Redrawing Köppen-Geiger classes with microclimate: implications for nature and society

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Scientists have long categorized the planet's climate using the Köppen-Geiger (KG) classification to research climate-change impacts, biogeographical realms, agricultural suitability, and conservation. However, global KG maps primarily rely on macroclimate data collected by weather stations, which may not represent microclimatic conditions experienced by most life on Earth. Few studies have explored microclimate at broad scales, largely due to data and computational constraints. Here, we predicted KG classes separately from macroclimate and microclimate for more than 32 million locations across six continents. As compared to macroclimate, microclimate had 14-fold lower error and reclassified 38% of the total area. Microclimate-derived KG classes were not only more spatially variable but also encompassed a broader range of latitudes, relative to macroclimate-derived KG classes. By redrawing the lines of climate classes, our study prompts a reevaluation of the importance of meteorological drivers of ecology across scales, shedding light on how natural, agricultural, and social systems experience and respond to global change.

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Climate classification systems are a ubiquitous tool for understanding climate change and its impacts across space and time (Peel *et al*. 2007). The most prominent classification framework is the Köppen-Geiger (KG) system (Köppen 1918; Geiger 1954), which sorts the planet into major groups (A–E) subdivided into minor classes based on annual averages and variability of temperature and precipitation (Figure 1). Global KG maps are widely used in education from primary school through graduate teaching and inform research on crop suitability (Wang *et al*. 2022), species distributions (Mesgaran *et al*. 2014), human thermal comfort (Zhao *et al*. 2021), and disease spread (Savary *et al*. 2019).

Global KG maps (eg Kottek *et al*. 2006; Peel *et al*. 2007; Beck *et al*. 2018) have so far relied on macroclimate data obtained by weather stations situated 1.5–2 m above the ground, away from topographic features, human developments, water, or vegetation (WMO 2008). However, such climate data do not represent microclimates—the conditions shaped by local features (eg hills, valleys, and foliage) that impact near-surface heat and water exchange (Bramer *et al*. 2018). For most terrestrial species, microclimates are the broker of climate exposure, influencing physiology, community composition, and climate-change-induced extinction risk (Suggitt *et al*. 2018). Given the discrepancies between regional macroclimate and local microclimate (De Frenne *et al*. 2019), macroclimate-derived (hereafter, macro-derived) KG classes may poorly represent the climatic reality for most ecosystems and human communities. Analyses using macro-derived KG maps have suggested that rice, corn, and millet croplands will need to shift considerably in space as large swaths of land become climatically unsuitable (Berg *et al*. 2013; FAO 2021). Yet these efforts may be misguided because most crops are sensitive to fine-scale soil and air conditions—crops can be replanted into suitable microclimates a few meters away, rather than across hundreds of miles. Deriving KG classes from microclimate may also prominently reshuffle classes globally, revealing higher environmental heterogeneity (eg many KG classes expressed in a relatively small area) or anomalies relative to macroclimate (eg "tropical" KG classes located at high latitudes). Reclassifications based on microclimate could be immensely useful for better describing the climatic gradients experienced by all terrestrial life on Earth.

Here, we generated predictions of KG classes using macroclimate and near-surface microclimate for a broad range of land uses and landforms globally. While an abundance of recent work has compared microclimate and macroclimate for particular ecosystems and taxa (Bramer *et al*. 2018), few have done so at the global extent. We discovered that microclimate-derived (hereafter, micro-derived) KG classes dramatically diverge from macro-derived KG classes, exhibiting greater spatial variation and broader latitudinal ranges, which reshapes our understanding of the geography of climate. Reevaluating climate classes, and thereby integrating how most life experiences climate, sheds light on the drawbacks of using macroclimate for understanding the responses of ecosystems and societies to global change.

Methods

Calculating KG classes

We produced KG class maps, derived from macroclimate and microclimate data separately, using the classification

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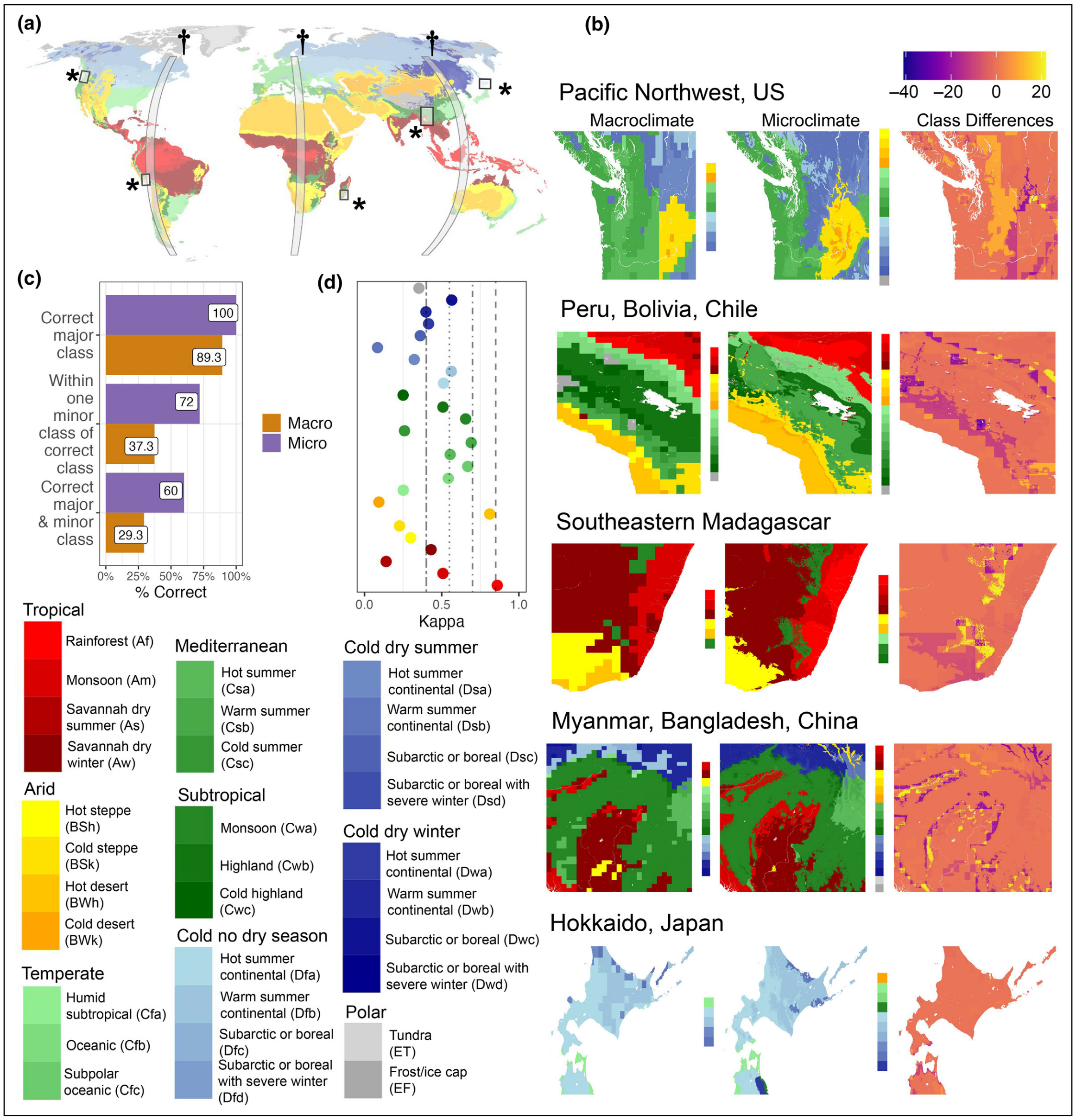

Figure 1. The Köppen-Geiger (KG) classification system subdivides the planet into discrete categories based on annual averages and variability in temperature and precipitation. (a) KG classes across the planet as represented by Kottek *et al.* (2006), displaying locations of case study regions (*) and latitudinal strips (†) for which we predicted KG classes from macroclimate and microclimate data. (b) Maps of KG classes for each study region, with color legends depicting the sets of classes predicted by macroclimate and microclimate, and maps of the differences between macroclimate-derived and microclimate-derived KG class predictions. (c) Micro-derived KG classes were consistently more accurate than macro-derived KG classes (indicated by percent correct classification), as validated with KG classes derived from 75 sensors placed in a variety of ecosystems across four continents. (d) Amount of agreement, as measured by Fleiss' kappa, between macroclimate and microclimate on the locations of KG classes, with higher values indicating greater agreement between macroclimate and microclimate. Dashed vertical lines indicate thresholds for (from left to right) poor, fair, good, very good, and excellent agreement; most classes (18/26) had poor or fair agreement, indicating large discrepancies between macroclimate and microclimate. Classes missing from this panel include those that were not predicted by macroclimate within case study regions or latitudinal strips.

system employed by Beck *et al.* (2018) (see Appendix S1: Table S1). Macroclimate data, sourced from ERA5 (Hersbach *et al.* 2020), were 770-km^2 resolution hourly datasets of air temperature and precipitation representative of conditions measured by free-standing weather stations. Microclimate data were 0.25-km^2 resolution hourly predictions of 15-cm aboveground air temperature and precipitation, subject to the influences of terrain and vegetation.

For microclimate, temperature was mechanistically predicted using the *microclimf* microclimate model (Maclean 2022), and precipitation was derived from 1-km^2 CHELSA data (v2.1; Karger *et al.* 2021) bilinearly interpolated to 0.25 km^2. With respect to representing near-surface temperatures, the accuracy of the *microclimf* model exceeds that of ERA5 by a factor of 1.58 (Trew *et al.* 2024). We parameterized *microclimf* using the vegetation, terrain, and climate forcing variables shown in Appendix S1: Table S2. Given our focus on spatial rather than temporal comparisons, our maps represented conditions in 2015. However, we also validated predictions of micro- and macro-derived KG classes via two methods. First, we assessed how closely microclimate and macroclimate temperature predictions matched time series of in situ microhabitat temperature measurements, as reported in Klinges *et al*. (2024). Furthermore, we calculated KG classes from temperature measurements across nine years (2011–2019) and 75 locations on four continents, and then quantified the frequency that macro- and micro-derived KG classes correctly matched empirical KG classes (Appendix S1: Figure S1). Given that empirical precipitation data were not available for all sites, we used the same publicly available precipitation product (CHELSA v2; Karger *et al*. 2021) for calculating KG classes from macroclimate, microclimate, and empirical temperature; validation here therefore served to compare temperature products (ie *microclimf* and ERA5).

Case study regions and latitudinal strips

We generated macro- and micro-derived KG classes for five case study regions: the US Pacific Northwest (PNW); areas of the Atacama Desert, Andean Altiplano, and Western Amazon basin (henceforth "Peru", the country in which most of this region is located); subtropical southeastern Madagascar; south Asian lowlands and Himalayan foothills (henceforth "Myanmar"); and Hokkaido of Japan (Figure 1). To more thoroughly examine macro- and micro-derived KG classes across latitudes, we also generated KG classes for three discrete latitudinal strips from 60° S to 60° N in the Americas (75° W–70° W), Africa and Europe (20° E–22.5° E), and Oceania and Asia (115° E–120° E).

Analysis

We compared macro- and micro-derived KG classes using three methods: cell-level class differences, latitudinal distributions, and spatial variability. We measured the difference in KG classes, per spatial grid cell, when derived from macroclimate versus microclimate by using a simplified scoring system (Eccel *et al*. 2016): 10 for each change in major KG class (eg A to B = 10; A to C = 20), 1 for each first-degree subclass difference (eg Af to Am = 1), and 0.1 for each second-degree subclass difference (eg BSh to BSk = 0.1) (Appendix S1: Table S1). We calculated class differences both with microclimate at 0.25-km^2 resolution and microclimate classes aggregated to their median and mode at 770-km^2 resolution (to match macroclimate). For each class, we then calculated Fleiss' kappa for the level of agreement between micro- and macro-derived KG predictions (Fleiss 1981).

Within each latitudinal strip, we compared the 2.5–97.5% percentile latitudinal range of each micro- and macro-derived KG class. We then identified poleward or equatorward extensions, defined as any location where a micro-derived KG class lay outside the latitudinal range of its corresponding macro-derived KG class (demonstrated in Figure 2). For instance, if class Bf from macroclimate ranged between 12° and 45°, and class Bf from microclimate ranged between 7° and 53°, then the poleward extension was 53°–45° = 8°, and the equatorward extension was 7°–12° = –5°. We also tested for differences in the latitudinal distributions of each KG class using two-sample Wilcoxon tests.

We measured spatial variability by calculating the number of macro- and micro-derived KG classes falling within the same spatial area. To explore variability across spatial scales, we performed this calculation within sets of concentric circles of increasing decimal degree diameter (from 0.005° to 16° for study regions, and from 1° to 180° for latitudinal strips; Figure 3). Across 50 randomly placed sets of circles within each case study region and latitudinal strip, we calculated the mean number of macro- and micro-derived KG classes, and the 95% quantiles of each mean. We also repeated this analysis for all regions/latitudinal strips using micro-derived KG classes that were aggregated from 0.25-km^2 resolution to their median value at 770-km^2 resolution, thereby matching the spatial resolution of the macro-derived KG classes.

Results

From validation with empirical measurements, micro-derived KG classes were about twice as likely to be correct relative to macro-derived KG classes (Figure 1) and microclimate had 14-fold lower average error in classifications (0.14) relative to macroclimate (1.99). Micro- and macro-derived KG classes also differed considerably from each other globally. Across all five study regions and three latitudinal strips, 38% of cells differed by subclass (eg Af versus Am), 13% of cells differed by at least one major class (eg A versus B), and 4% of cells differed by at least two major classes (eg A versus C). D group classes ("continental") on average diverged the most, with 52.6% of all macroclimate D cells designated as non-continental when derived by microclimate. According to Fleiss' kappa, average agreement between macro- and micro-derived KG classes was 0.435 (and 0.431 when the median microclimate class was taken for each macroclimate grid cell; Appendix S1: Figure S1), which is considered "fair" but not "good" agreement (Fleiss 1981). Agreement was highest for classes Af "tropical rainforest" (0.86) and BWh "hot desert" (0.81), and lowest for classes Dsb "dry warm summer continental" (0.084), BWk "cold desert" (0.093), and As "savannah dry summer" (0.14) (Appendix S1: Table S3).

The distribution of latitudes of each class was on average 2.94° broader, and centered 2.3° farther from the equator, when derived from microclimate than from macroclimate. On average for each class within latitudinal strips, 9046 km^2 of

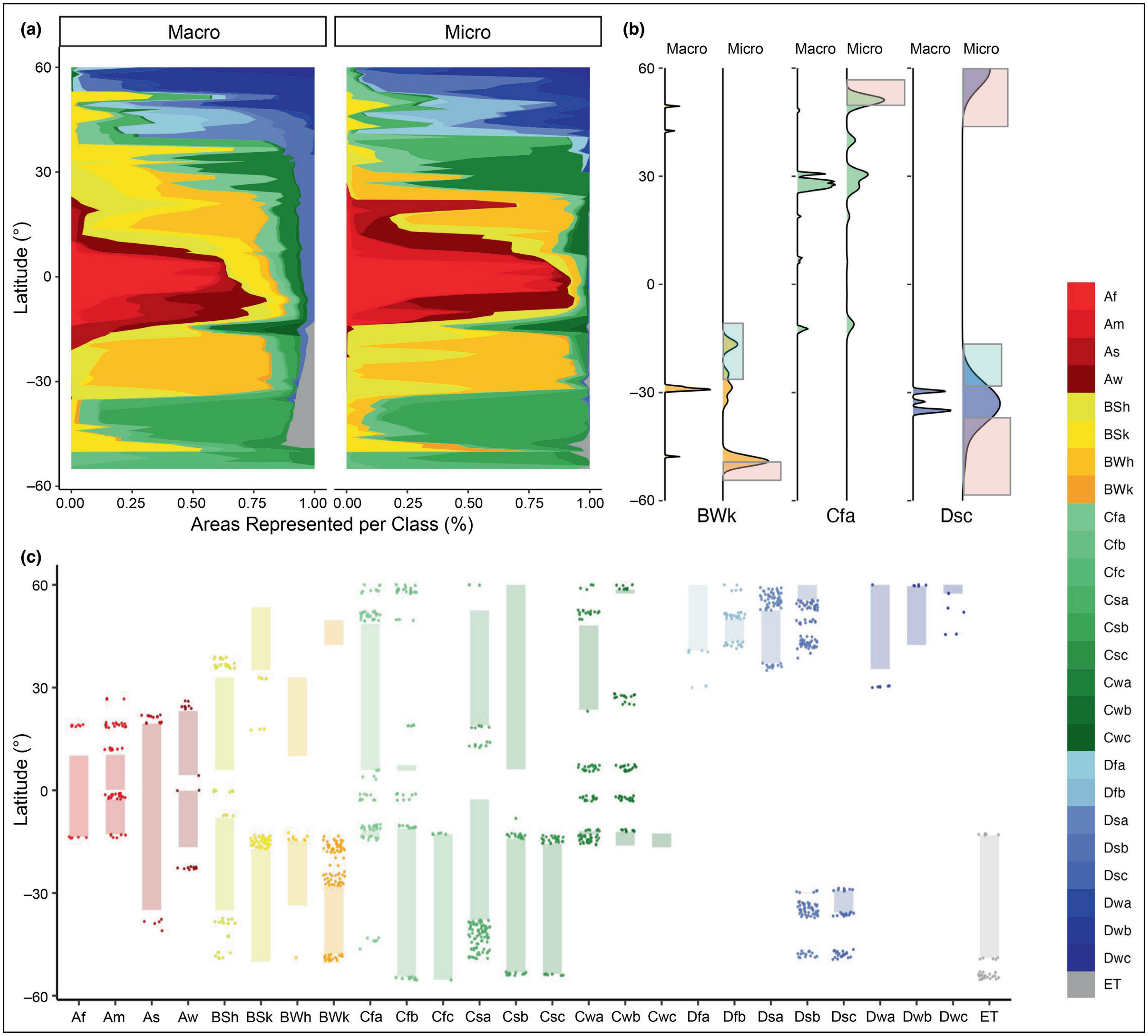

Figure 2. The latitudinal distributions of KG classes near the Earth's surface differ from the distributions of macroclimate-derived KG classes. (a) Density plots of each KG class across latitude as derived from macroclimate and microclimate. (b) Density plots of three example classes (BWk, Cfa, and Dsc) that demonstrate poleward extensions (shaded in pink) and equatorward extensions (shaded in light blue) of microclimate relative to macroclimate. (c) Microclimate extensions occurred for almost all KG classes. Lightly shaded bars are distributions of each macro-derived KG class in northern and southern hemispheres, with microclimate extensions represented as points above and below shaded bars (to reduce point density, each point represents all microclimate grid cells within 0.1° latitude of one another). Note that only the KG classes predicted in latitudinal strips by both macroclimate and microclimate are plotted in (c), and therefore classes Dfc, Dfd, Dsd, Dwd, and EF are missing.

microclimate predictions were extensions (ie fell outside the range of macroclimate predictions for the same class). Poleward extensions were more frequent, and of higher magnitude, than equatorward extensions (Figure 2). Wilcoxon tests indicated significant differences in latitudes between macroclimate and microclimate for all classes, with effect sizes ranging from very small (0.01, class Dwb "dry winter warm summer continental") to moderate (0.33, class As "savannah dry summer"; Appendix S1: Table S3).

For all study regions, micro-derived KG classes also consistently demonstrated higher spatial variability than macro-derived KG classes (Figure 3), even when microclimate was aggregated to the same spatial resolution as macroclimate (Appendix S1: Figure S2). Notably, the difference in spatial variability between micro- and macro-derived KG classes increased with spatial scale (Figure 3c).

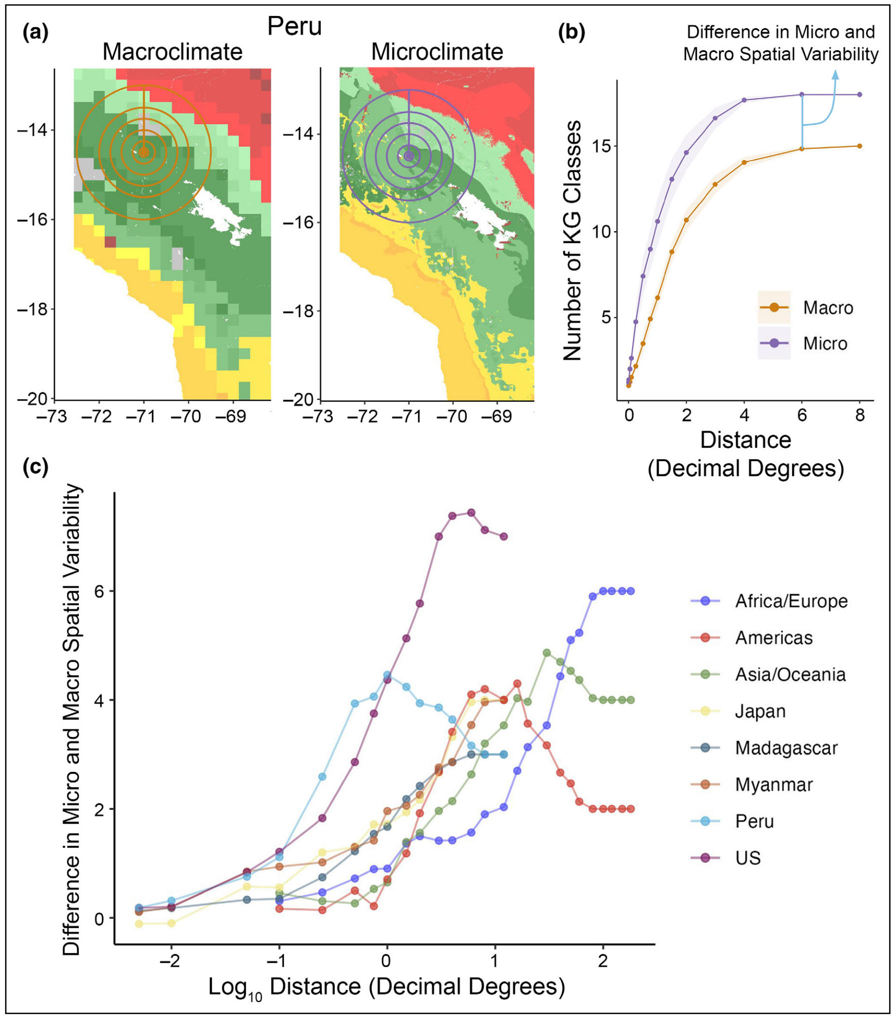

Figure 3. Predicting KG classes with microclimate results in higher spatial variability in classes than predicting KG classes with macroclimate, a trend that holds across spatial scales. (a) For each case study region and latitudinal strip (here, using Peru as an example), we quantified the number of KG classes within each of a set of increasing distances from a center coordinate (represented by concentric circles on maps), separately for microclimate and macroclimate, and then repeated this for 50 coordinates. (b) The mean number of classes for each distance (points), plotted with 95% quantiles (shaded ribbons surrounding points), demonstrates higher variability in micro-derived KG classes than macro-derived KG classes across spatial scales. (c) The difference in spatial variability between micro- and macro-derived KG classes for all study regions and latitudinal strips (plotted across $\log_{10}$ transformed distances) was almost always positive, indicating consistently more variability in micro-derived KG classes than in macro-derived KG classes. This difference also increased with spatial area (increasing distance), peaking for most regions at 10–25 decimal degrees (~1000–2000 km), suggesting that microclimate may play an important role for macroscale ecological responses to climate.

Discussion

Persistent disagreement between macroclimate- and microclimate-derived KG classes

Globally pervasive differences in the composition and configuration of KG classes were evident when derived from near-surface microclimate rather than from free-air macroclimate, even when both were calculated at the same spatial resolution. Given that most life on Earth experiences microclimates instead of ambient macroclimate, these discrepancies entail meaningful errors in knowledge drawn from prior macroclimate classifications. Transitioning to the next generation of micro-derived KG classes could aid biological research, conservation, and land planning.

The disagreement between macro- and micro-derived KG classes manifests in real differences in land use and agricultural suitability, as is clear in the Pacific Northwest of the US (PNW; Figure 4). Here, the regional cash crops of apples, wine grapes, and beer hops are specifically planted in classes BWk "cold desert" and BWh "hot desert", which are most suitable for these crops due to lower disease pressure (Smith 2001). Microclimate successfully predicted BWk and BWh for 23.8% of the land where these three crops are planted, while macroclimate predicted BWk or BWh for only 3.9% of such cropland. Notably, these crops were also planted in many locations categorized as less suitable by micro-derived KG class predictions, likely as crop planting is also determined by land ownership, policy, and proximity to infrastructure. Given that the PNW accounts for 99% of all US hops acreage (and 25% of global acreage), amounting to US$662 million in revenue in 2021 (Houston *et al.* 2018), the accuracy and scale of climate class maps used for interpreting present and future climate suitability can have substantial economic ramifications.

Microclimate expands latitudinal distributions of KG classes

We found that 86% (24/28) of KG classes had broader latitudinal distributions when derived using microclimate (Figure 2). Of these 24 classes, an average of 11.2% of the total surface area of each microclimate class fell outside the latitudinal range of that same class delineated using macroclimate. If this extension of KG classes across latitude remained constant across the terrestrial planet, then the global area of latitudinal extensions per KG class would be 232,555 km^2, or roughly the area of the state of Oregon (US) or the country of Ghana. Broader latitudinal distributions of micro-derived KG classes also suggested the need

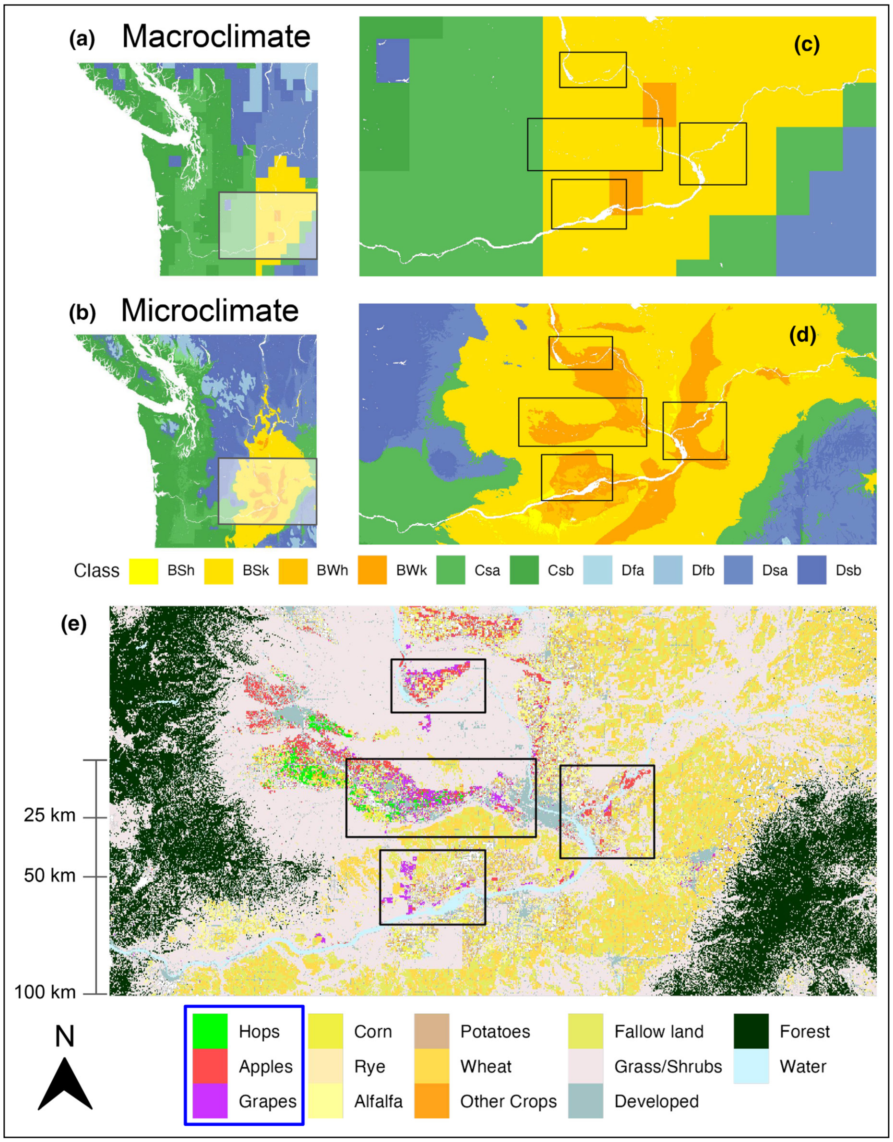

Figure 4. KG classes as predicted by microclimate more closely reflected actual landform and land use than did classes predicted by macroclimate. In the US Pacific Northwest, climate regimes at large scales are driven by distance to coasts, elevation, and latitude, which are generally reflected in class predictions by both (a) macroclimate and (b) microclimate. (c and d) However, as shown in insets from eastern Washington State, microclimate's higher spatial resolution and better proximity at representing near-surface conditions generate class discrepancies. (e) Within the Columbia River basin (center of [c] and [d] scenes), one of the most commercially important agricultural regions in the US, micro-derived KG classes more closely reflected fine-scale changes in agricultural land use (USDA NASS 2023). Microclimate predicts swaths of BWh "hot desert" and BWk "cold desert", which are the most suitable climate zones for planting hops used to brew beer, apples, and regional strains of wine grapes (noted with the outline of the blue rectangle in the key), given that desert-like conditions reduce pressure from disease-causing fungi and other crop pathogens. (c–e) Black rectangles indicate areas of cash crop production in BWk and BWh climates. Microclimate successfully predicted BWk and BWh climates for 23.8% of the land where these three crops are planted, while only 3.9% of such cropland was predicted as BWk by macroclimate (and macroclimate failed to predict BWh at all). Not all lands of suitable microclimate are planted with cash crops, in part due to constraints from residential development and irrigation. When predicting future land suitability for such climate-sensitive crops, relying on macroclimate may lead to inaccurate predictions (eg minimal future area of suitable regional climate despite many suitable microclimates) and risk losses in the billions of US dollars.

for some class rebranding. For instance, microclimates of class Cfa "humid subtropical" were abundant above 50° latitude, far beyond latitudes typically considered "subtropical".

For 64% of all KG classes, the equatorward latitudinal range limit of micro-derived KG classes extended further than the corresponding macro-derived KG class. These equatorward extensions generally entail cooler microclimates than the regional macroclimate and may thus provide refugia against contemporary climate change (Dobrowski 2011). Poleward extensions were even more prevalent (71% of all KG classes) and encompassed larger areas (Figure 2). Although these warmer extensions situated amid cooler regional climate may afford opportunities for certain agricultural crops, they may hinder dispersal of wild species tracking their thermal niches as the climate warms (Senior *et al*. 2019). Microclimates found beyond macroclimate latitudinal ranges may therefore either facilitate or disrupt species' responses to climate change.

Spatially variable microclimate across scales

Micro-derived KG classes had consistently higher spatial variability than macro-derived KG classes across scales (Figure 3), and this held even when microclimate was coarsened to match the resolution of macroclimate (Appendix S1: Figure S2). For our microclimate classes, the average distance from any cell to the nearest different major class was 4.14 km, whereas for macroclimate this average distance was 127.12 km. Climate classification systems have often been employed to group broad areas of the globe, yet when microclimate is considered, small extents of a few square kilometers may contain multiple classes. For example, the city of Cusco, Peru, represented six microclimate classes, ranging from tropical monsoon to Mediterranean warm/cool summer (Am, As, BSh, Cfa, Csa, Csb), while macroclimate predicted only one class here. Upgrading climate classifications by using microclimate may enhance city planning to reduce human thermal mortality, given different risks faced by those near urban green spaces than in urban heat sinks (Aram *et al*. 2019).

With such fine spatial variability in climate, many mobile organisms could easily traverse multiple micro-derived KG classes in a single day as a thermoregulatory response to climatic extremes (Woods *et al*. 2015). In addition, individuals of the same population may persist in separate KG classes, leading to local physiological adaptations. This also helps explain why the directions of species' range shifts often do not follow macroclimate gradients across elevation and latitude (Maclean and Early 2023) or why climate-sensitive species are less prone to extirpation in topographically heterogeneous locations (Suggitt *et al*. 2018).

Across continents, micro-derived KG classes were also more spatially variable than macro-derived KG classes. Across distances of 10,000 km, microclimates on average expressed four more KG classes than macroclimate (Figure 3), suggesting that microclimate is important even for macroecology. For instance, the difference in climate variability experienced by tropical versus temperate organisms, situated thousands of kilometers apart, may have more to do with what microclimates they occupy (eg forest understories versus open grasslands) than the change in macroclimate across latitude (Klinges and Scheffers 2021). We encourage further exploration of how microclimate shapes physiology, behavior, and evolution across broad scales (Kearney 2020).

Improving the utility of climate classification systems

Our study, in conjunction with growing evidence of the importance of biometeorology to ecology, suggests that macro-derived KG classes do not accurately reflect the composition, nor the configuration, of climate regimes as experienced by most life on Earth. These differences were not merely due to spatial resolution, as macro-derived KG classes did not match micro-derived KG classes even when at the same spatial resolution. Furthermore, it is well-known that microclimate varies vertically as well as horizontally. Climate classifications may therefore be more useful if developed in three dimensions rather than two, or at least if using climate measurements from the height(s) relevant to the target species and processes.

Climate classification approaches that are updated to capture ecologically relevant variation can help inform conservation and forecast the effects of climate change. Spatial variation in microclimate at both small and large scales points to its relevance when estimating climate connectivity or informing restoration to improve connectivity (Senior *et al*. 2019). Predicted changes in climate classes have been used to understand rates of climate change (Kottek *et al*. 2006) and climate impacts on future agricultural suitability (Wang *et al*. 2022), carbon stocks (Gibson *et al*. 2021), and human thermal comfort (Mishra and Ramgopal 2013)—yet all such work has relied on macroclimate. Using microclimate is paramount for establishing relevance of forecasts to most ecosystems and species, especially as microclimates may warm faster or slower than ambient macroclimate (Maclean *et al*. 2017; De Lombaerde *et al*. 2022). Given the dynamic nature of microclimates, especially in areas of rapidly changing land use, micro-derived KG classes may need to be updated regularly to maintain utility. Furthermore, new "ultra-tropical" or "ultra-desert" classes may need to be defined as the world experiences no-analog conditions (Trew *et al*. 2024). Although we urge caution when using climate classes derived from macroclimate, climate classification systems in general are still useful heuristics for simplifying multiple climate variables (eg temperature and precipitation) into single categories, as well as for communicating where and when consequential changes in climate occur (ie a shift from one class to another).

Conclusion

When compared to their macroclimate-derived counterparts, microclimate-derived KG classes are consistently different and have higher spatial variability across scales. Moreover, not all "tropical" and "polar" classes are found solely in the tropics or near the poles, respectively, thereby necessitating a redrawing of the boundaries of climate classes across the planet. Macroclimate remains adequate for understanding the climatic "backdrop" of a region, but researchers and practitioners must use caution when assuming that all species within a given macroclimate-derived KG class experience similar climate regimes. Most climate-relevant management decisions, such as planning cities or planting crops, are also best informed by microclimate data. The influence of microclimates on ecosystems and species distributions is neither ephemeral nor only felt at local scales and may greatly impact macroecology. By recognizing the unique patterns and broad consequences of microclimates, we can refine our understanding of multiscale climate-driven ecological dynamics.

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Data Availability Statement

ERA5 data (Hersbach *et al*. 2023) are available in the Copernicus Climate Change Service (C3S) Climate Data Store (CDS) at https://doi.org/10.24381/cds.adbb2d47. Raw data, code, and microclimate modeling software (Klinges 2024) are available in Zenodo at https://doi.org/10.5281/zenodo.8372920.

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Supporting Information

Additional material can be found online at http://onlinelibrary.wiley.com/doi/10.1002/fee.2831/suppinfo