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Standardised drought indices in ecological research: why one size does not fit all

Running title: Drought indices in ecological research

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Defining and quantifying drought is essential when studying ecosystem responses to such events. Yet, many studies lack either a clear definition of drought, and/or erroneously assume drought under conditions within the range of “normal climatic variability” (c.f. Slette et al., 2019). To improve the general characterization of drought conditions in ecological studies, Slette et al. (2019) propose that drought studies should consistently relate to the local climatic context, assessing whether reported drought periods actually constitute extremes in water availability.

While we generally agree with their proposal, we argue that standardised climatic indices, such as the Standardized Precipitation and Evapotranspiration Index SPEI (Sergio M Vicente-Serrano, Beguería, & López-Moreno, 2010) as highlighted in Slette et al., cannot be recommended as stand-alone criteria for drought severity, especially when applied in a global context. We base our critique on three major points: (1) standardisation can lead to a misrepresentation of actual water supply, especially for moist climates, (2) standardised values are not directly comparable between different reference periods, (3) spatially coarsely resolved data sources are unlikely to represent site-level water supply.

Due to standardization with respect to local conditions, negative index values always signify dryer than average conditions, while positive values represent wetter than average conditions. Yet in both cases, an index value alone cannot tell if the ecosystem under study is experiencing water shortage or surplus, as revealed by the synopsis of SPEI with the corresponding difference between potential evapotranspiration and precipitation (P-PET, Figure 1, Figure S1). A direct comparison of SPEI with P-PET underlines that negative SPEI values do not quantify water shortage (i.e. P-PET < 0) per se; a picture which is consistent but systematically shifted for dry (mean P-PET < 0) and moist (mean P-PET > 0) climates (Figure 2), with substantial differences across biomes (Figure S2). Consequently, interpreting SPEI uncritically as a drought indicator across ecosystems can lead to erroneous interpretation of ecosystem responses to climatic variability. A recent example is the global application of SPEI to quantify the effect of drought on the end of season dates in terrestrial vegetation phenology (Peng, Wu, Zhang, Wang, & Gonsamo, 2019), where spatial variations of mean annual SPEI are misinterpreted as a water balance gradient (see their Figure 7). Moreover, in their study, as well as in other studies correlating time series of ecosystem response with a standardized climatic index over a large geographical extent, sign changes occur in the correlation between ecosystem response and the index (Chen, Werf, Jeu, Wang, & Dolman, 2013; Sergio M. Vicente-Serrano, Camarero, & Azorin-Molina, 2014). We argue that in regions where a negative index value does not directly correspond to the organismic experience of water shortage, variability in the index does not predominantly reflect the drought status of the corresponding ecosystems. Similar issues exist with other standardized indices, such as the scPDSI (Wells, Goddard, & Hayes, 2004; Figure S3). The described decoupling between standardised drought indices and ecosystem response to drought is widely acknowledged in tropical ecology, where non-standardised drought metrics, predominantly the Maximum Climatic Water Deficit, are preferred (e.g., Lewis, Brando, Phillips, Heijden, & Nepstad, 2011).

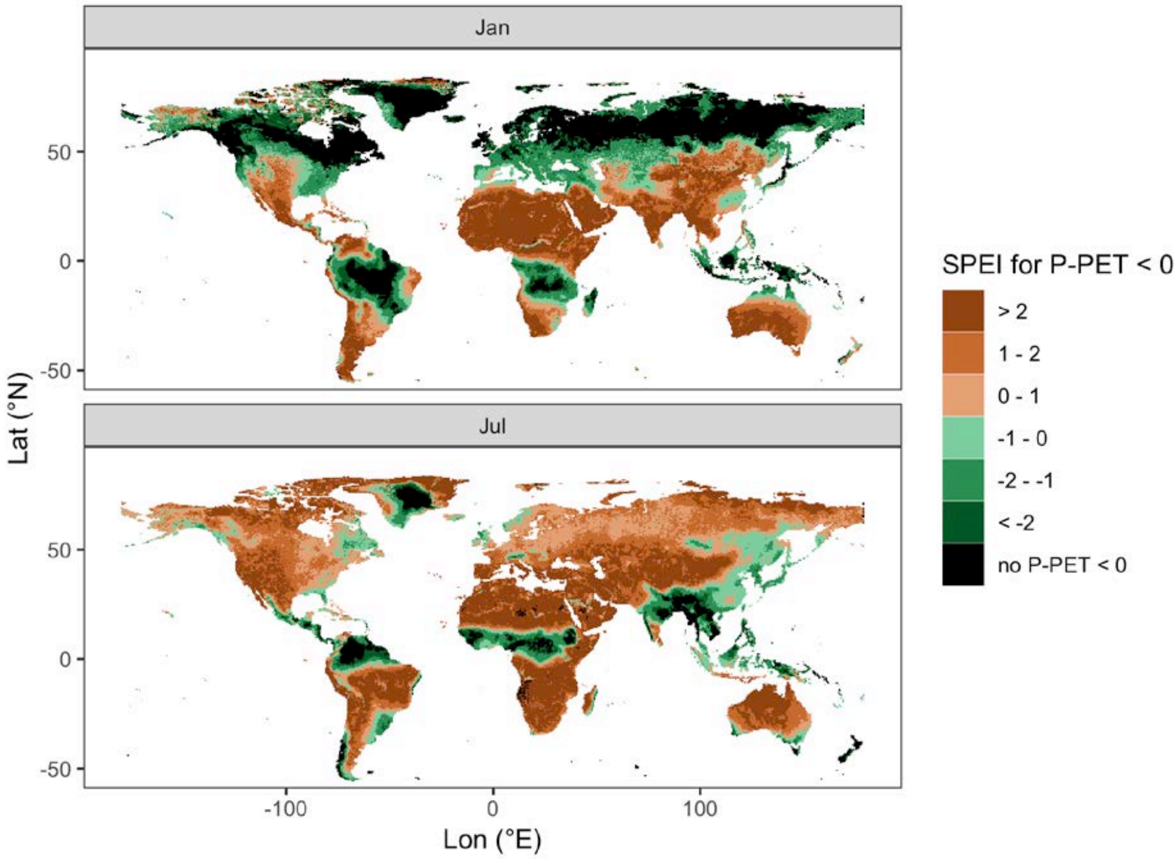

Fig. 1 *Representation of water supply by a standardized drought index (SPEI1: SPEI at 1 month integration): critical SPEI values for January and July that mark the transition from negative to positive P-PET, i.e. from water shortage to water surplus. Note that depending on season and climate zone, SPEI values between -1 and -2, referred to as "moderately dry" to*

"severely dry" by Slette et al. 2019, do not correspond to acute water shortage (dark green colors). In large parts of the boreal zone and the tropics, negative SPEI values never indicate water shortage since P-PET does not reach negative values (black colors). This pattern changes across months as a consequence of monthly standardisation; an extended map covering all months is provided with Figure S1. SPEI1 is extracted from the Global SPEIbase v2.5 (Vicente-Serrano, Beguería, López-Moreno, Angulo, & El Kenawy, 2010), *P-PET (sometimes referred to as climatic water balance; Stephenson & Das, 2011) is computed as the difference between precipitation and potential evapotranspiration (both from CRU TS 3.24.01, Mitchell & Jones, 2005, the data set underlying SPEIbase v2.5). We focus on SPEI1, since with increasing temporal aggregation, drought metrics based on P-PET lose biological meaning (Stephenson & Das, 2011).*

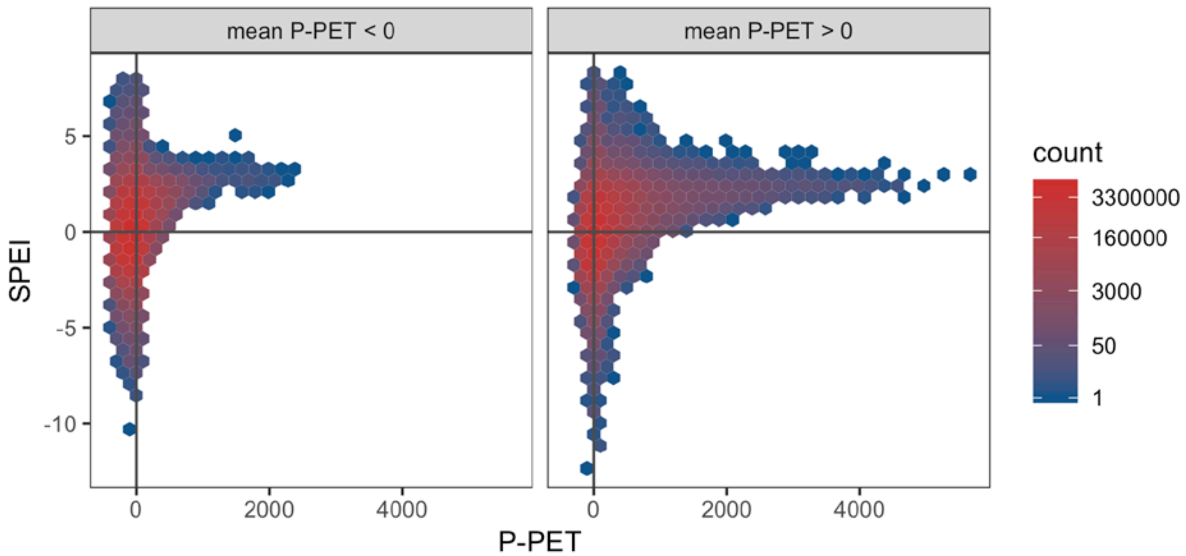

Fig. 2 *Comparison of monthly SPEI1 values and associated P-PET at the scale of one month across all grid cells and monthly time steps of the SPEIbase data set. In dry climates (mean P-PET < 0, left panel), 8% of observations with negative SPEI featured positive P-PET while 33% of observations with positive SPEI featured negative P-PET. In moist climates (mean P-PET > 0, right panel) these patterns were reversed, i.e. 27% (10) of observations with*

negative (positive) SPEI featured positive (negative) P-PET. We show point densities (counts per hexagon, colour scale is log10) due to strong overplotting.

In a spatio-temporal context, the demonstrated limitation of large-scale applicability of standardized indices is aggravated by limitations in their temporal comparability. Since standardized indices are designed to reflect deviations from the mean state of a given drought metric (e.g. P-PET in the case of SPEI), their individual values depend on the distribution of all values in the reference period. As a consequence, retrospective evaluation of past drought events is systematically biased by climatic trends affecting the distribution of drought values in the reference period (Figure S4).

Finally, Slette et al.'s recommendation to validate site-level water shortage for a given study site using easily accessible, but spatially coarsely resolved data sets, such as SPEIbase, can lead to substantial mischaracterisation of drought severity. As an example, P-PET of 95% of German weather stations varies by -70 to +126 mm in comparison to the nearest 0.5° SPEIbase grid cell (Figure S5).

Consequently, it is not enough to report standardized climate index values alone in drought studies. In addition to considering the anomaly experienced by the system (as measured by a standardised index like SPEI), ecologists should also take into account the actual stress experienced, which could be estimated from P-PET or even better from the climatic water deficit, as the difference between PET and actual evapotranspiration (Stephenson & Das, 2011).

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Additional **supporting information** may be found in the online version of this article:

Figure S1: Representation of water supply by a standardised drought index (SPEI).

Figure S2: Percentage of biome area for which SPEI1 <= -2 does not indicate negative P-PET, by month.

Figure S3: Representation of water supply by a standardised drought index (scPDSI).

Figure S4: Difference of SPEI1 (SPEI on a 1 month time scale) between the reference period 1901-1980 and the reference period 1901-2015 for Sierra Valley, California, USA.

Figure S5: Mean differences of P-PET (mean Delta P-PET) estimates as derived from DWD (German meteorological service) climate station data as well as gridded climate products.