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Abstract

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

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

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

Introduction

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

Horizontal and vertical features driving microclimate

The offset between micro- and macroclimate is particularly pronounced around the soil surface, as temperatures measured at 2 m above the ground can differ substantially from those at ground level, or in the layers just above and below it (Geiger, 1950, Lembrechts *et al.*, 2019). This offset can result from both 'horizontal' and 'vertical' features (Fig. 1), and can exceed several degrees centigrade in annual averages. For example, Kearney (2019) modelled coarse-scale soil temperatures at various depths considering the vertical features affecting the radiation balance. These vertical features include the effects of vegetation characteristics (e.g. structure and cover), snow cover and soil characteristics (e.g. moisture content, geological types, texture and bulk density) (Li, 1926, Zhang *et al.*, 2008, Lembrechts *et al.*, 2019). The result of these vertical features is not only an instantaneous temperature offset between air and soil temperatures, but also a buffering effect, i.e. the temporal variability in temperature changes is lower in the soil than in the air (Geiger, 1950, Ashcroft & Gollan, 2013). Horizontal processes on the other hand relate more to the spatial resolution of the climatic data. They can be broken up into those that require only fine-resolution environmental information for specific sites (e.g. effects of slope and aspect on radiation balances; Bennie *et al.*, 2008), and those where temperatures are also affected by neighboring locations (e.g. topographic shading, cold-air drainage and atmospheric temperature inversions, which are landscape context dependent; Whiteman, 1982, Ashcroft & Gollan, 2012).

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

The need for microclimate data across the field of ecology

Many organisms living in the soil and close to the soil surface (e.g. soil micro-organisms like fungi, ground arthropods, herbs, mosses, tree seedlings and small vertebrates) only experience fine-scale soil and/or near-surface temperatures, and thus likely relate less strongly to free-air temperatures (Randin *et al.*, 2009, Niittynen & Luoto, 2017, Lembrechts *et al.*, 2019). This may be reflected in a species' distribution, but also their morphology, physiology and behavior (Körner & Paulsen, 2004, Kearney *et al.*, 2009, Opedal *et al.*, 2015, de Boeck *et al.*, 2016). Many species indeed survive, live and reproduce where average background climate appears unsuitable, and equally may be gone from sites within apparently suitable areas where microclimatic extremes exceed their limits (Suggitt *et al.*, 2011). Without microclimate data, we not only lack information on the potential thermal heterogeneity that is available for species to thermoregulate in situ, but also on the true magnitude of climate change that species will be exposed to (Pincebourde *et al.*, 2016, Maclean *et al.*, 2017). Accurately predicting how species' ranges will shift under climate change requires a good understanding of the variety of climate niches truly available to them (Maclean *et al.*, 2015, Lenoir *et al.*, 2017). The latter requires both a good understanding of what defines current microclimates, as well of how climate change will interact with the drivers of microclimatic conditions (Maclean, 2019). Additionally, it is the soil temperature rather than the air temperature that defines many ecosystem functions in and close to the soil, like evapotranspiration, decomposition, root growth, biogeochemical cycling and soil respiration (Pleim & Gilliam, 2009, Portillo-Estrada *et al.*, 2016, Hursh *et al.*, 2017, Gottschall *et al.*, 2019, Medinets *et al.*, 2019). Given the repeatedly proven sensitivity of many of these processes to temperatures (Rosenberg *et al.*, 1990, Coûteaux *et al.*, 1995, Schimel *et al.*, 1996), here again having accurate measurements will be of utmost importance. The carbon balance in boreal forests, for example, is largely dependent on soil thaw and thus soil rather than air temperatures (Goulden *et al.*, 1998).

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

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

Launch of the SoilTemp database

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

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

Ultimately, this joint global effort and the resulting global microclimatic products will enable us to improve analyses of the relationships between species' macroecology and the microclimate they experience, identify microrefugia and stepping stones and improve global models of ecosystem functioning and element cycling. Indeed, replacing the coarse-scaled free-air temperature averages used traditionally in models in all fields of ecology with these more relevant soil-specific data products is likely to increase their descriptive and predictive power, as the countless above-mentioned regional studies exemplify (Lembrechts *et al.*, 2019). Additionally, this first global effort to combine and collect in-situ measurements will help solve long-standing issues regarding sensor comparability and data collection variability (Bramer *et al.*, 2018), as well as address the question at what spatial scale microclimate data can prove most informative for ecological modelling (Jucker *et al.*, 2020). The temperature time series in the database, many of which are covering increasingly long time periods of up to a decade or more, will also allow fine-tuning forecasts of microclimate data into the future by deepening our understanding of the link between microclimatic dynamics in the soil and the air (Lenoir *et al.*, 2017, Wason *et al.*, 2017, Bramer *et al.*, 2018, Maclean, 2019), improving our predictions of biodiversity and ecosystem functioning under climate change.

Dig out your loggers! A call for contributions

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

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

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

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

Table

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

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

Figures

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

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

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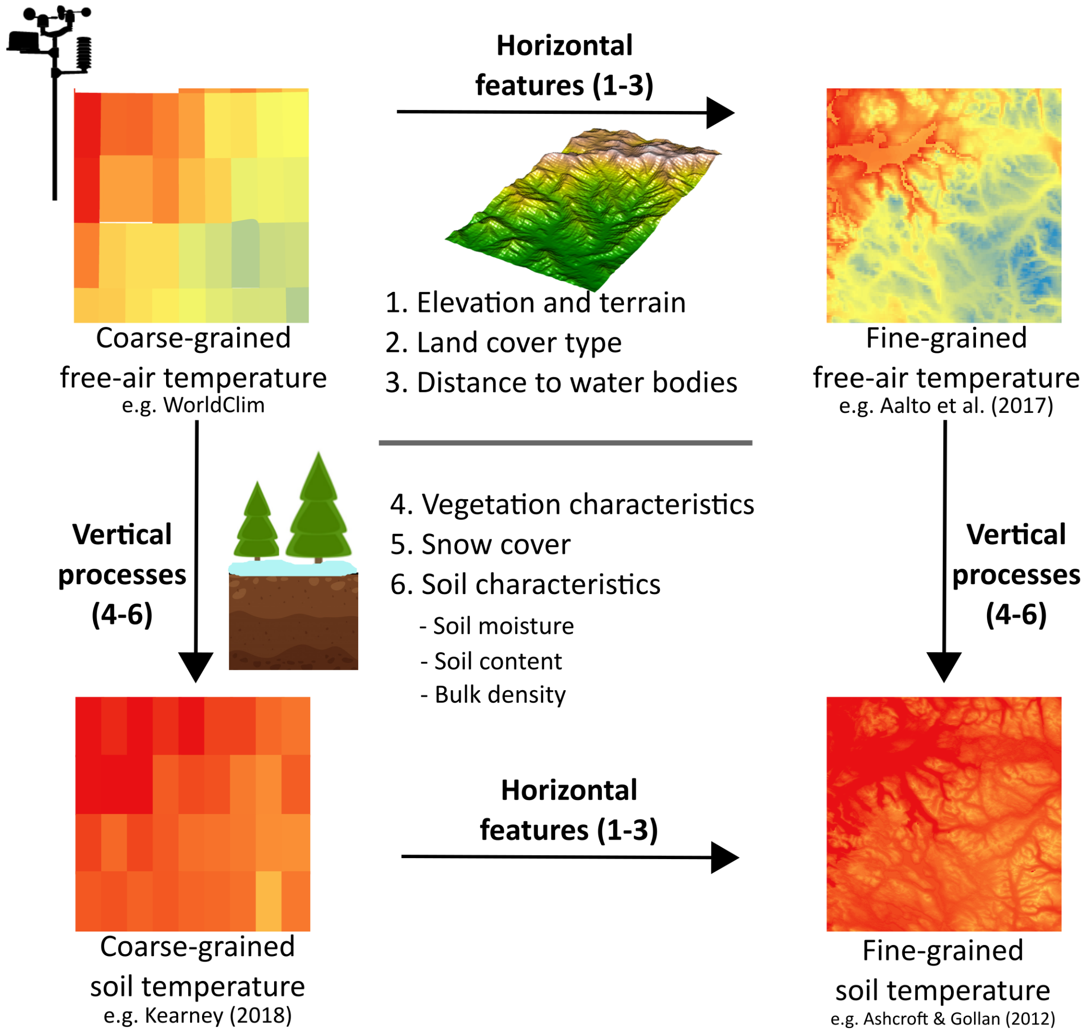

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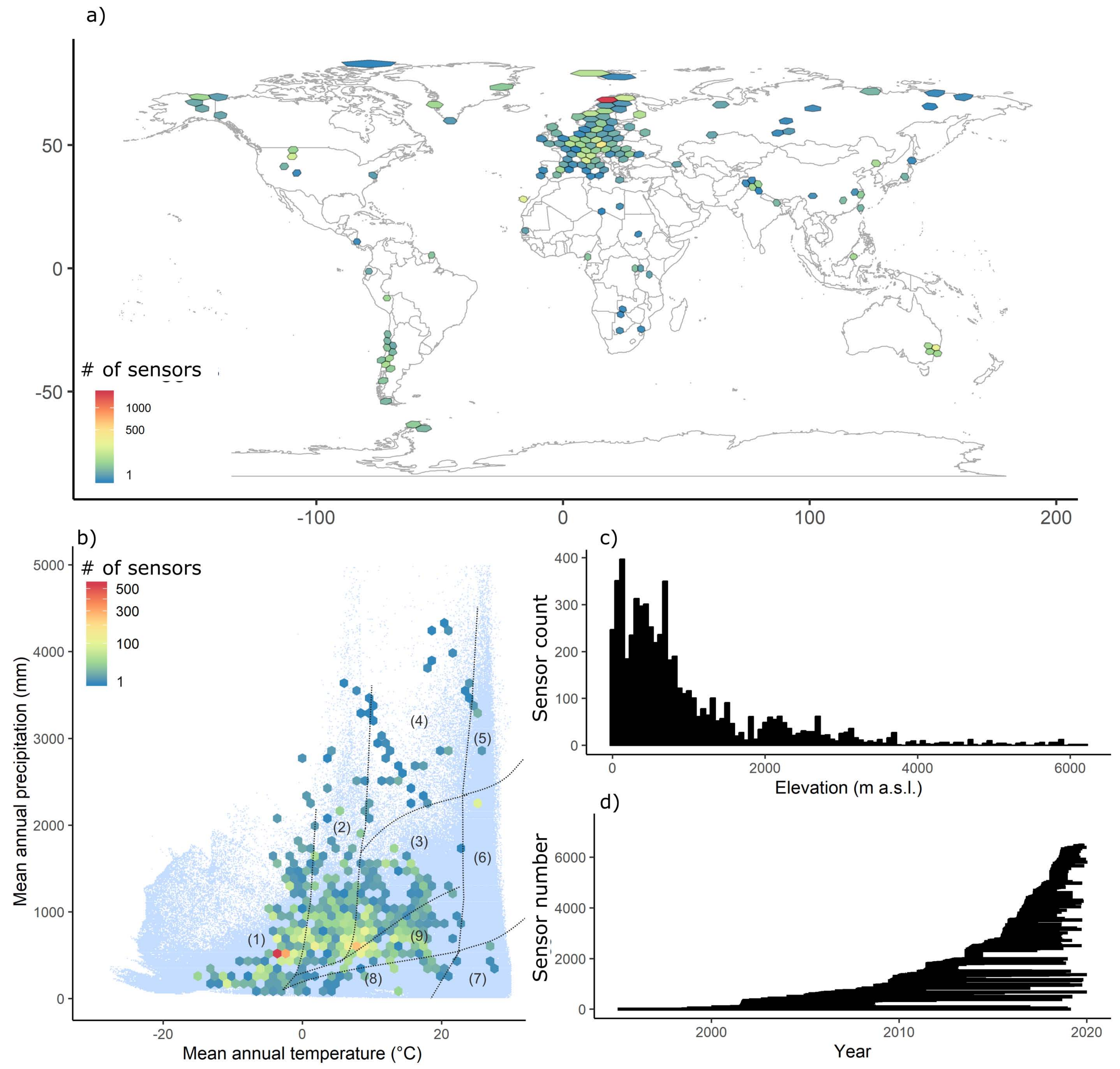
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