

Quantifying Heatwaves' Contemporary Association with Continental Biodiversity

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Abstract. In recent years, extreme high temperature events have created great threat to humanity and socio-economy. However, a comprehensive evaluation on the degrees to which ecosystems are affected by heatwaves is yet to be fully resolved and becomes a hot-spot in climate and ecological research. This study aims to quantify the relationship between global heatwave occurrence and environmental indicators such as continental biodiversity quantified by the Living Planet Index, thereby generating a way to understand the extent to which future heatwaves may impact the planet. Analyzing global meteorological data from the last 43 years (1980-2022), heatwave definition is standardized to daily maximum temperatures over the 90th percentile (threshold), with a consecutive occurrence of at least three days, in the 1981-2010 climatological period. A significantly strong, negative correlation (coefficient of determination=0.766) between the occurrence of the standardized heatwave and continental biodiversity is established through Pearson correlation analysis and linear regression, followed by Student-t test. This research provides the scientific community a better comprehension to the variability of heatwaves during the past decades over global continental regions. Through diagnosing the heatwave-biodiversity relationship and the underlying mechanism of how extreme temperature events impact ecosystems, this research will shed light on a better solution to alleviate the impact of heatwaves on biodiversity, or better, to alleviate global warming purposefully.

Keywords: heatwave; biodiversity; extreme weather; global warming; Living Planet Index.

1. Introduction

Heatwaves are periods of abnormally and uncomfortably hot and usually humid weather [1]. Heatwave is emerging as a research hot-spot in the science community: studies have inspected the impact of recent heatwaves on indicators of the economy [2], [3], and human mortality [4]. The impact of future heatwaves on human health would also likely be profound unless efforts are made to cut carbon emissions [5], and, presumably, to effectively mitigate climate change. Current anthropological climate change has been triggering biodiversity crisis in many parts of the world [6], [7], [8]. Specifically, the risk of species extinction increases with every degree of warming [9] the extent and integrity of natural ecosystems, distinctiveness of local communities, size and geographical spread of plant and animal populations, number of species, and the intra-specific genetic diversity of wild and domesticated organisms have all decreased in the past five centuries; this decline features a scale coinciding with step changes in globalization and economic mercantilism [10].

While a great number of studies have attempted to determine the impact of global warming on biodiversity and/or the impact of heatwaves on biodiversity in a certain region or of a single species [11], [12], [13], [14], less research studies have focused exclusively on the quantification of extreme high temperature events (i.e., heatwave) on a larger scale and have not compared the extent to which heatwaves impact biodiversity in different regions.

Hence, this study aims to quantify the correlation between terrestrial heatwave and biodiversity across continents and time. This study will (1) generate a globally comparable set of historical terrestrial heatwave statistics (oceans excluded) and (2) associate it with biodiversity. With an established correlation between the two factors, potential influences of heatwaves on biodiversity loss can be better addressed and inter-compared across regions.

Remainder of this manuscript is structured as follows: data and methods used in this study will be discussed in Section 2, including the specific standardized definition of heat-waves; results of global historical changes of heatwaves during 1980-2022 will be presented and discussed with respect to biodiversity loss in Section 3, followed by a conclusion in Section 4 summarizing the study's key findings, potential socio-environmental contributions, and limitations.

2. Data and Methodology

2.1. Data Description

To estimate the global changes of heatwave, daily maximum temperature data is obtained from Climate Prediction Center (CPC) globally unified temperature data produced by NOAA Physical Science Laboratory, a set of 2m surface temperature dataset from 1980 to 2022 gridded to 0.5×0.5 degrees resolution (link: <https://psl.noaa.gov/data/gridded/data.cpc.globaltemp.html>). The Living Planet Index (LPI) data produced by Zoological Society of London and WWF (link: <https://livingplanetindex.org>) is applied in this study to examine the relationship between heatwave and biodiversity. This index contains 5270 species spanning 48 years from 1970 to 2018. LPI has been proven to have low bias on vertebrate species [15] and reflects substantial declines in biodiversity over the last decades despite a proposed 9.6% error introduced by random population fluctuations [16].

Table 1. Various Heatwave Definitions in Different Countries or Institutions

Country/ Region/ Institution	Temperature History Time Period	Months Included	Minimum Duration (days)	Determinants	Relative Position in Temperature Distribution
China (NCC)	1996-2005 (May to September)	All	n/a	Tmax	50th percentile among data points with Tmax>33 degC
US (EPA)	1895-2021	All	4	Tmean	Once every 10 years (85th percentile**)
UK (Met Office)	1981-2010* (July 15th only)	All	3	Tmax	n/a
India (IMD)	1981-2010	All	2	Tmax	4 5 degC above normal
Europe (EDO)	1981-2010	April to September	3	Tmax, Tmin	90th percentile in temperatures of 1981- 2010
Australia (BOM)	Last 30 days	All	3	Tmax, Tmin	n/a

2.2. Heatwave Standardization

There are two major definitions of heatwaves with absolute thresholds and relative thresholds based on percentile estimates. As shown in I, among countries and institutions, heatwaves are also commonly defined with the relative percentile of a temperature in the climatology distribution and a minimum duration.

In the science world, comparative analyses such as those conducted by Perkins and Alexander on various heatwave definitions have shown the advantage of relative (percentile-based) heatwave thresholds over absolute temperature thresholds on nondiscriminatory analysis of heatwaves across regions [17]. The preferred methods are shown to have used the 90th percentile in respective climatology as the daily maximum temperature (Tmax) (and the 10th percentile for daily minimum temperature (Tmin), if included) threshold value(s), and often include a duration measure (of at least three consecutive days) [18].

Hence, combining effective definitions utilized before, the 90th percentile threshold of the daily Tmax 1981-2010 climatology distribution is applied to define heatwave of a specific location in this study. A heatwave event is thus identified when daily Tmax exceeds the threshold over at least three consecutive days. This discussion does not include oceanic regions and analysis to marine biomes, so ocean regions are masked prior to processing. In operation, Antarctica is also excluded since a biodiversity index capable of performing a globally comparable analysis including this lone cold continent is yet to come to existence. Heatwave data is concluded from a Python 3.9 algorithm that calculates the respective temperature threshold values for each point on the grid and compare it to observational data. Tmax threshold value at each geographical location is calculated by applying an inverse to the cumulative density function of each time series of daily maximum temperature data from 1981 to 2010 (for every data point on the grid). Threshold values are then compared to observational data to generate an array of Boolean values. Among those exceeding threshold, a method is then introduced to remove non-consecutive heat days and only keep those that meets both criteria to be counted as a heatwave. This data is then stored into a netCDF4 dataset for next steps.

2.3. Correlation and Quantification

To quantify the relationship between changes in heatwave and biodiversity, linear regression and Pearson's linear correlation analyses are conducted. Considering that Living Planet index is constituted of several 1d time series featuring the change in biodiversity for each region respectively, this study first examined the correlation between descriptive statistics of global heatwave occurrence and continental biodiversity. The formulas for linear regression implemented in this study is given as follows,

$$Y_i = \beta_0 + \beta_1 X_i + \varepsilon_i \quad (1)$$

Where β_0 is the intercept and β_1 the linear coefficient, Y_i the biodiversity index (dependent variable) and $X_i = \mu_{H,i}$ the mean number of heatwave events (H) in a selected region, in a given year (i). The coefficient can thus be calculated by

$$\beta_1 = \frac{\sum(X_i - \bar{X})(Y_i - \bar{Y})}{\sum(X_i - \bar{X})^2} \quad (2)$$

and the intercept as

$$\beta_0 = \bar{Y} - \beta_1 \bar{X} \quad (3)$$

This study also attempted to correlate Living Planet Index with the full set of individual observations/model results based on the respective region in which the specific grid belongs to. They are then compared with each other to, in a sense, confirm and further elaborate on subcontinental association between heatwave and biodiversity. Each available grid in the dataset went through a bivariate correlation analysis process with the respective living planet index time series. Here, the function for the calculation of Pearson product-moment correlation coefficient (r) is shown below,

$$r = \frac{N \sum(X_i - \bar{X})(Y_i - \bar{Y})}{\sqrt{(\sum(X_i - \bar{X})^2)(\sum(Y_i - \bar{Y})^2)}} \quad (4)$$

Where r is the correlation coefficient, x is the heatwave frequency at year i ; \bar{X} is mean heatwave frequency across years; \bar{Y} is the mean of LPI, and n is the total number of data points within which proper bi variate correlation can be conducted.

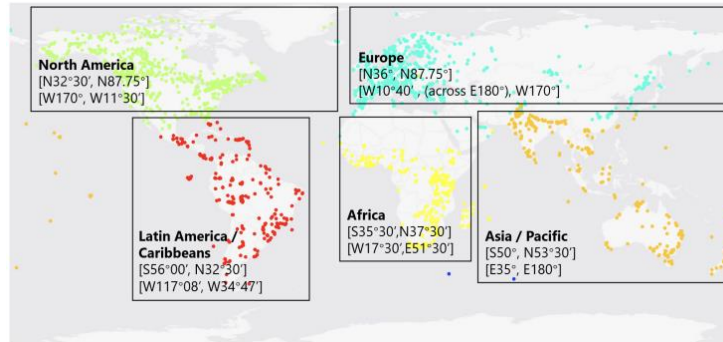


Figure 1. Geographical boundaries of five continental regions used during quantification of the Living Planet Index

Note: Boundary boxes are approximates of actual values. This figure is adapted from WWF & ZSL’s Map of terrestrial & freshwater populations in the Living Planet Database (link: <https://www.livingplanetindex.org/stats>). Only populations monitored in a specific location are plotted on the map.

The reliability and precision of the concluded correlations are then checked with a t-test for linear regression. In the series of significance tests, H_0 is an assumption that there is no relation between the correlated variables, while the alternative hypothesis (H_A) assumes a definite relation, regardless if positive or negative, between the two variables. t-values are obtained by

$$t = \frac{\beta_1}{\sigma_{\beta_1}} \quad (5)$$

Within which σ_{β_1} , the standard error of β_1 is obtained from

$$\sigma_{\beta_1} = \frac{\sigma}{\sqrt{\sum(X_i - \bar{X})^2}} \quad (6)$$

Results are organized into areas corresponding to their Living Planet Index regions. As specified in Figure 1. After converting geographic coordinates to grid coordinates, using the Rioxarray package, temperature data is matched to their respective geographic areas according to LPI’s separation of population type. These geographic areas include: Europe and Russia, Africa, Latin America and the Caribbeans, North America, and Asian and the Pacific (Oceania).

3. Results and Discussion

3.1. Existing Trends in Maximum Temperatures

Ever since the last century, there has been proofs for a strong equator-to-pole temperature gradient to exist on our planet, and some 30 years ago, Peixoto & Oort found that this phenomenon intensifies in the northern hemisphere during winter times [19] Observation revealed a difference in mean maximum temperature of over 25 degC between the equator and the arctics, and a significant trend is also present between the 90th percentile value, with both having a more drastic decrease in the Northern hemisphere than the South. Hence, although previous studies have shown that the accelerating climate change is reducing the seasonal impact of latitudes [20], this signature to the atmospheric temperature system was not changed yet.

In addition to maximum temperature values, trend in maximum temperature is also a point that has to be clarified before proceeding in this changing era. There are a few key regions such as in the Andes, southern African regions (in particular regions surrounding the Zambezi River, south of Lake Victoria), and west Australia that are more or less escaping from a great increase in temperature. These primary results confirm the validity of the heatwave definition implemented in this study.

3.2. Standardized Heatwave Trends

Inputting CPC globally unified temperature data and 90th percentile values into the aforementioned algorithm returns annual terrestrial heatwave event counts gridded to 0.5×0.5 resolution, whose mean over time is gridded in Figure 3a. Figure 3b reflects a general increase in heatwave occurrence over the last 43 years that correspond to trends revealed by previous studies [21], [22]. Hence, there is a high possibility that the generated heatwave occurrence results are generally precise. A few regions with an annual change in heatwave number over .2 has also been reported before to have significant increase in heatwave occurrence over the late 20th and early 21st century (e.g., South African Regions by Russo et al. [23]; Southeast Asia by Li [24]; Southeast Brazil by Geirinhas et al. [25], etc.).

Overall, by observation, Asia and Latin America are the two continents subjecting to the highest degree of heatwave increase, which is also reflected together with the generally increasing trend in mean terrestrial heatwave event counts around the globe and in regions shown in Figure 4a.

3.3. Correlation between Global Heatwave Occurrence and Biodiversity Loss

Applying formulae 1, 2 and 3, six linear models are obtained from a regression function between LPI and annual number of heatwave events in the respective regions (Figure 5). All resulting expressions show negative correlations between annual heatwave frequency and Living Planet Index, a measure of continental biodiversity, with the global mean number of heatwave events strongly correlating with global.

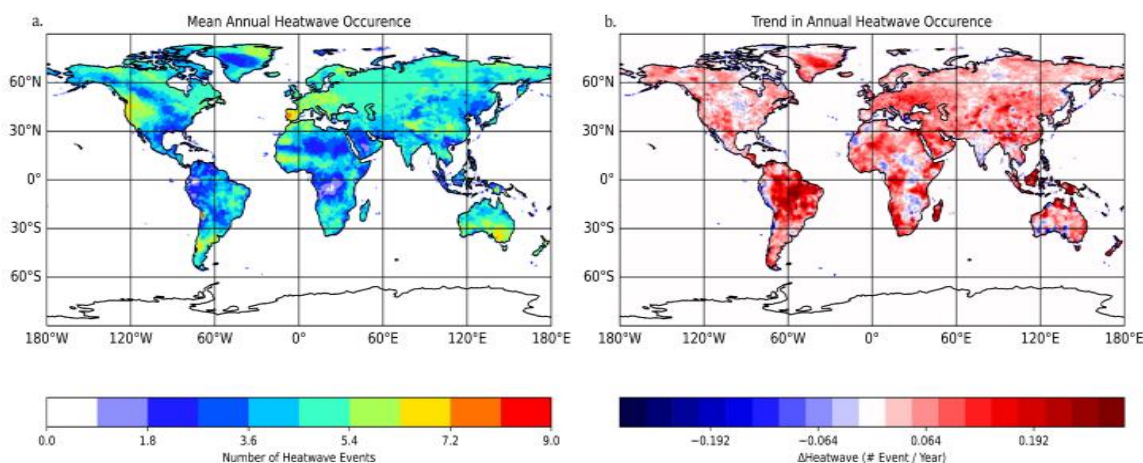


Figure 2. Global mean values (a) and trend (b) of number of annual heatwave event during 1980-2022 based on calculated Tmax thresholds

LPI (Coefficient of determination (R^2) = 0.727; Significant at 99% significance level via t-test for linear regression). Most regions pass their respective t-test for linear regression on 99% significance level as they feature p-value less than 0.01 (1E-2). Except for North America, other continents have an acceptable R-squared value of over 0.4. This might be influenced by region-specific factors as will be discussed later in this section. African heatwave occurrence has the largest impact on biodiversity, as its standardized linear coefficient (β_i) between area mean heatwave occurrence and biodiversity reaches a value of -0.726. This result is significant as its t-test for linear regression results in a t-value of 5.064 and a p-value of 3.983E-5 (less than 0.05).

More specific patterns between the level of biodiversity and heatwave occurrence are only concluded with Pearson’s correlation analysis (Formula 4) on each grid. Similar to geographic trends in temperature (Section 3.1) The degree of correlation (absolute values of correlation coefficients) between LPI and HWO are higher between latitudes 30degN to 30degS than the polar and sub-polar regions. This is potentially because reduced cold increases the organism’s chance of survival and reduce temperature extremity in sub- arctic ecosystems such as tundra [28] and taiga [29].

Comparing primary results in contemporary heatwave occurrence (Section 3.2), and the correlation map (Figure 4), the low degrees of correlation are, in most cases, observed to have two plausible causes. (1) One of them is region-specific behaviors disrupting continental mean HWO, often the occasion when regional heatwave occurrence decreased over time. For example, previously mentioned regions such as the Andes Mountains, the great plains of the United States, Northeast Canadian Regions and African regions with decreasing HWO often shares the location with the those with a positive Pearson correlation coefficient (r). Most of these positive trends associates with an overall decreasing trend of heatwave occurrence over the 43 years previously reflected by Figure 2b. (2) Regions such as Europe and Russia, on the other hand, does feature a substantial increase in Living Planet index despite the increase in heatwaves in the late 20th century. Previously mentioned peaking of bio- diversity around 1990 is acting as high leverage points in the correlation analysis (represented by highlighted data points in Figure 3b).

Hence, except for certain particular regions subject to the influence of other determinants capable of impacting regional biodiversity, within the context of global warming, heatwave negative correlates with LPI across multiple continents. This is consistent with previous studies conducted in marine and freshwater ecosystems [11], [12], [30], [31], and fits the general trends indicated by smaller-scale studies that focused exclusively on a certain region [13], [14]. But notably, there is a role of global warming in the increase of heatwaves that influences the impact of a unit of increase in heatwave frequency. In an additional analysis that features a dynamic summary period for historical climate (i.e., using temperature data of the respective decade to generate threshold values, which removes global warming’s influence on heatwave occurrence from the definition level), there is but only a slight increase to heatwave frequency. So, given the known influence of global warming on biodiversity mentioned earlier in this manuscript, this study does possess a caveat that it does not isolate the impact of global warming on heatwave occurrence.

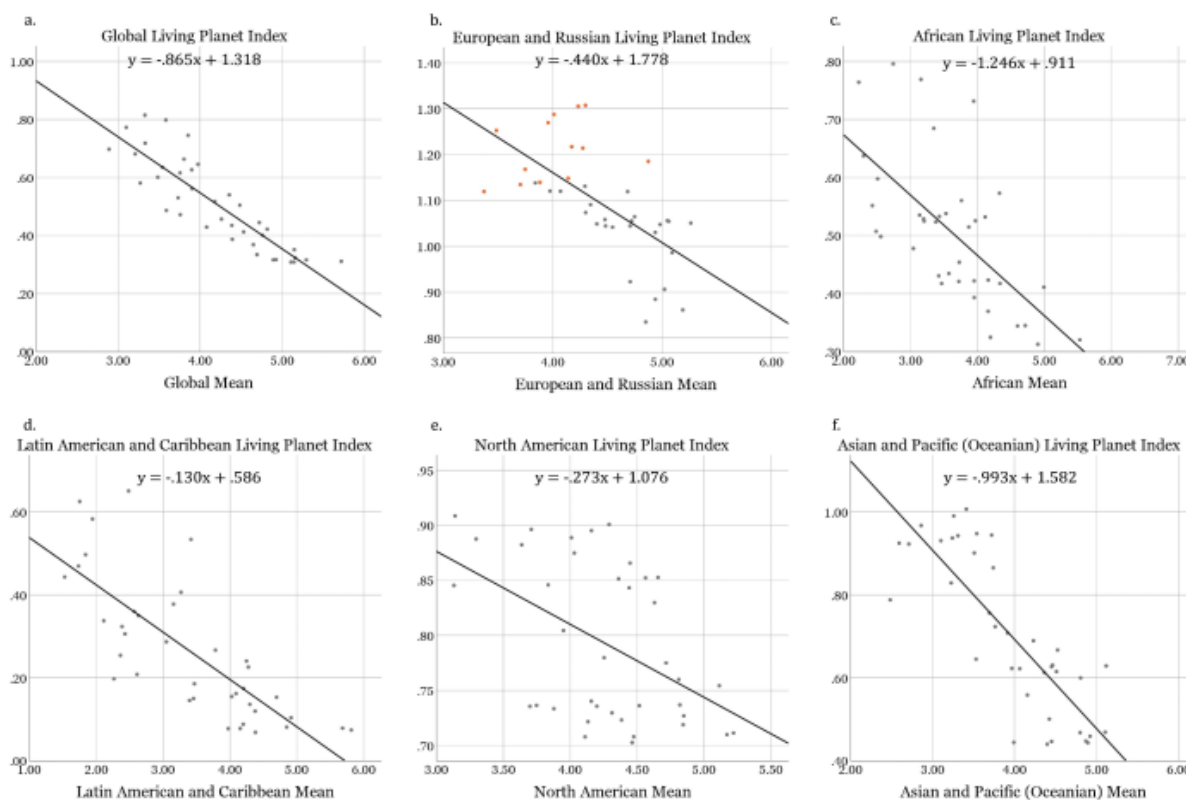


Figure 3. Scatter plots of LPI mapped to (a) global, (b) European and Russian, (c) African, (d) Latin American and Caribbean, (e) North American, and (f) Asian and Pacific (Oceanian) annual mean number of heatwave events

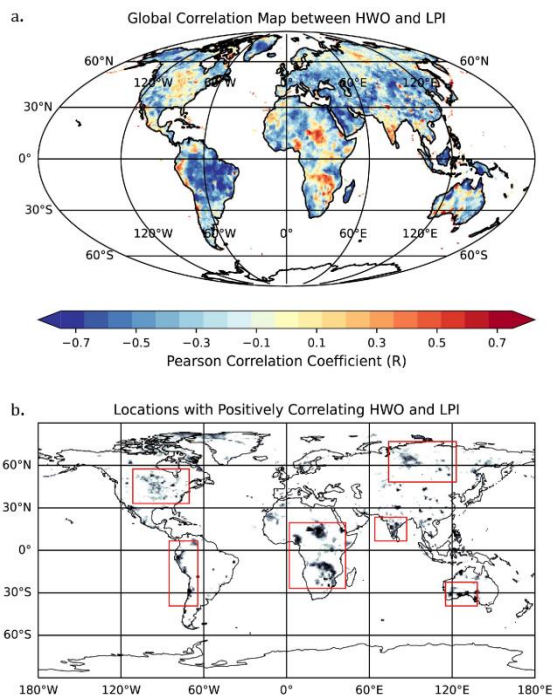


Figure 4. (a) correlation between final continental Living Planet Index time series and annual number of heatwave events gridded to 0.5x0.5 resolution. (b) locations with positive correlation between annual number of heatwave events and LPI derived from (a), with significant regions boxed in red

Table 2. Global and Regional Correlations Between Heatwave Occurrence and Biodiversity

Region	b	a	R ^{2*}	t ^{**}	p-value ^{**}
Global	-.853	.997	.727	-7.991	3.218E-8
Europe and Russia	-.634	1.805	.402	-3.935	6.608E-3
Africa	-.726	.719	.527	-5.064	3.983E-5
Latin America and Caribbean	-.689	.374	.475	-4.564	1.379E-4
North America	-.216	.841	.046	-1.059	3.005E-1
Asian and Pacific	-.643	1.107	.413	-4.024	5.306E-4

4. Conclusion

In this study, terrestrial heatwaves follow a similar pattern in that they all have a very high chance to negatively impact biodiversity in any area, with a strong influence of latitudes on the extent of the change: heatwave frequency has a higher correlation with the Living Planet Index values (a macro measure of biodiversity) in the equatorial tropics than in temporal and near-arctic regions. Through proved definitions, often-cited formulae and high geographic resolution, this study provides a platform for inter-comparison of regional results concluded by earlier studies.

Aside from primary and direct socioeconomic impacts revealed by previous studies (examples cited in Introduction), since the diversity around humanity were providing us essential and irreplaceable ecosystem services to humanity for thousands of years, quantifying the correlation between heatwave and biodiversity sheds lights on the secondary effects of heatwave occurrence. With it capable of affecting crop yield, soil quality and numerous ecosystem services essential to the survival of humanity [32], biodiversity loss impacts hard on humanity. But, compared to the skyrocketing increase in heatwave occurrence in vulnerable regions (Section 3.2), species are much slower in their adjustment to heat [33]. In another perspective, through examining the impact heatwave (together with other factors) are already capable of creating, this study also poses a warning: it is almost certain that only through actively alleviating the degrees to which environmental

degradation happen would a habitable environment be available to human in the near future. Here, effectuating time is a key determinant for solution/policy success, because “in the long run we are all dead. Economists set themselves too easy, too useless a task, if in tempestuous seasons they can only tell us, that when the storm is long past, the ocean is flat again”.

Uncertainty remains in this study, which requires further investigation. (1) Global warming is an influence factor that simultaneously impact both HWO and LPI, yet it is not ruled out of this study. Much analogous to putting a coefficient before the independent variable, heatwave occurrence is almost uniformly influenced by global warming, influencing the absolute extent to which it impacts biodiversity despite not harming comparability. (2) Heatwave severity and duration all change with respect to a changing climate [34], but this study only isolated number of heatwave events for analysis, with the impact of the other two factors remaining unknown. (3) The compiled data are highly summarized and is generated from rounds of smoothing and averaging, making the final numbers unsuitable for causation analysis: a major reason why only correlation, not causation, is analyzed in this study. As of now, this study explicitly examined the variability of heatwaves globally and their close relationship with biodiversity, thus shedding light on future warning system and preparation strategy with increasing frequency and severity of extreme weather, but in the future, the extent to which biodiversity is impacted by heatwaves in a stable environment, the macro (i.e., cross-regional/continental/global) impact of extreme temperature on a specific taxon, and the methods with which heatwaves impact biodiversity, are all possible topics for further investigation.

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