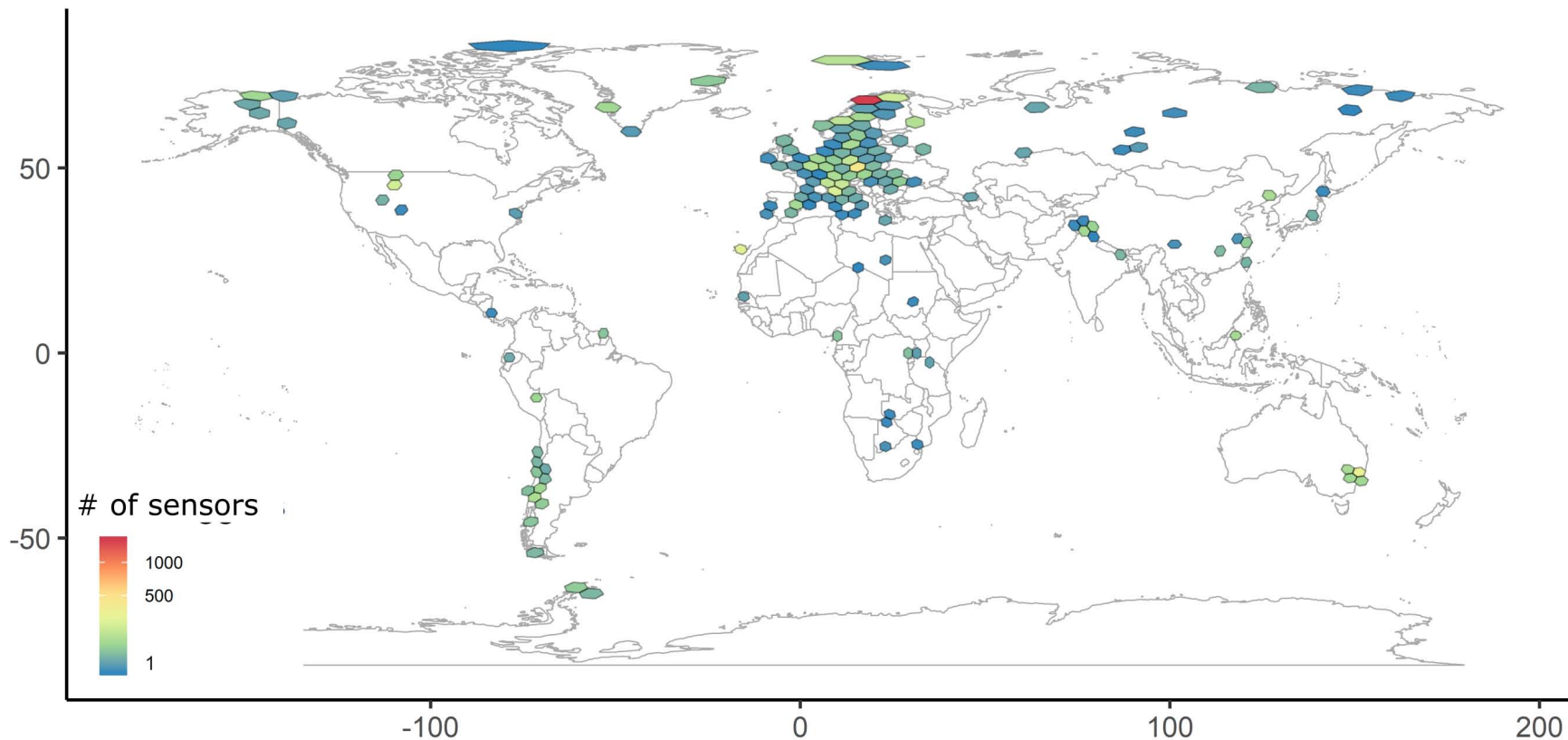
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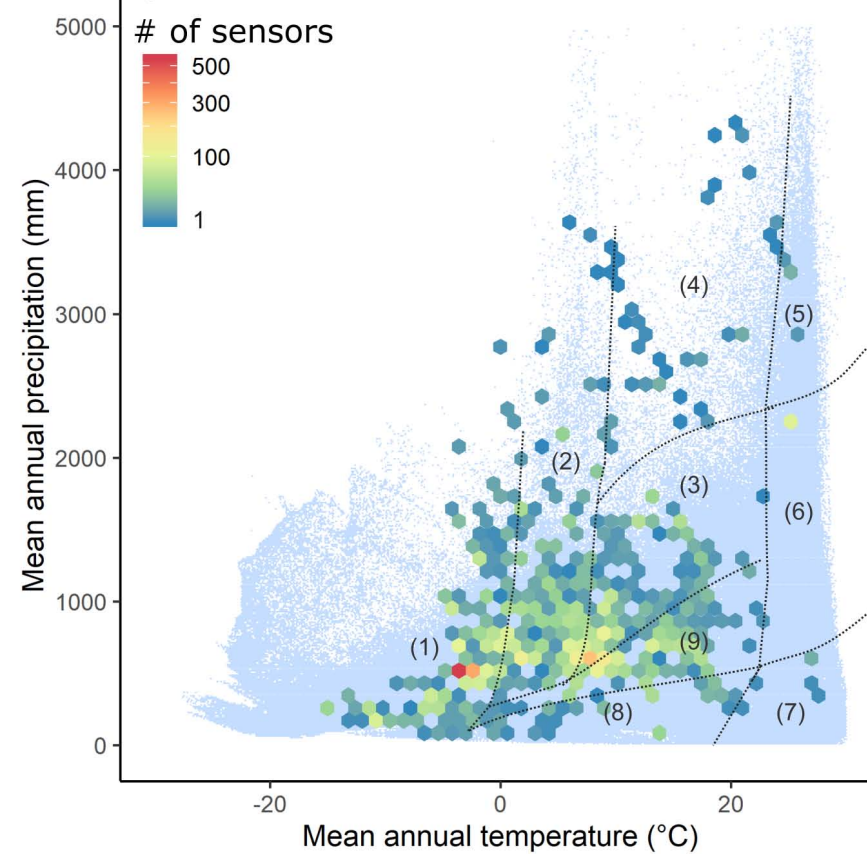


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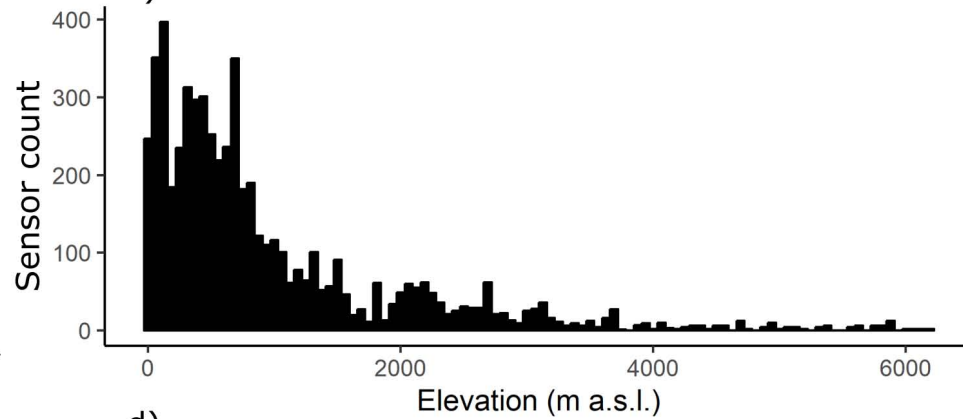
a)



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