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Peer Review File

Growing aridity poses threats to global land surface

Corresponding Author: Professor Jordi Sardans

This file contains all editorial decision letters in order by version, followed by all author rebuttals in order by version.

Version 0:

Decision Letter:

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Dear Professor Sardans,

Your manuscript titled "Growing threat: arid surfaces on the rise" has now been seen by 2 reviewers, and we include their comments at the end of this message. They find your work of interest, but some important points are raised. We are interested in the possibility of publishing your study in Communications Earth & Environment, but would like to consider your responses to these concerns and assess a revised manuscript before we make a final decision on publication. Specifically, we ask you to:

a) Improve the accuracy and transparency of the methods used to calculate aridity and potential evapotranspiration, with a focus on clarifying the equations and accounting for any associated uncertainties.

b) Provide a more detailed and focused analysis of the results, particularly in linking human activities to aridity changes and exploring the causes of increased aridity in specific regions, such as Central Africa.

We therefore invite you to revise and resubmit your manuscript, along with a point-by-point response that takes into account the points raised. Please highlight all changes in the manuscript text file.

Please submit your point-by-point responses as a separate file, distinct from your cover letter where you can add responses to the Editors' comments that you do not want to be made available to the reviewers. Word files are preferred.

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We are committed to providing a fair and constructive peer-review process. Please don't hesitate to contact us if you wish to discuss the revision in more detail.

Please use the following link to submit your revised manuscript, point-by-point response to the referees' comments (which should be in a separate document to any cover letter), a tracked-changes version of the manuscript (as a PDF file) and the completed checklist:
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We hope to receive your revised paper within six weeks; please let us know if you aren't able to submit it within this time so that we can discuss how best to proceed. If we don't hear from you, and the revision process takes significantly longer, we may close your file. In this event, we will still be happy to reconsider your paper at a later date, as long as nothing similar has been accepted for publication at Communications Earth & Environment or published elsewhere in the meantime.

Please do not hesitate to contact us if you have any questions or would like to discuss these revisions further. We look forward to seeing the revised manuscript and thank you for the opportunity to review your work.

Best regards,

Rodolfo Nobrega, PhD
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Associate Editor
Communications Earth & Environment

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REVIEWER COMMENTS:

Reviewer #2 (Remarks to the Author):

This manuscript aims to investigate “land surface on the rise”. This line of research is timely and tackles important questions, while this study has major issues. I recommend that the article undergo major revisions before publication. Based on the current context, I have some comments below.

Lines 44-46. The manuscript mentions that semi-humid and semi-arid areas decreased by 1.45 and 0.53 million km², respectively, while arid and hyper-arid areas increased by 6.34 and 4.18 million km², respectively. However, arid regions include semi-humid, semi-arid, arid, and hyper-arid areas. The article pointed out that the total increase in arid regions is 10.52 million km², but this takes into account the increase in arid and hyper-arid areas without considering the decreases in semi-humid and semi-arid areas.
Therefore, I have the following questions that I hope the author can clarify:
1. Why was the decrease in semi-humid and semi-arid areas not considered when calculating the total increase in aridity? Why only the increase in arid and hyper-arid areas are considered, without accounting for the decrease in semi-humid and semi-arid areas.
2. Is there any omission or oversight in the data statistics? If the total increase in aridity is 10.52 million km² should this figure also reflect a decrease in semi-humids and semi-arid (1.98 million km²)?

Lines 50. "atmospheric warmth" refers to the overall increase in the temperature of the atmosphere caused by an increase in greenhouse gases, while "temperature rise" is a direct result of atmospheric warmth. Please clarify why "atmospheric warmth" and "temperature rise" are used together as driving factors.

Lines 50. Keywords should accurately reflect the main topics of the manuscript. Upon reviewing the manuscript, there is a lack of discussion or evidence connecting biodiversity to the core topics of this paper. Please adjust keywords to accurately reflect content and avoid misleading readers.

Lines 64-66. Other limiting factors restrict the CO_2 fertilization effect. It seems that the intended message is that while CO_2 increase can improve water-use efficiency, this effect is limited if water resources are insufficient. Particularly in arid regions, the lack of water can become a primary limiting factor for plant growth. I suggest the author reorganize this section to emphasize the importance of your research on surface aridity expansion.

Lines 70 & 80. Both sections highlight the role of increased evapotranspiration as a major cause of increased aridity. The second section mentions vegetation dynamics but does not link them to evapotranspiration.

Lines 110：The logic of the introduction in the manuscript is very weak. For example, the three paragraphs focus extensively on the role of human activities. However, this topic is not revisited or integrated into the discussion of results. Please rewrite the introduction.

Lines 112：The results section of the manuscript is notably brief and lacks sufficient detail. A more thorough presentation of the information contained in these figures is necessary. For instance, in the section titled "Causes underlying aridity spread," the current explanation is insufficient and does not provide an analysis of the causes of aridity spread. Besides, in the section "The acceleration/deceleration in aridity patterns", the authors should quantify these rates and discuss their implications.

Lines 146：The manuscript does a good job of explaining regions with decreases in aridity, such as India and Indonesia. However, it should focus more on the significant increase in aridity areas. The current manuscript lacks an in-depth analysis of the specific causes behind this increase. In addition, central Africa as a new hotspot for aridity, is a highlight of the article. I suggest the author provide a comprehensive explanation for why Central Africa has emerged as a new drought hotspot.

Reviewer #3 (Remarks to the Author):

This manuscript analyzed the aridity changes according to the ERA5-Land Monthly Aggregated ECMWF Climate Reanalysis dataset, and found an increase of 10.52 million km² in arid regions represents 5.9% of the global land surface excluding Greenland and Antarctica. The aridity change and its impacts is an interesting and hot topic. On the other hand, regarding this topic, there are many previous studies. It is necessary to clearly show readers what the new methods or findings are. Besides, another major concern is on the calculation of potential evaporation, which has large impact on the results. Therefore, I don’t think that this version can be accepted in Communications Earth & Environment.
Detailed comments
1. The authors reviewed many references vegetation greening, increasing atmospheric CO2 concentration, which are closely related to aridity change. However, these issues are barely involved in Discussion and Conclusion. It’s better to give more discussions on the relation with aridity change.
2. The calculation of potential evaporation. In this manuscript, the aridity index (AI) was used to define the climate zones, which is dependent on the calculation of potential evaporation. To calculate potential evaporation, there are several different formulas. Under climate changes, these formulas give different trends in potential evaporation, and in turn lead to different trends in AI. Therefore, it is necessary to introduce which formula was used for calculating PET. In addition, the uncertainty caused by the choice of PET formula should be further explained and discussed. In fact, regarding the PET calculation, (Liu

and Wang et al., 2023a) proposed a physical formula considering the impacts from atmospheric CO2 concentration and leaf area index, and (Liu and Wang et al., 2023b) found an overestimated global dryland expansion if ignoring the impact of increasing CO2 concentration.
3. There are a few confusions of evapotranspiration with potential evapotranspiration, such as Line 162 and 242. Evapotranspiration is influenced by both potential evapotranspiration and precipitation, and in another words, it is controlled by available energy and available water.

References:
Liu, Z. and T. Wang, et al. (2023a). "A physically-based potential evapotranspiration model for global water availability projections." Journal of hydrology (Amsterdam) 622: 129767.
Liu, Z. and T. Wang, et al. (2023b). "Overestimated global dryland expansion with substantial increases in vegetation productivity under climate warming." ENVIRONMENTAL RESEARCH LETTERS 18 (5).

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Version 1:

Decision Letter:

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Dear Professor Sardans,

Your manuscript titled "Growing threat: arid surfaces on the rise" has now been seen by our reviewers, whose comments appear below. In light of their advice we are delighted to say that we are happy, in principle, to publish a suitably revised version in Communications Earth & Environment.

We therefore invite you to revise your paper one last time to address the remaining concerns of our reviewers. At the same time we ask that you edit your manuscript to comply with our format requirements and to maximise the accessibility and therefore the impact of your work.

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We hope to hear from you within two weeks; please let us know if you need more time.

Best regards,

Alireza Bahadori, PhD
Associate Editor
Communications Earth & Environment

Rodolfo Nobrega, PhD
Editorial Board Member
Communications Earth & Environment
orcid.org/0000-0002-9858-8222

REVIEWERS' COMMENTS:

Reviewer #2 (Remarks to the Author):

1. All my previous comments have been properly addressed and I have no further comments.

2. Keywords: Please check whether the keyword “biodiversity” has been corrected.

Reviewer #3 (Remarks to the Author):

The authors well addressed my concerns. I have only one suggestion. In Line 447 and Line 455, regarding “introduce additional sources of variation”, I suggest revising it into “introduce additional sources of uncertainty”.

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Responses to reviewer 2's comments.

1.This manuscript aims to investigate "land surface on the rise". This line of research is timely and tackles important questions, while this study has major issues. I recommend that the article undergo major revisions before publication. Based on the current context, I have some comments below.

Response: Thanks for the favorable comments about the importance and novelty of the topic. We have corrected/changed/improved/completed all the questions you have insightfully posed. See below responses one-by-one

2.Lines 44-46. The manuscript mentions that semi-humid and semi-arid areas decreased by 1.45 and 0.53 million km^2, respectively, while arid and hyper-arid areas increased by 6.34 and 4.18 million km^2, respectively. However, arid regions include semi-humid, semi-arid, arid, and hyper-arid areas. The article pointed out that the total increase in arid regions is 10.52 million km^2, but this takes into account the increase in arid and hyper-arid areas without considering the decreases in semi-humid and semi-arid areas.

Response: Thanks for making us notice this confusion.

First, we have clarified that "*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]."

Second, consequently with the previous information we have considered as arid expansion of 9.99 Km^2 of arid lands hyper-arid, arid and semi-arid lands but not subhumid-land. Certainly, in the text we forgot to mention semi-arid lands. We have now corrected it. The revised text now reads:

"Overall, arid areas—comprising semi-arid, arid, and hyper-arid regions—now cover 9.99 million km^2 more than they did in 1960, which is a surface area similar than that of Canada.

Third, the real increase is arid (+6.34), hyper-arid (+4,18) and semiarid (-0.5), in total a net balance of 9.99 more millions of km^2"

3, Therefore, I have the following questions that I hope the author can clarify:
1. Why was the decrease in semi-humid and semi-arid areas not considered when calculating the total increase in aridity? Why only the increase in arid and hyper-arid areas are considered, without accounting for the decrease in semi-humid and semi-arid areas.

Response: See previous response, where we have solved the confusion.

4.2. Is there any omission or oversight in the data statistics? If the total increase in aridity is 10.52 million km^2 should this figure also reflect a decrease in semi-humids and semi-arid (1.98 million km^2)?

Response: Remember that semi-humid areas are not considered in this study, now clarified.

5.*Lines 50. "atmospheric warmth" refers to the overall increase in the temperature of the atmosphere caused by an increase in greenhouse gases, while "temperature rise" is a direct result of atmospheric warmth. Please clarify why "atmospheric warmth" and "temperature rise" are used together as driving factors.*

Response: Thanks for making us notice it. Now corrected. The revised text now reads:

"*The primary driver is the disproportionate increase in potential evapotranspiration relative to rainfall, attributed to the rising atmospheric temperatures."*

6.*Lines 50. Keywords should accurately reflect the main topics of the manuscript. Upon reviewing the manuscript, there is a lack of discussion or evidence connecting biodiversity to the core topics of this paper. Please adjust keywords to accurately reflect content and avoid misleading readers.*

Response: Thanks for making us notice of this confusion. We have changed "biodiversity" by "plant cover"

7.*Lines 64-66. Other limiting factors restrict the CO_2 fertilization effect. It seems that the intended message is that while CO_2 increase can improve water-use efficiency, this effect is limited if water resources are insufficient. Particularly in arid regions, the lack of water can become a primary limiting factor for plant growth. I suggest the author reorganize this section to emphasize the importance of your research on surface aridity expansion.*

Response: Reorganized to now read:

"*The rise in CO_2 levels can stimulate plant productivity through a fertilization effect and improve water-use efficiency, although plants may also acclimate to increased atmospheric CO_2 concentrations. Furthermore, the increase in other limiting factors, such as nutrients and water, can restrict this CO_2 fertilization effect and contribute to acclimation over time. Additionally, there is a general rise in evapotranspiration[10] and potential global changes in rainfall intensity and frequency[11], leading to multiple consequences. These range from negative impacts on net* *primary production (NPP) due to the destructive effects of increased frequency and intensity of tropical hurricanes[12], to the positive effects of increased rainfall in some regions, primarily in temperate areas[13]. Increases in evapotranspiration have been identified as the primary cause of the observed rise in aridity in various regional studies14 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[16],[17]. 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[18]. 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[19].*

Consequently, the expansion of arid lands may diminish the buffering effects of increased CO_2 on climate change by reducing plant productivity. Shifts in aridity are not uniform, as different regions and arid ecosystems have shown heterogeneous responses to recent climate changesFrom a climate perspective, the overall consequences for global plant cover are largely determined by the balance between the positive effects of elevated atmospheric greenhouse gases and temperature, and the negative effects of increased aridity, mainly due to higher evapotranspiration[19].

In fact, under increasing temperatures, the rise in vapor pressure deficit frequently counteracts vegetation growth due to CO_2 fertilization20. Thus, we can expect a decrease in plant cover and an increase in aridity where the rise in temperature and evapotranspiration pressure surpasses the positive effects of CO_2 on plant growth and water use efficiency (WUE). These distinct yet simultaneous effects—the general rise in evapotranspiration and CO_2 fertilization, which have opposing influences on aridity, along with rainfall patterns—are direct causes that can drive future climate changes and the spread of aridity in both the recent past and future[21].

Reference

Li, S., Wang, G., Zhu, C., Lu, J., Ullah, W., Hagan, D. F.T., Kattel, G., Liu, Y., Zhang, Z., Song, Y., Sun, S., Zheng, Y., Peng, J. 2013. Vegetation growth due to CO2 fertilization is threatened by increasing vapor pressure deficit. Journal of Hydrology, 619, 129292.

Pan, S., Tian, H., Dangal, S.R.S., Yang, Q., Yang, J., Lu, C., Tao, B., Ren, W., Ouyang, Z., 2014. Responses of global terrestrial evapotranspiration to climate change and increasing atmospheric CO2 in the 21st Centuty. Earth's Future, 3, 15-35.

8.*Lines 70 & 80. Both sections highlight the role of increased evapotranspiration as a major cause of increased aridity. The second section mentions vegetation dynamics but does not link them to evapotranspiration*.

Response:

Now linked: "*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*."

9.*Lines 110: The logic of the introduction in the manuscript is very weak. For example, the three paragraphs focus extensively on the role of human activities. However, this topic is not revisited or integrated into the discussion of results. Please rewrite the introduction.*

***Response**:*

Now we have added new information/data about the direct impact of human in aridity rise. It now reads:

"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]. 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 thawing[59].

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 approximately 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*[61,62]*. 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 to 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 climate*[61]*."*

References 52-61

Beekman, H. E., Saayman, I., & Hughes, S. (2003). Vulnerability of water resources to environmental change in Southern Africa. Council for Scientific and Industrial Research. PO Box 320, Stellenbosch 7599, South Africa.

Granados-Sanchez, D., Hernández-García, M. A., Vázquez-Alarcon, A., & Ruíz-Puga, P. (2012). Los procesos de desertificación y las regiones áridas. *Revista Chapingo, Serie Ciencias Forestales y del Ambiente*, 19(1), 45-66. (10 September 2024).

Smith, C., Baker, J. C. A., & Sprakelen, D. V. (2023). Tropical deforestation causes large reductions in observed precipitation. *Nature*, 615, 270-275.

10.*Lines 112: The results section of the manuscript is notably brief and lacks sufficient detail. A more thorough presentation of the information contained in these figures is necessary. For instance, in the section titled "Causes underlying aridity spread," the current explanation is insufficient and does not provide an analysis of the causes of aridity spread. Besides, in the section "The acceleration/deceleration in aridity patterns", the authors should quantify these rates and discuss their implications*.

Response: Thanks for making us notice these incomplete explanations of the causes. We have now gone in depth in explaining it. The revised text now reads:

"Causes Underlying the Spread of Aridity

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 Figure 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 (Figure 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."

11.Lines 146:The manuscript does a good job of explaining regions with decreases in aridity, such as India and Indonesia. However, it should focus more on the significant increase in aridity areas. The current manuscript lacks an in-depth analysis of the specific causes behind this increase. In addition, central Africa as a new hotspot for aridity, is a highlight of the article. I suggest the author provide a comprehensive explanation for why Central Africa has emerged as a new drought hotspot.

Response: Solved. Please see responses to previous questions. Now all these commented necessary information has been included in the new version of the discussion of the manuscript. The new discussion now reads:

"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 km^2. 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.

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 km^2 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% (Figure 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) paradigm[32]. 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 sites[33]. Similar findings were reported by Xiong et al[34]. 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 scale[35]. 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 studies[36]. Sherwood and Fu[37] (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.[38]. noted that during the 20th century, surface warming over drylands (1.2-1.3 ºC) was 20-40% higher than over humid areas (0.8-1.0 ºC). 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 CO_2 concentrations and global temperatures keep rising[38,39]. Additionally, various modeling experiments conducted by Dai et al.[40]. have shown that the *surface drying effect of GHG-induced warming dominates over the wetting effect of plants' physiological responses to increasing CO_2.*

The observations generally align with the findings of Huang et al.,[41] who reported a clear global increase in aridity affecting 1.6 million km^2, primarily in North America and Asia, using the REConstruction over Land (PREC/L) dataset. Similarly, a study by Feng and Fu[15] (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 km^2, predominantly in North America and Asia. Feng and Fu[15] also reported a 4% increase in the area of global drylands from the 1950s to the period 1991-2005, totaling approximately 2.4 million km^2. Notably, India has shown a unique trend, exhibiting a decrease in aridity over the past six decades, particularly in tropical and warm-temperate regions (Figure 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 Mishra[42], 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 Rajeevan[44] 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 precipitation[45], 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 decades[46]. 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 years[51].

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]. 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 thawing[59].

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 approximately 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[61,62]. 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 to 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 climate[61]

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 demand[68].

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].

Responses to the comments of Referee 3

1*This manuscript analyzed the aridity changes according to the ERA5-Land Monthly Aggregated ECMWF Climate Reanalysis dataset, and found an increase of 10.52 million km^2 in arid regions represents 5.9% of the global land surface excluding Greenland and Antarctica. The aridity change and its impacts is an interesting and hot topic. On the other hand, regarding this topic, there are many previous studies. It is necessary to clearly show readers what the new methods or findings are. Besides, another major concern is on the calculation of potential evaporation, which has large impact on the results. Therefore, I don't think that this version can be accepted in Communications Earth & Environment*.

Response: We have now highlighted the novelty of our study and have solved the concerns on the calculation of potential evaporation. We thank the revised version is now suitable to be published in Com Earth Env. We hope you can agree. Regarding to the novelty of this study we have now explained it extensively. The revised text now reads:

"*Global warming can increase plant production and net primary production (NPP), contributing to CO_2 storage in biomass (a negative feedback on global warming), or it can diminish plant productivity and NPP by increasing extreme climate events[27] or by exacerbating global aridity[15]. This underscores the need for consistent information on how global warming could impact land aridity worldwide. 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 meters height) worldwide, with a resolution of 11132x11132 meters 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 CO_2 fertilization effect on vegetation dynamics and structure[28-30]. 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 global 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 pattern[31]. 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)[32]. We use the 1-AI of such AI as the estimated aridity value, with larger values indicating 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."

Detailed comments
2. The authors reviewed many references vegetation greening, increasing atmospheric CO_2 concentration, which are closely related to aridity change. However, these issues are barely involved in Discussion and Conclusion. It's better to give more discussions on the relation with aridity change.

Response: Thanks for making us notice it. We have now added more explanation at this regard in the discussion section. The most direct effect of CO_2 of global aridity is indirect through the global increase in temperature and thus in global evapotranspiration. It now reads:

"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]. 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 thawing[59].

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 approximately 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[61,62]. 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 evapotranspiration60,61 .

Regarding the Congo rainforest, there is evidence of an increased dry season length of 6.4 to 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 climate[61]

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 demand[68].

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] ."*.

3*The calculation of potential evaporation. In this manuscript, the aridity index (AI) was used to define the climate zones, which is dependent on the calculation of potential evaporation. To calculate potential evaporation, there are several different formulas. Under climate changes, these formulas give different trends in potential evaporation, and in turn lead to different trends in AI. Therefore, it is necessary to introduce which formula was used for calculating PET. In addition, the uncertainty caused by the choice of PET formula should be further explained and discussed. In fact, regarding the PET calculation, (Liu and Wang et al., 2023a) proposed a physical formula considering the impacts from atmospheric CO2 concentration and leaf area index, and (Liu and Wang et al., 2023b) found an overestimated global dryland expansion if ignoring the impact of increasing CO2 concentration.*

Response: We have rewritten this part accordingly. It now reads:

"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 (Allen et al., 1998; Muñoz-Sabater et al., 2021). 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 CO_2 fertilization effect in the coming century (Yang et al., 2019; Liu et al., 2023a; Masson-Delmonte et al., 2021). These variations introduce a dependence on vegetation dynamics and structure relative to atmospheric CO_2 concentration. However, they require new parameters to be approximated, which may introduce additional sources of variation. 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 variation. 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 CO_2 fertilization effect is not prominent enough to offset *the challenges and uncertainties introduced in the estimation procedure (Liu et al., 2023b). This is particularly evident for drylands, where CO_2 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 – (mean annual precipitation)\ 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."

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4. *There are a few confusions of evapotranspiration with potential evapotranspiration, such as Line 162 and 242. Evapotranspiration is influenced by both potential evapotranspiration and precipitation, and in another words, it is controlled by available energy and available wate*r.

Response: Clarified. Now reads:

" 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 Figure 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 (Figure 4)."