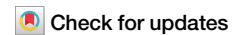


<https://doi.org/10.1038/s43247-024-01935-1>

Growing aridity poses threats to global land surface



Jordi Sardans^{1,2} , Albert Miralles^{1,2}, Akash Tariq^{3,4,5}, Fanjiang Zeng^{3,4,5,6}, Rong Wang^{7,8,9} & Josep Peñuelas^{1,2}

Global warming has impacted water cycle, but not exist a global study of the changes at global scale of the impacts on water available for plants. Here, cloud-optimized monthly aggregated climate reanalysis from the European Centre for Medium-Range Weather Forecasts dataset indicates that from 1960 to 2023, 27.9% of the global land surface became significantly more arid, while 20.5% became significantly less arid. This indicates a shift towards drier climates, with humid, semi-humid, and semi-arid areas decreasing by 8.51, 1.45, and 0.53 million-km², respectively, and arid and hyper-arid areas increasing by 6.34 and 4.18 million-km², respectively. This total increase of 9.99 million km² in arid areas represents 5.9% of the global land surface, excluding Greenland and Antarctica. Accelerated aridification has occurred in already dry regions, such as South-west North-America, North-Brazil, the European-Basin, North-Africa, the Middle-East, the Sahel, and central-Asia, with central-Africa as a new hotspot. The main driver is the disproportionate increase in potential evapotranspiration relative to rainfall, attributed to rising atmospheric temperatures, which also reduces the land's carbon sink capacity, potentially exacerbating climate warming.

In the current scenario of global warming, it is crucial to have consistent information regarding changes in climate aridity on a global scale¹. Understanding how the global arid land surface is evolving is essential for understanding its impacts on fundamental environmental variables such as global Net Primary Productivity (NPP), biodiversity, and human well-being². While some studies report increased greening in land surfaces regionally and globally, others observe a rise in browning areas alongside decreasing greening³. The rise of CO₂ can stimulate plant productivity through a fertilization effect and improve water-use efficiency, although plants also acclimate to increased atmospheric CO₂ concentrations^{4–6}. Moreover, the rise of other limiting factors such as nutrients and water also limits this CO₂ fertilization effect and contributes to this acclimation over time^{5,7–9}. Additionally, there is a general rise in evapotranspiration¹⁰ and a potential global change in rainfall intensity and frequency¹¹, with multiple consequences ranging from negative impacts on NPP due to the destructive impacts of increased frequency and intensity of tropical hurricanes¹² to the positive effect of increased rain in some regions, mainly in temperate

areas^{13,14}. Increases in evapotranspiration have been identified as the primary cause of the observed rise in aridity in some regional studies and on a global scale. However, shifts in aridity are not uniform, as different regions and arid ecosystems have demonstrated heterogeneous responses to recent climate changes. For instance, while greening and shrub encroachment have been observed in areas such as the Sahel, Tibetan Plateau, and the Western United States, vegetation cover has declined in dryland systems of other regions, including the southwestern United States, southern Argentina, Kazakhstan, Mongolia, Afghanistan, and parts of Australia. From a climate perspective, the overall impact on global plant cover is largely determined by the interplay between the positive effects of elevated atmospheric greenhouse gases and temperature, and the negative effects of increased aridity, primarily driven by higher evapotranspiration.

Consequently, the expansion of arid lands may diminish the buffering effects of increased CO₂ on climate change by reducing plant productivity. In fact, under increasing temperatures, the rise of vapor pressure deficit frequently counteracts vegetation growth due to CO₂ fertilization¹⁵. Thus,

¹CSIC, Global Ecology Unit CREAF-CSIC-UAB, Bellaterra, Catalonia, 08193, Spain. ²CREAF, Cerdanyola del Vallès, Catalonia, 08193, Spain. ³Xinjiang Key Laboratory of Desert Plant Roots Ecology and Vegetation Restoration, Xinjiang Institute of Ecology and Geography, Chinese Academy of Sciences, 830011 Urumqi, China. ⁴State Key Laboratory of Desert and Oasis Ecology, Xinjiang Institute of Ecology and Geography, Chinese Academy of Sciences, 830011 Urumqi, China. ⁵Cele National Station of Observation and Research for Desert–Grassland Ecosystems, 848300 Cele, China. ⁶University of Chinese Academy of Sciences, 100049 Beijing, China. ⁷Shanghai Key Laboratory of Atmospheric Particle Pollution and Prevention (LAP3), Department of Environmental Science and Engineering, Fudan University, 200438 Shanghai, China. ⁸IRDR International Center of Excellence on Risk Interconnectivity and Governance on Weather/Climate Extremes Impact and Public Health, Fudan University, 200438 Shanghai, China. ⁹Institute of Atmospheric Sciences, Fudan University, 200438 Shanghai, China. e-mail: j.sardans@creaf.uab.cat

we can expect a decrease in plant cover and an increase in aridity where temperature rise and evapotranspiration pressure surpass the positive effect of CO₂ on plant growth and WUE. These distinct and simultaneous effects, the general rise in evapotranspiration and CO₂ fertilization with opposite effects on aridity together with the patterns of rain are the direct causes that must drive future in general climate changes and aridity spread in the recent past and future¹⁶.

The causes of increased aridity are multifactorial and extend beyond global warming to include various human activities such as increases in water consumption, oil development, extensive water infrastructure projects, land use changes, land reclamation, land abandonment, fires, and overgrazing^{17–21}. Global warming can increase plant production and NPP, contributing to CO₂ storage in biomass (negative feedback on global warming) or diminish plant productivity and NPP by increasing extreme climate events²² or by increasing global aridity¹⁵. This underscores the need for consistent information on how global warming could impact global land aridity. It is imperative to understand how aridity is expanding on a global scale. We propose new research to investigate the global impacts of warming on land aridity, leveraging advanced technological tools that provide more accurate information on climate variables across all land sites without the need for interpolation.

The novelty of our approach lies in utilizing the ERA5-Land Monthly Aggregated—ECMWF Climate Reanalysis dataset from Google Earth Engine datasets as the primary source of global climate information spanning the past 63 years. This dataset includes monthly aggregates of Potential Evapotranspiration (PET), total precipitation, and temperature (measured at 2 m height) worldwide, with a resolution of 11,132 × 11,132 m per pixel, covering the period from January 1, 1960, to December 1, 2023. PET is calculated using the Penman–Monteith reference crop (PM-RC) equation, the best available estimation method for historical reanalysis that does not require parameterization of the CO₂ fertilization effect on vegetation dynamics and structure^{23–25}. Produced by the European Centre for Medium-Range Weather Forecasts (ECMWF), the ERA5-Land Monthly Aggregated dataset is generated through the ERA5-Land reanalysis system. This system integrates observations with advanced numerical weather models to create a consistent and comprehensive set of meteorological data. The data undergo rigorous quality control procedures to ensure their accuracy and reliability before incorporation into the reanalysis. The reanalyzed meteorological data are aggregated monthly and subjected to thorough validation, involving comparisons with independent observations and reference datasets to assess accuracy and reliability.

Given the impacts of global warming, it is imperative to understand how aridity is expanding on a global scale. We propose new research on the impacts of global warming on global land aridity, leveraging new technological tools that provide more consistent information on all land sites related to climate variables without the need for interpolation. Our hypothesis is based on energy balances, suggesting that the increasing energy captured by the atmosphere due to greenhouse gas increment causes a more general and symmetrical impact on evapotranspiration increase globally than on rainfall changes globally. This is because atmospheric warming is more homogeneous in space, whereas higher production of rainfall is not, as storms and anticyclones are asymmetrically distributed according to the general atmospheric circulation pattern²⁶. Thus, while evapotranspiration increases everywhere, rainfall maintains an asymmetrical distribution, potentially leading to significant changes in global land aridity distribution.

To verify this pattern of aridity change, we aim to evaluate changes in aridity year-by-year at a global scale from 1960 to 2023, disentangle the percentage of changes in the surfaces of different climate types based on FAO criteria, and detect potential long-term trends in aridity over this 63-year period. We follow FAO criteria, using the aridity index (AI) as the ratio between Mean Annual Precipitation (MAP) and Potential Evapotranspiration (PET). In this study, we included as arid lands: hyper-arid (AI < 0.05), arid (AI = 0.05–0.2), and semi-arid (AI = 0.2–0.5)²⁷. We use the 1-AI of such AI as the estimated aridity value, with larger values indicating

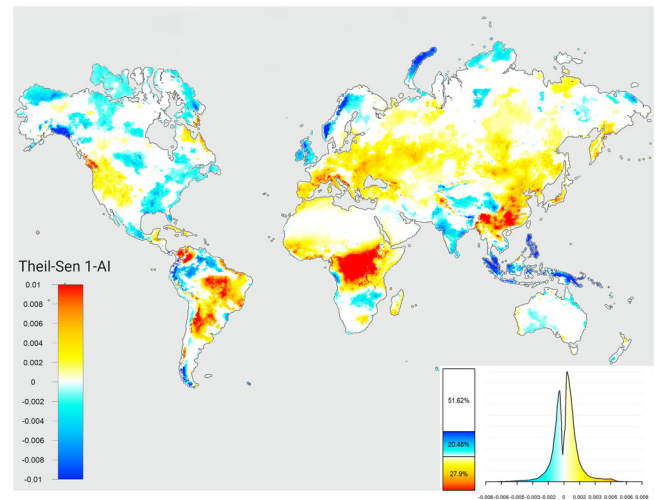


Fig. 1 | Changes in aridity in the period 1960–2023. Evolution of aridity in land areas at global scale in the period 1960–2022.

Global land (except Greenland and Antarctica) aridity changes from 1960s to 2012–2023

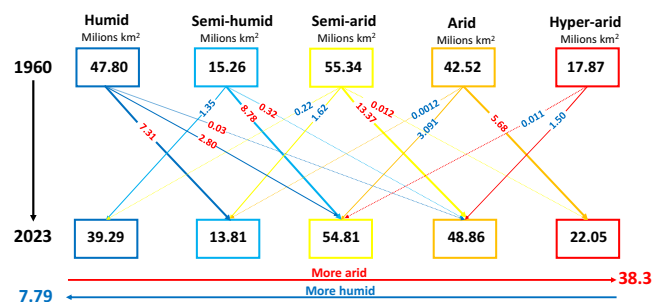


Fig. 2 | Global land (except Greenland and Antarctica) aridity changes from 1960s to 2012–2023. Squared km that have changed aridity level in the period 1960–2022.

greater aridity. Zones were defined as follows: hyper-arid (values between 1 and 0.95), arid (values between 0.95 and 0.8), semi-arid (values between 0.8 and 0.5), sub-humid (values between 0.5 and 0.45), and humid (values smaller than 0.45). Each pixel was classified into one of these zones accordingly.

Results

General patterns of aridity rise (1960–2023)

The results illustrating significant changes in aridity intensity across world regions over the past 63 years are depicted in Fig. 1. The intensification of aridity has spread across practically all regions that were already arid in 1960, such as Southwest North America, the Mediterranean Basin, North Africa, the Near East, the Sahel, North Brazil, and Central Asia. Central Africa has emerged as a hotspot for aridity increase, while some previously wet areas, such as the southeastern United States, have become more humid. The real increase is arid (+6.34), hyper-arid (+4.18) and semiarid (−0.5), in total a net balance of 9.99 more million km² from 1960 to 2023, which is a surface area similar to that of Canada.

Analyzing deeper into aridity changes and focusing on the changes among the five climatic areas, we observe that humid, semi-humid, and semi-arid areas have decreased by 8.51, 1.45, and 0.53 million km², respectively, whereas arid and hyper-arid areas have increased by 6.34 and 4.18 million km², respectively, from 1960 to 2023 (see Figs. 2 and 3). Thus, the results clearly show a net displacement from humid to more arid climates. In the case of hyper-arid lands, only 1.5 million km² have transitioned

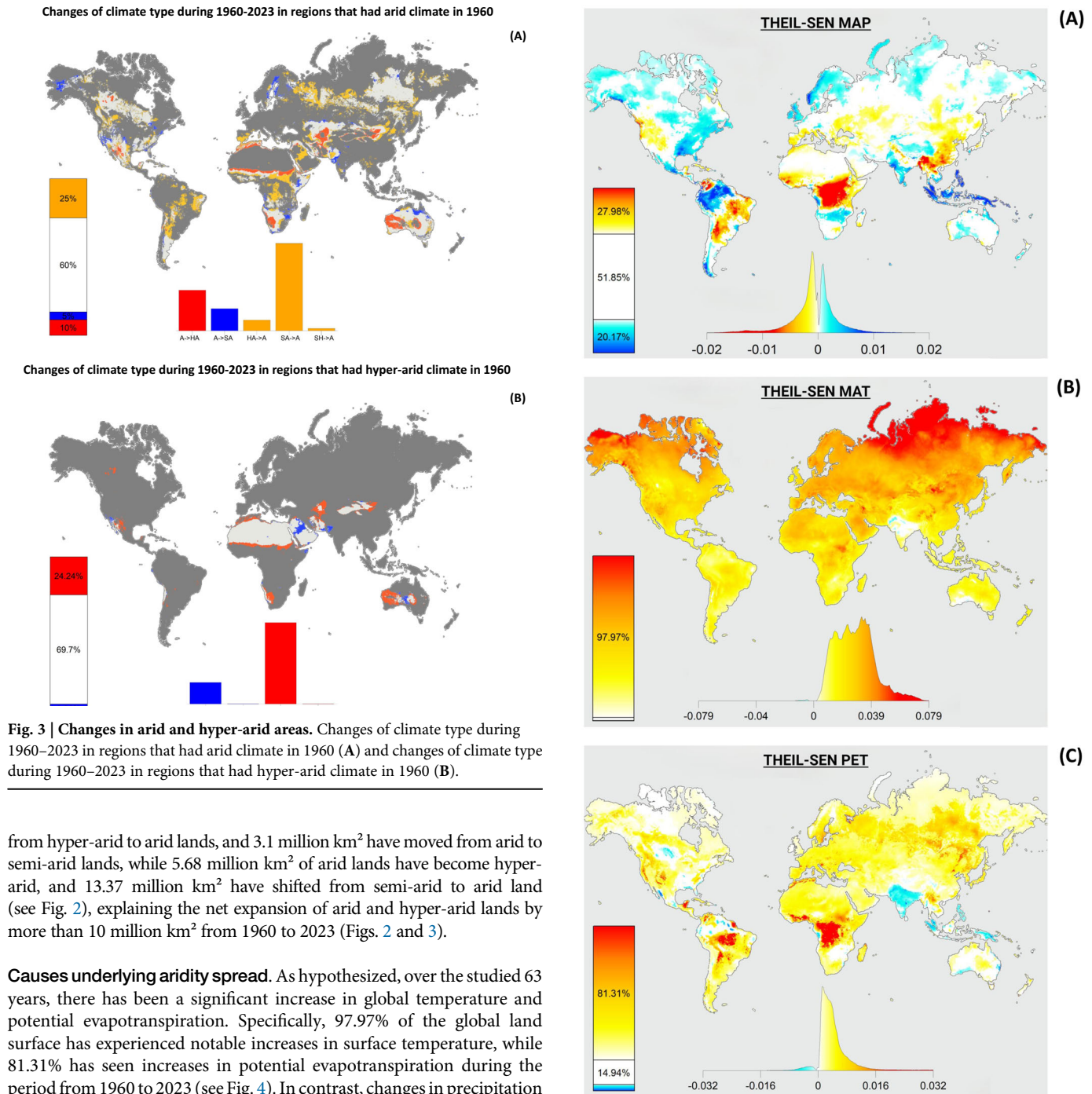


Fig. 3 | Changes in arid and hyper-arid areas. Changes of climate type during 1960–2023 in regions that had arid climate in 1960 (A) and changes of climate type during 1960–2023 in regions that had hyper-arid climate in 1960 (B).

from hyper-arid to arid lands, and 3.1 million km² have moved from arid to semi-arid lands, while 5.68 million km² of arid lands have become hyper-arid, and 13.37 million km² have shifted from semi-arid to arid land (see Fig. 2), explaining the net expansion of arid and hyper-arid lands by more than 10 million km² from 1960 to 2023 (Figs. 2 and 3).

Causes underlying aridity spread. As hypothesized, over the studied 63 years, there has been a significant increase in global temperature and potential evapotranspiration. Specifically, 97.97% of the global land surface has experienced notable increases in surface temperature, while 81.31% has seen increases in potential evapotranspiration during the period from 1960 to 2023 (see Fig. 4). In contrast, changes in precipitation have been highly asymmetrical worldwide: 20.17% of the land surface has become wetter, whereas 27.98% has become drier (Fig. 4).

Thus, the rise in evapotranspiration emerges as the primary cause of this expansion of aridity, with temperature increases identified as the main driving factor. This trend is largely linked to climate change, which has shown a strong correlation with rising temperatures. However, other factors related to human activities that directly impact the land also play a significant role.

The acceleration/deacceleration in aridity patterns. Focusing on changes in the rates of aridity change during the period 1960–2023, it is observed that in sites where aridity has increased the most, the rates of aridity increase have become higher over time (see Fig. 5). Conversely, in sites that have globally transitioned to more humid conditions during this period, the rates of becoming more humid have decreased over time (Fig. 5). In summary, our data analysis shows that,

Fig. 4 | Changes in the aridity components 1960–2023. Land areas with changes in MAP (A), MAT (B) and PET (C) during the period 1960–2022.

in general, the rates of aridification have increased globally during the studied period.

Discussion

The balance between areas that have become less arid and those that have become more arid and hyper-arid from 1960 to 2023 amounts to an increase of 10.52 million km². Utilizing the equation employed by major international agencies such as the FAO and the IPCC, alongside one of the most comprehensive climate databases available, raises an intriguing question regarding the increases in aridity over recent decades on a global scale. Additionally, a majority of these areas are experiencing an acceleration rather than a deceleration in this trend of increasing aridity.

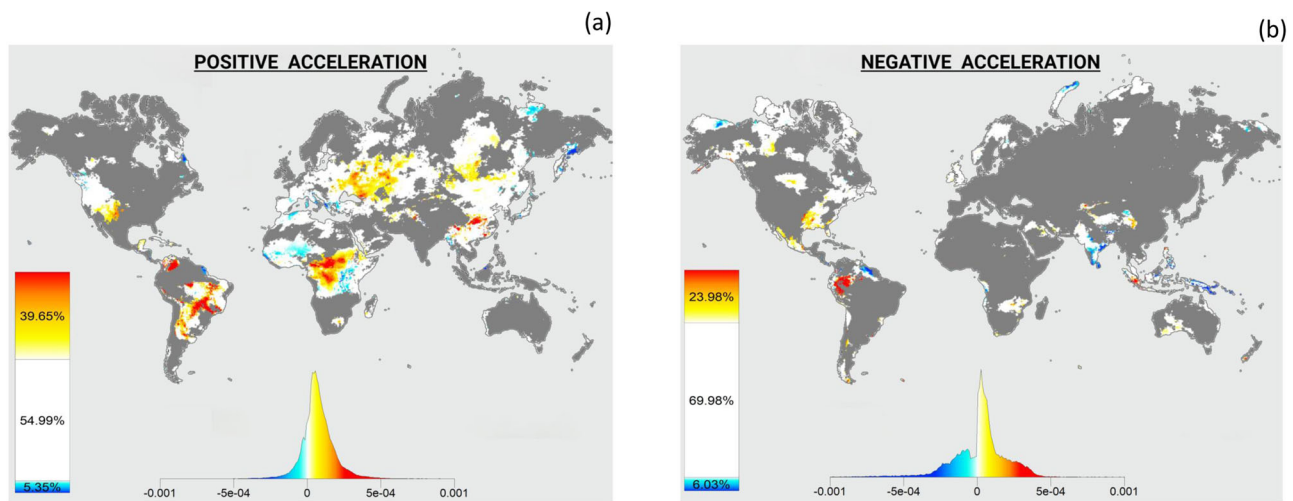


Fig. 5 | Acceleration of aridity rates. Land areas that have changed their aridity in increasing rate (a) or decreasing rate (b) during the period 1960–2022.

An examination of the territorial changes among the five climates along the aridity gradient reveals a global displacement of terrestrial land area from humid to arid and hyper-arid regions. Arid and hyper-arid lands now cover more than 10 million km² more in 2023 than they did in 1960. The primary direct cause of this significant shift towards more arid conditions lies in the increase of evapotranspiration, which has risen substantially everywhere, primarily linked to the general rise in atmospheric temperatures. In contrast, changes in precipitation are more unevenly distributed, resulting in a disproportionate increase in potential evapotranspiration compared to precipitation affecting a larger surface area.

Indeed, over the 63 years studied, evapotranspiration has increased on 97.97% of the land surface, while mean annual precipitation (MAP) has increased on only 20.17% of the land surface and decreased on 28.98% (Fig. 4). The increase in wetter conditions was primarily observed in currently wet climates, whereas the rise in arid conditions was mainly noted in currently arid, semi-arid, and semi-humid lands. This observation partially supports the “dry gets drier, wet gets wetter” (DGDWGW) paradigm²⁷. In a study of soil moisture trends using satellite-derived data, it was found that 30% of the global land surface significantly changed its soil moisture levels between 1979 and 2013. Of this, 22.16% became drier, while only 7.7% became wetter; furthermore, 52.69% of the drying trend occurred in dry areas, with 48.34% in wet sites²⁸. Similar findings were reported by Xiong et al.²⁹ in a recent study. Additionally, the terms “drier” and “wetter” are often used for different considerations, such as the presence of higher stocks or contents of hydroclimate variables, rather than reflecting a direct balance between precipitation inputs and potential evapotranspiration outputs at the pixel scale³⁰. Thus, using soil moisture to directly evaluate changes in aridity may not be suitable. Instead, potential evapotranspiration linked to temperature rise has proven to be the most significant variable in the increase of aridity. Therefore, from the perspective of land water balance—using precipitation as inputs and evapotranspiration as outputs—the overall correlation between global warming and aridity indicates a global increase in land surface becoming more arid, aligning with some recent studies³¹. Sherwood and Fu³² (2014) propose that on land, increased warming has a greater impact on air surface temperature and evaporation than on precipitation, which reduces the P/PET (precipitation to potential evapotranspiration) ratio due to enhanced land warming relative to oceans and decreased relative humidity on land. Thus, many regions may receive more rain, but few will receive sufficient moisture to keep up with growing evaporative demands. This observation is further consistent with previous studies. For instance, Huang et al.³³ noted that during the 20th century, surface warming over drylands (1.2–1.3 °C) was 20–40% higher than over humid areas (0.8–1.0 °C). Furthermore, several reports based on modeling and current data analyses project that the expansion of arid land will

continue until the end of this century, particularly if atmospheric CO₂ concentrations and global temperatures keep rising^{33,34}. Additionally, various modeling experiments conducted by Dai et al.³⁵ have shown that the surface drying effect of GHG-induced warming dominates over the wetting effect of plants’ physiological responses to increasing CO₂.

The observations generally align with the findings of Huang et al.³⁶, who reported a clear global increase in aridity affecting 1.6 million km², primarily in North America and Asia, using the REConstruction over Land (PREC/L) dataset. Similarly, a study by Feng and Fu^{37–41} (2015) utilized historical observations from over 17,000 gauge stations (from two large datasets: The Global Historical Climatology Network version 2 and the Climate Anomaly Monitoring System) to analyze aridity shifts between 1948–1962 and 1990–2004. They observed a clear global increase in aridity affecting 1.6 million km², predominantly in North America and Asia. Feng and Fu³⁷ also reported a 4% increase in the area of global drylands from the 1950s to the period 1991–2005, totaling ~2.4 million km². Notably, India has shown a unique trend, exhibiting a decrease in aridity over the past six decades, particularly in tropical and warm-temperate regions (Fig. 1). This change is attributed to a significant increase in irrigation, which has altered local hydrology. This finding is consistent with previous studies by Ambika and Mishra⁴², who documented a substantial decline in atmospheric aridity due to the intensification of irrigation in many regions of India from 1979 to 2018.

Specifically, Maity et al.⁴³ reported that sub-humid regions have increased by 6.3% between the pre-change point (1902–1951) and the post-change point (1982–2021), while semi-arid zones have been found to shrink over time in India. A report by Guhathakurta and Rajeevan⁴⁴ from the National Climate Centre of the Indian Meteorological Department (2019) concluded that, on average, India has experienced a wet period over the last 30 years.

Another region experiencing a significant decrease in aridity—largely due to an increase in precipitation⁴⁵, but also due to a surprising stability or minimal change in potential evapotranspiration despite rising temperatures—is a large part of Indonesia. This observation aligns with various local and regional studies that have reported an increase in precipitation in this area over the last few decades⁴⁶. Consequently, Indonesia is undergoing substantial changes, characterized by a rising population and extensive deforestation of tropical rainforests^{47,48}. The considerable deforestation occurring could, at least in part, explain this pattern^{49,50} of changing aridity, warranting further research, particularly as deforestation continues, albeit at a reduced intensity in recent years⁵¹.

The observed increase in aridity, particularly in regions such as the Mediterranean Basin, Southwest North America, North Brazil, the Sahel, Central Asia, the Middle East, and North Africa (MENA), is fully consistent

with most previous regional reports^{52–56} (Supplementary Note). Our findings also align with earlier studies that noted a more pronounced rise in temperature and evapotranspiration in boreal regions^{57,58}, which corresponds with expectations of rapid permafrost thawing⁵⁹.

One of the most threatened areas is South Africa, extending from the Congo to the Republic of South Africa. Recurrent droughts, influenced by the El Niño Southern Oscillation (ENSO), have significantly impacted this region. Average rainfall has decreased by ~25.6% between 1960 and 2007. In Central Africa, located to the north of this area, the most striking change in aridity detected over the past 63 years is a significant increase, corroborating the findings from the IPCC 2022 reports regarding temperature increases and decreases in precipitation. This underscores the urgent need for further research and action to address the consequences of deforestation and climate change.

The extensive deforestation that has occurred over recent decades in this region^{60,61} may contribute to the rise in aridity^{61–65}. Additionally, annual temperature anomalies indicating higher temperatures have been observed in the equatorial region of West Africa, linked to a drop in precipitation and an increase in evapotranspiration^{60,61}. Regarding the Congo rainforest, there is evidence of an increased dry season length of 6.4–10.4 days between 1988 and 2013, which has resulted in a reduction of rainfall during that period, potentially inducing a negative feedback loop affecting moisture provision for rainfall^{66,67}. This trend is particularly concerning, as this region is the second-largest tropical rainforest area in the world, with several potential feedback impacts on current climate change due to the demonstrated importance of African tropical forests in the global climate⁶¹.

Our study also observed an increase in aridity in southern Amazonia. Research analyzing changes in the length of the dry season in tropical areas has reported that southern Amazonia (due to a delayed end) and Central Africa (due to an earlier onset and delayed end) are hotspots for lengthening dry seasons, with greater certainty when factoring in changes in water demand⁶⁸.

While global warming is the main driver of this widespread increase in aridification, some local factors linked to human activities have also played a significant role. In regions of Southern Europe, North Africa, and Central Asia, excessive application of intensive agriculture has depleted aquifers, which, in combination with high livestock pressure and general resource over-exploitation^{68–70} has contributed to a reduction in plant cover and soil degradation^{71–73}. These factors have been observed to significantly reduce local and regional precipitation^{74,75}.

Conclusion

In the ERA5-land reanalysis, potential evapotranspiration (PET) is calculated using the Penman–Monteith equation, an energy-balance equation that requires a model for surface resistance due to vegetation. The Food and Agriculture Organization (FAO) proposed a reference crop model to efficiently estimate this parameter, making it a reliable and feasible method for climate analysis^{23,76}. This method is referred to as the Penman–Monteith reference crop (PM-RC) model.

In recent years, slight variations of the PM-RC equations have been developed to incorporate the expected CO₂ fertilization effect in the coming century^{24,73,77}. These variations introduce a dependence on vegetation dynamics and structure relative to atmospheric CO₂ concentration. However, they require new parameters to be approximated, which may introduce additional sources of uncertainty. Furthermore, some important relationships, such as differences between C3 and C4 metabolism and bulk ecological approximations for upscaling stomatal conductance models, are still not clearly modeled. These are parameterized through stomatal conductance and leaf area index (LAI), respectively. Stomatal conductance is predicted to decrease potential evapotranspiration (PET) and increase water use efficiency (WUE), while LAI is expected to increase PET through enhanced overall transpiration. The relationships of these new parameters, particularly their association with ecological resistance in the photosynthesis model (PM) equation, need to be approximated, which could introduce additional sources of uncertainty. Furthermore, some important relationships, such as those between C3 and C4 photosynthetic pathways, have not

yet been clearly integrated into these models. For accurate long-term projections, these additional parameterizations must be considered. However, for historical reanalysis, it is not appropriate to include them since the CO₂ fertilization effect is not prominent enough to offset the challenges and uncertainties introduced in the estimation procedure²⁵. This is particularly evident for drylands, where CO₂ concentration must increase significantly to overcome water demand constraints and influence vegetation surface resistance. Moreover, these new methods have yet to be integrated into large-scale, high-resolution reanalysis datasets.

Additionally, our definition of the Aridity Index (AI)—calculated as $(1 - (\text{mean annual precipitation}) / (\text{potential evapotranspiration}))$ —is resilient to minor errors in PET in areas with already high PET values (i.e., drylands), where the PM-RC model might produce inaccuracies. This can be demonstrated by taking the partial derivative with respect to PET, showing that it approaches 0 with quadratic velocity. This robust index, combined with a reliable Theil–Sen estimator, provides a confident trend analysis of the aridity index for our study.

Methods

Material

For the analysis, we utilized the ERA5-Land Monthly Aggregated—ECMWF Climate Reanalysis dataset from Google Earth Engine datasets as the primary source of global climate information spanning the past 63 years. This dataset includes monthly aggregates of Potential Evapotranspiration (PET), total precipitation, and temperature (measured at 2 m height) worldwide, with a resolution of $11,132 \times 11,132$ m per pixel, covering the period from January 1, 1960, to December 1, 2023. PET is calculated with the Penman–Monteith reference crop (PM-RC) equation, the best available estimation procedure for historical reanalysis where parametrization of CO₂ fertilization effect on vegetation dynamics and structure is not required^{23–25}.

Produced by the European Centre for Medium-Range Weather Forecasts (ECMWF), the ERA5-Land Monthly Aggregated dataset is generated through the ERA5-Land reanalysis system. This system integrates observations from various sources, including weather stations, satellites, and other data sources, with advanced numerical weather models to create a consistent and comprehensive set of meteorological data. The data undergo rigorous quality control procedures to ensure accuracy and reliability before incorporation into the reanalysis. The reanalyzed meteorological data are aggregated monthly and subjected to thorough validation, involving comparisons with independent observations and reference datasets to assess accuracy and reliability.

The study area encompassed six continents, excluding Antarctica, the North Pole, Greenland, and neighboring islands, totaling 1,450,532 sample points. From these datasets, we computed Mean Annual Temperature (MAT), Mean Annual Precipitation (MAP), and mean annual PET (MAPET). A new variable, $1 - \text{MAP} / \text{MAPET}$ (equivalent to $1 - \text{AI}$), was defined as a descriptor of the aridity index (AI). This new definition of the aridity index offers clarity, as it increases with aridity. Furthermore, it offers a buffer for possible errors in PET estimation, as the partial derivative of this new index with respect to PET approaches 0 quadratically as PET increases.

For statistical robustness and to avoid bias, we employed the Theil–Sen estimator for non-parametric trend analysis over the 63-year period for each pixel in our dataset for the four variables: MAT, MAP, PET, and AI. Hypothesis testing was performed using the Mann–Kendall correlation test, with the normality approximation for the null distribution ($n = 63$). For the AI variable, the analysis was also conducted for five typical AI zones. These zones were defined as follows:

- Hyper-arid: AI values between 1 and 0.95
- Arid: AI values between 0.95 and 0.8
- Semi-arid: AI values between 0.8 and 0.5
- Sub-humid: AI values between 0.5 and 0.45
- Humid: AI values smaller than 0.45

Each pixel was classified into one of these zones based on the median value of its temporal series between 1960 and 1980.

For all maps plotted, a bar plot displaying the number of increasing, decreasing, and zero Theil–Sen estimators was provided alongside a cross-validated kernel density estimation of the Theil–Sen slopes. To explore changes in the surface area of the five AI zones over time, two analyses were conducted: comparing the surface area of each defined zone with its current area and examining the transitions of pixels and areas between different climate zones. Additionally, to examine these changes in surface area for each zone continuously, the number of pixels belonging to each defined interval was quantified yearly, creating a temporal series for each AI zone.

Correlations between significant AI slopes and slopes of the other three variables (MAT, MAP, and PET) were assessed using Pearson (linear), Kendall, and Spearman (non-linear) correlation coefficients. Due to the large number of significant AI Theil–Sen slopes ($n = 748,768$), the estimated variance for these coefficients was small, leading to significant deviations from the null hypothesis of zero correlation. To further explore these correlations, ordinary least squares (OLS) estimators were computed pairwise and collectively. Given the high correlation between the explanatory variables, ridge regression was also performed to mitigate multicollinearity effects.

To examine how the predicted Theil–Sen slope of AI was distributed relative to the standard AI value, bivariate and percentile plots were generated for each AI zone. Additionally, the correlation between OLS error and AI value was computed to test for increasing variance in humid areas. Finally, to assess whether slopes were accelerating or decelerating with time, Theil–Sen moving windows of 20 years were computed, followed by the estimation of Theil–Sen estimators for these windows to calculate potential acceleration or deceleration (positive and negative accelerations) of these estimators in a non-parametric manner.

Data availability

All the data used in this study is available in: ERA5-Land Monthly Aggregated—ECMWF Climate Reanalysis dataset from Google Earth Engine datasets is available at: https://developers.google.com/earth-engine/datasets/catalog/ECMWF_ERA5_LAND_MONTHLY_AGGR.

Received: 22 June 2024; Accepted: 27 November 2024;

Published online: 19 December 2024

References

- Winkler, A. J. et al. Slowdown of the greening trend in natural vegetation with further rise in atmospheric CO₂. *Biogeosciences* **18**, 4985–5010 (2021).
- Chen, X. et al. The global greening continues despite increased drought stress since 2000. *Glob. Ecol. Conserv.* **49**, e02791 (2024).
- De Jong, R., Verbesselt, J., Schaepman, M. E. & de Bruin, S. Trend in global greening and browning: contribution of short-term trends to longer-term change. *Glob. Change Biol.* **18**, 642–655 (2021).
- Keenan, T. F. et al. Increase in forest water-use efficiency as atmospheric carbon dioxide concentrations rise. *Nature* **499**, 324–327 (2013).
- Peñuelas, J. et al. Shifting from a fertilization-dominated to a warming-dominated period. *Nat. Ecol. Evol.* **1**, 1438–1445 (2017).
- Mathias, J. M. & Thomas, R. B. Global tree intrinsic water use efficiency is enhanced by increased atmospheric CO₂ and modulated by climate and plant functional types. *Proc. Natl Acad. Sci. USA* **118**, e2014286118 (2021).
- Nowak, R. S., Ellsworth, D. S. & Smith, S. D. Functional responses of plants to elevated CO₂—do photosynthetic and productivity data from FACE experiments support early predictions? *New Phytol.* **162**, 253–280 (2003).
- Wang, S. et al. Recent decline of CO₂ fertilization on vegetation photosynthesis. *Science* **370**, 1295–1300 (2000).
- Penuelas, J. Decreasing efficiency and slowdown of the increase in terrestrial carbon-sink activity. *One Earth* **6**, 591–594 (2023).
- Pascolini-Campbell, M., Reager, J. T., Chandapanpurkar, H. & Rodell, M. A 10 per cent increase in global land evapotranspiration from 2003 to 2019. *Nature* **593**, 543–547 (2021).
- Pendergrass, A. G. & Hartmann, D. L. Changes in the distribution of rain frequency and intensity in response to global warming. *J. Clim.* **27**, 8372–8383 (2014).
- Lin, K. C. et al. Impacts of increasing typhoons on the structure and function of a subtropical forest: reflexions of a changing climate. *Sci. Rep.* **7**, 4911 (2017).
- Motha, R. P. & Baier, W. Impacts of present and future climate change and climate variability on agriculture in the temperate regions: North America. *Clim. Change* **70**, 137–164 (2005).
- Liu, N. et al. Drought can offset potential water use efficiency of forest ecosystems from rising atmospheric CO₂. *J. Environ. Sci.* **90**, 262–274 (2020).
- Li, S. et al. Vegetation growth due to CO₂ fertilization is threatened by increasing vapor pressure deficit. *J. Hydrol.* **619**, 129292 (2013).
- Pan, S. et al. Responses of global terrestrial evapotranspiration to climate change and increasing atmospheric CO₂ in the 21st Century. *Earth's Future* **3**, 15–35 (2014).
- Jones, N. Heating up tensions. *Nat. Clim. Change* **1**, 327–329 (2011).
- Tariq, A. et al. Decade-long unsustainable vegetation management practices increase macronutrient losses from the plant–soil system in the Taklamakan Desert. *Ecol. Ind.* **145**, 109653 (2022b).
- Tariq, A. et al. *Alhagi sparsifolia*: an ideal phreatophyte for combating desertification and land degradation. *Sci. Total Environ.* **844**, 157228 (2022).
- Zheleznova, I., Gushchina, D., Meiramov, Z. & Olchev, A. Temporal and spatial variability of dryness conditions in Kazakhstan during 1979–2021 based on reanalysis data. *Climate* **10**, 144 (2022).
- Blanco-Rodriguez, M., Ameztegui, A., Gelabert, P., Rodrigues, M. & Coll, L. Short-term recovery of post-fire vegetation is primarily limited by drought in Mediterranean forest ecosystems. *Fire Ecol.* **19**, 68 (2023).
- Qu, Q. et al. Impacts of extreme weather events on terrestrial carbon and nitrogen cycling: a global meta-analysis. *Environ. Pollut.* **319**, 120996 (2023).
- Muñoz-Sabater, J. et al. ERA5-Land: a state-of-the-art global reanalysis dataset for land applications. *Earth Syst. Sci. Data* **13**, 4349–4383 (2021).
- Liu, Z., Wang, T., Li, C., Yang, W. & Yang, H. A physically-based potential evapotranspiration model for global water availability projections. *J. Hydrol.* **622**, 129767 (2023).
- Liu, Z., Wang, T. & Yang, H. Overestimated global dryland expansion with substantial increases in vegetation productivity under climate warming. *Environ. Res. Lett.* **18**, 054024 (2023).
- National Ocean Service. <https://oceanservice.noaa.gov/facts/horse-latitudes.html> (2024).
- Naorem, A. et al. Soil constraints in an arid environment—challenges, prospects, and implications. *Agronomy* **13**, 220 (2023).
- Feng, H. & Zhang, M. Global land moisture trends: drier in dry and wetter in wet over land. *Sci. Rep.* **5**, 18018 (2015).
- Xiong, J., Guo, S., Abhishek, Chen, J. & Yin, J. Global evaluation of the “dry gets dryer, and wet gets wetter” paradigm from a terrestrial water storage change perspective. *Hydrol. Earth Syst. Sci.* **26**, 6457–6476 (2022).
- Roth, N. et al. 2021. A call for consistency with the terms “wetter” and “drier” in climate change studies. *Environ. Evid.* **10**, 8 (2021).
- Zhou, S. et al. Land-atmosphere feedbacks exacerbate concurrent soil drought and atmospheric aridity. *Proc. Natl Acad. Sci. USA* **116**, 18848–18853 (2019).
- Sherwood, S. & Fu, Q. A drier future? *Science* **343**, 737–739 (2014).
- Huang, J. et al. Global semi-arid climate change over last 60 years. *Clim. Dyn.* **46**, 1131–1150 (2016).
- Yao, J. et al. Accelerated dryland expansion regulates future variability in dryland gross primary production. *Nat. Commun.* **11**, 1665 (2020).

35. Dai, A., Zhao, T. & Chen, J. Climate change and drought: a precipitation and evaporation perspective. *Cur. Clim. Change Rep.* **4**, 301–312 (2018).
36. Huang, J., Yu, H., Dai, A., Wie, Y. & Kang Drylands face potential threat under 2 °C global warming target. *Nat. Clim. Change* **7**, 417–422 (2017).
37. Feng, S. & Fu, Q. Expansion of global drylands under a warming climate. *Atmos. Chem. Phys.* **13**, 10081–10094 (2013).
38. Kaptué, A. T., Prihodko, L. & Hanan, N. P. On greening and degradation in Sahelian watersheds. *Proc. Natl Acad. Sci. USA* **112**, 12133–12138 (2015).
39. Brookshire, E. J., Stoy, P. C., Currey, B. & Finney, B. The greening of the Northern Great Plains and its biogeochemical precursors. *Global Change Biol.* **26**, 5404–5413 (2020).
40. Song, X. P. et al. Global land change from 1982 to 2016. *Nature* **560**, 639–643 (2018).
41. Gong, H. et al. Increasing atmospheric aridity moderates the accelerated rate of vegetation green-up induced by rising CO₂ and warming. *Remote Sens.* **14**, 3946 (2022).
42. Ambika, A. K. & Mishra, V. Substantial decline in atmospheric aridity due to irrigation in India. *Environ. Res. Lett.* **15**, 124060 (2020).
43. Maity, S. S., Shaw, R. P. & Maity, R. Climate change may cause oasisification or desertification both: an analysis based on the spatial–temporal change in aridity across India. *Theor. Appl. Clim.* **155**, 1167–1184 (2023).
44. Guhathakurta, P. & Rajeevan, M. *Trends in the Rainfall Pattern over India*. National Climate Centre Research Report no. 2/2006. <https://www.indiaspend.com/wp-content/uploads/2019/02/Trends-in-rainfall-pattern-study.pdf> (2019).
45. Siswanto, van der Schrier, G. & van den Hurk, B. Observed increase of urban extreme rainfall as surface temperature rise: the Jakarta case. *J. Meteorol. Soc. Jpn.* **100**, 475–492 (2022).
46. Avia, L. Q. Change in rainfall per-decades over Java Island, Indonesia. In *IOP Conference Series: Earth and Environmental Science*, Vol. 374, *The 8th International Symposium for Sustainable Humanosphere*, 18–19 October 2018, Medan, Indonesia (IOP Publishing Ltd., 2020).
47. Agusti, K. S., Al Amin, W. N. & Permatasari, D. The impact of economic variables and energy consumption on deforestation in Indonesia. *Indones. J. Dev. Stud.* **1**, 1 (2020).
48. Dwiyaeheni, A. A. et al. Changes in the human footprint in and around Indonesia's terrestrial national parks between 2021 and 2017. *Sci. Rep.* **11**, 4510 (2021).
49. Delire, C. et al. Simulated response of the atmosphere–ocean system to deforestation in the Indonesian Archipelago. *Geophys. Res. Lett.* **28**, 2081–2084 (2001).
50. Olchev, A. et al. Effects of land-use changes on evapotranspiration of tropical rain forest margin area in Central Sulawesi (Indonesia): modelling study with a regional SVAT model. *Ecol. Model.* **24**, 131–137 (2008).
51. Santoro, A., Piras, F. & Yu, Q. Spatial analysis of deforestation in Indonesia in the period 1950–2017 and the role of protected areas. *Biodivers. Conserv.* <https://doi.org/10.1007/s10531-023-02679-8> (2023).
52. MacDonald, G. M. Water, climate change, and sustainability in the southwest. *Proc. Natl Acad. Sci. USA* **105**, 21256–21262 (2010).
53. Marengo, J. A., Rodrigues Torres, R. & Muniz Alves, L. Drought in Northeast Brazil—past, present and future. *Theor. Appl. Clim.* **129**, 1189–1200 (2016).
54. El Kenawy, A. M., McCabe, M. F., Vicente-Serrano, S. M., Robaa, S. M. & Lopez-Moreno, J. I. Recent changes in continentality and aridity conditions over the Middle east and North Africa Region, and their association with circulation patterns. *Clim. Res.* **69**, 25–43 (2016).
55. Shinoda, M. Evolving a multi-hazard focused approach for arid Eurasia. In *Climate Hazard Crises in Asian Societies and Environments* 73–102 (ed. Sternberg, T.) (Routledge, Oxon, UK, 2017).
56. Zeng, H. et al. Dryland ecosystem dynamics change and its drivers in Mediterranean region. *Curr. Opin. Environ. Sustain.* **48**, 59–67 (2021).
57. Rantanen, M. et al. The Arctic has warmed nearly four times faster than the global since 1979. *Commun. Earth Environ.* **3**, 168 (2022).
58. Rao, M. P. et al. Approaching a thermal tipping point in the Eurasian boreal forest at its southern margin. *Commun. Earth Environ.* **4**, 247 (2023).
59. Biskaborn, B. K. et al. Permafrost is warming at a global scale. *Nat. Commun.* **10**, 264 (2019).
60. Mayaux, P. et al. State and evolution of the African rainforests between 1990 and 2010. *Phil. Trans. R. Soc. B-Biol. Sci.* **368**, 20120300 (2013).
61. Bennett, A. C. et al. Resistance of African tropical forest to an extreme climate anomaly. *Proc. Natl Acad. Sci. USA* **118**, e2003169118 (2021).
62. Duku, C. & Hein, L. The impact of deforestation on rainfall in Africa: a data-driven assessment. *Environ. Res. Lett.* **16**, 064044 (2021).
63. Dai, A. G. Hydroclimatic trends during 1950–2018 over global land. *Clim. Dyn.* **56**, 4027–4049 (2021).
64. Daramola, M. T., Eresanya, E. O. & Erhabor, S. C. How has aridity changed over West Africa in the past four decades? *J. Afr. Earth Sci.* **197**, 104745 (2023).
65. Jiang, Y. et al. Widespread increase of boreal summer dry season length over the Congo rainforest. *Nat. Clim. Change* **9**, 617–622 (2019).
66. Wang, X. X. Weakened seasonality of African rainforest precipitation in boreal winter and spring driven by tropical SST variabilities. *Geosci. Lett.* **8**, 22 (2022).
67. Xu, H. et al. Rising ecosystem water demand exacerbates lengthening of tropical dry season. *Nat. Commun.* **13**, 4093 (2022).
68. Calatrava, J., Barbera, G. G. & Castillo, V. M. Farming practices and policy measures for agricultural soil conservation in semi-arid Mediterranean areas: the case of the Guadalentin basin in Southeast Spain. *Land Degrad. Dev.* **22**, 58–69 (2011).
69. Aleksandrova, M., Lamers, J. P. A., Martius, C. & Tischbein, B. Rural vulnerability to environmental change in the irrigated lowlands of Central Asia and options for policy-makers: a review. *Environ. Sci. Policy* **41**, 77–88 (2014).
70. Maïga-Yaleu, S. B. et al. Impact of sheet erosion mechanisms on organic carbon losses from crusted soils in Sahel. *Catena* **126**, 60–67 (2015).
71. Ruiz-Sinoga, J. D. & Martínez-Murillo, J. F. Effects of soil surface components on soil hydrological behavior in a dry Mediterranean environment (Southern Spain). *Geomorphology* **108**, 234–245 (2009).
72. Ruiz-Sinoga, J. D., Pariente, S., Romero Díaz, A. & Martínez Murillo, J. F. Variability of relationships between soil organic carbon and some soil properties in Mediterranean rangelands under different climatic conditions (South of Spain). *Catena* **94**, 17–25 (2012).
73. Yang, Y., Roderick, M. L., Zhang, S., McVicar, T. R. & Donohue, R. J. Hydrologic implications of vegetation response to elevated CO₂ in climate projections. *Nat. Clim. Change* **9**, 44–48 (2019).
74. Granados-Sanchez, D., Hernández-García, M. A., Vázquez-Alarcon, A. & Ruiz-Puga, P. Los procesos de desertificación y las regiones áridas. *Rev. Chapingo Ser. Cienc. For. Ambiente* **19**, 45–66 (2024).
75. Smith, C., Baker, J. C. A. & Spraklen, D. V. Tropical deforestation causes large reductions in observed precipitation. *Nature* **615**, 270–275 (2023).
76. Allen, R. G., Pereira, L. S., Raes, D. & Smith, M. *Crop Evapotranspiration: Guidelines for Computing Crop Water Requirements*. FAO Irrigation and Drainage Paper No. 56 (Food and Agriculture Organization, 1998).
77. Masson-Delmotte, V. et al. Climate change 2021: the physical science basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change. **2**, 2391 (2021).

Author contributions

J.S.: Planification, conceptualization, financing, first draft writing, figures realization. A.M.: Data analysis, figures realization, check and text improvement, and writing. A.T.: Conceptualization, check and text improvement, and writing. F.Z.: Check and text improvement, end writing. R.W.: Check and text improvement, and writing. J.P.: Conceptualization, financing, check and text improvement, and writing.

Competing interests

The authors declare no competing interests.

Additional information

Supplementary information The online version contains supplementary material available at <https://doi.org/10.1038/s43247-024-01935-1>.

Correspondence and requests for materials should be addressed to Jordi Sardans.

Peer review information *Communications Earth & Environment* thanks the anonymous reviewers for their contribution to the peer review of this work. Primary Handling Editors: Rodolfo Nóbrega and Alireza Bahadori. A peer review file is available.

Reprints and permissions information is available at <http://www.nature.com/reprints>

Publisher's note Springer Nature remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.

Open Access This article is licensed under a Creative Commons Attribution-NonCommercial-NoDerivatives 4.0 International License, which permits any non-commercial use, sharing, distribution and reproduction in any medium or format, as long as you give appropriate credit to the original author(s) and the source, provide a link to the Creative Commons licence, and indicate if you modified the licensed material. You do not have permission under this licence to share adapted material derived from this article or parts of it. The images or other third party material in this article are included in the article's Creative Commons licence, unless indicated otherwise in a credit line to the material. If material is not included in the article's Creative Commons licence and your intended use is not permitted by statutory regulation or exceeds the permitted use, you will need to obtain permission directly from the copyright holder. To view a copy of this licence, visit <http://creativecommons.org/licenses/by-nc-nd/4.0/>.

© The Author(s) 2024