Authors’ Response to Reviews of

Using statistical models to depict the response of multi-time scales drought to forest cover change across climate zones

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RC: Reviewers’ Comment AR: Authors’ Response

Forest cover changes (e.g., deforestation and afforestation) have profound impacts on climate through biophysical processes. Prior studies have mostly focused on the impacts of forest cover changes on temperature and precipitation. However, the impacts of forest cover changes on drought have not been sufficiently examined and remain largely unknown. In this paper, Li and the coauthors try to fill this knowledge gap using a statistical model. They found varying effects of forest cover changes on different timescale droughts across climate zones. Moreover, the impacts of forest cover changes may vary with precipitation and temperature within a climate zone.

This paper is well organized, clearly written and presents some novel results on the impacts of forest cover change on drought. However, I am a little concerned about whether the statistical model used in this work is a useful tool to address the relevant questions. Moreover, the statistical model-based results are not sufficiently convincing due to the lack of mechanisms or explanations in some cases. I think that the methods and results should be further clarified or explained. Please see my specific comments listed below.

AR: Thanks for the appreciation of our work and the useful feedbacks to improve the quality of the manuscript.

Major:

1. The authors used a statistical model, and the model is in principle a linear multiple regression model. While the model can reasonably reproduce the year-to-year variations in drought in equatorial, arid and temperate regions, it is difficult for us to interpret the results and mechanisms derived from such a statistical model. For example, changes in drought can be attributed to changes in forest cover, precipitation and temperature and the interactions between the three variables in a mathematical way (Equation 5). However, how can the individual effects on drought be interpreted? Specifically, what does the effect of forest and precipitation interactions on drought (Xforest: Xprecip) mean? Does Xforest: Xprecip mean that precipitation changes influence forest cover and subsequently drought or forest cover changes influence precipitation and subsequently drought?

AR: We adopt the notation for (generalized) linear models as introduced by McCullagh and Nelder (1989). While interpreting so-called direct effects $response \sim term$ is relatively straightforward, understanding interactions can be more challenging. To facilitate intuitive interpretation, we propose the following approach: consider a simple model with a direct effect, where response ~ term_A. Mathematically, this is represented as $\mathrm{Y} = a_0 + a_1 X_1 + \varepsilon$, with a_0

and a_1 as unknown but constant parameters. If a_1 is found to be dependent on another term, X_2, we can model a_1 itself linearly, resulting in $Y = a_0 + a_1 X_1 + \varepsilon = a_0 + (b_0 + b_1 X_2) X_1 + \varepsilon$, where b_0 and b_1 are again unknown but constant parameters. The effect of X_1 on Y now depends on the value of X_2. Expanding further, we have $Y = a_0 + b_0 X_1 + b_1 X_2 X_1 + \varepsilon$. In model notation, we can express this as $Y \sim X_1 + X_2 : X_1$. The interpretation of $X_2 : X_1$ is a modulation of the effect of X_1 on Y by X_2 (or vice versa: modulation of the effect of X_2 on Y by X_1). Another perspective is to view this as approximating the unknown function $Y = f(X_1, X_2)$ using a second-order Taylor expansion, with the resulting unknown parameters estimated from data. By employing this approach to investigate how meteorological conditions and forest cover influence droughts, we aim to generate ideas for potential mechanisms based on data.

2. Owing to the shortcomings of the statistical model mentioned above, some results based on the statistical model are also not clearly explained. For example, Figure 6F shows that SPEI24 decreases as forest cover increases when precipitation is low. The authors explain that a small amount of water is transpired into the atmosphere due to a high fraction of available trees (Line 310-311). Here are two problems. First, why does a higher tree cover fraction contribute to lower evapotranspiration when precipitation is low? Second, how are changes in evapotranspiration further related to changes in drought? Moreover, Figure 6L shows that the SPEI24 increases as forest cover increases when precipitation is high. The authors explain that "the types of trees here can adapt their leaves and roots to absorb all of the excess water (Line 328-329)", but they do not explicitly explain the positive response of SPEI to forest cover changes. Furthermore, some results shown in Figure 7 are not sufficiently explained. For example, it remains unclear why the dependence of drought on temperature and precipitation varies with forest cover.

AR: Here, we give more explanations.
SPEI = P-PET with Potential Evapotranspiration (PET) being an upper bound of what could be transpirated if there was sufficient water supply and sufficient vegetation to realize evapotranspiration. More trees will transpirate more water but this does not directly affect PET, as PET is only the potential evapotranspiration. However, there are indirect effects mediated by the effect of trees on temperature and vapour pressure deficit (humidity). The latter two variables in turn influence PET. As we evaluate the model for constant temperatures (in Fig 6F), humidity is the only remaining factor influencing PET and thus SPEI in the following way: increasing vapour pressure deficit (drier air) leads to increasing PET and thus decreasing SPEI. For larger amounts of precipitation, we expect more transpiration to be realized with increasing forest fraction leading to a smaller vapour pressure deficit and thus also reduced PET; Hence increasing values for the SPEI with increasing forest fraction. If precipitation is lower, this effect decreases and the slopes in Fig. 6F get smaller. There is not sufficient water to be evapotranspirated, even if the forest fraction increases. For a specific amount of precipitation (about the median) the slope is 0. For less than this amount, we see a negative slope suggesting the interpretation that for restricted water supply, an increase of trees leads to an increase of PET and hence to a decrease of SPEI. As we do not see a potential explanatory mechanism for this effect, we expect that it is due to the restriction of the model to a linear change in slope with precipitation and extrapolation beyond the validity of the model. This case calls for a more detailed investigation allowing for a non-linear change of slope with precipitation.
It's important to note that trees can still play a role in promoting water circulation and increasing air humidity in arid regions. When there is more precipitation, especially in the presence of a substantial number of trees, it can provide some relief from drought conditions (in the temperate region). However, the extent of this relief depends on various factors, including the amount and timing of the precipitation, the type of tree species present, and other environmental factors.

In Figure 6L, we aim to depict the impact of changes in forest cover on SPEI24 in the temperate region, with temperature as a conditioning factor and precipitation fixed at its 0.5 quantiles. Increasing tree cover results in increasing rates of evaporation, which contributes to higher atmospheric moisture, thus reducing PET and hence increasing SPEI. However, if temperatures are reduced, i.e. are close to their 0.1 quantiles, this effect vanishes. In the temperate region, water resources are relatively abundant compared to the arid region. This suggests that higher temperatures and more trees can indeed increase the SPEI24, as shown in Figure 6L, as they contribute to higher evaporation and transpiration rates, leading to increased atmospheric moisture and potentially mitigating drought conditions.

Figure 7 aims to investigate the impact of precipitation and temperature on drought indices while considering the observed minimum and maximum forest cover fractions in different regions. In the equatorial region, drought indices are primarily influenced by changes in precipitation when there is less tree cover. However, as the forest cover increases (row 2 and 4), higher temperatures become more significant in driving drought conditions. The elevated temperature leads to increased rates of evaporation and transpiration, potentially making the region drier. Therefore, in regions with comparable water availability, forests can act as a medium for the temperature to have a greater impact on drought changes. In arid regions, as more trees are present, the influence of temperature becomes more visible as it shapes drought conditions in the way that for constant precipitation increasing temperature leads to increasing SPEI. In temperate regions, SPEI24 is strongly influenced by temperature in the minimum-forest-cover plot (7K), this effect is reduced in the maximum-forest-cover plot (7L), consistent with Fig. 6L. For given precipitation, we see an increase of SPEI from Fig. 7K (minimum forest) to Fig. 7L (maximum forest) for high temperatures but not so much for low temperatures. Increasing forest cover reduced the dependence of SPEI on temperature. We hypothesize that increasing forest cover leads to more transpiration and thus less water vapour deficit in the air which implies reduced PET and thus increased SPEI. When the forest fraction is maximal, the influence of precipitation becomes more visible, as demonstrated in Figure 7. In snow regions, the interaction between precipitation and temperature plays a crucial role in shaping drought conditions when there is a maximal forest cover fraction (Fig. 7P). However, when the forest cover fraction is minimal, precipitation remains the dominant factor affecting drought changes for SPEI24 (Fig. 7O). Thus increasing forest cover in regions with sufficient water supply by precipitation implies an increase of transpiration with increasing temperature and thus a reduction of PET, leading to an increase of SPEI.

Overall, our study indicates that the relative influence of precipitation and temperature on drought indices varies across different regions and forest cover fractions, however, the specific physicochemical and biological processes underlying this relationship require further verification through climate models.

3. I note that the forest cover range (X-axis) in Figure 6 varies with region, but why? In arid regions, forest cover ranges between 0.0383 and 0.0393 (Figure 6L), and such a range (~ 0.001) is much smaller than the historical actual changes in forest cover (Figure 2). Why? Such a small increase in forest cover even corresponds to an increase of 0.3 in SPEI24 when precipitation is high (Figure 6L). It can be estimated that historical actual loess in forest cover (~ -3) will cause a decrease of 900 in SPEI24 in arid regions.

AR: In Fig. 6, the X-axis represents the forest cover fraction in various regions. The graph illustrates that the equatorial and snow regions have approximately 50% forest cover fraction, while the arid region has a relatively lower forest cover fraction. Despite the arid region having less forest cover, the results obtained from the linear models indicate that this region is particularly susceptible to the impacts of forest cover change. This finding suggests that even a small change in forest cover can have a significant influence on drought conditions in the arid region.

It is important to note that the forest cover values depicted in Fig. 2 have undergone a standardization process, where they have been centered and scaled to unit variance. Therefore, the forest cover fractions presented in Fig. 6 and Fig. 2 are not directly comparable since they are not represented in the same unit. The scaling and standardization of the forest cover values were done to facilitate analysis and interpretation within the context of the specific study.

4. The authors categorize the global land into four climate zones and aggregate the forest cover, precipitation and temperature values within a climate zone for further analysis. I cannot understand why the author do this. Forest cover, precipitation and temperature are spatially highly heterogeneous within a climate zone. Therefore, why not apply the statistical model pixel by pixel?

AR: Thanks for the remark! A pixel-based analysis would of course be possible but also a lot more complex. To reduce the complexity of an initial study, we decided to integrate over climate regions in order to average out various localized effects. Going into more detail, also spatially, would be further analysis and beyond the scope of this work.

5. The authors selected temperature, precipitation and forest cover as three independent variables to build the statistical model (Equation 5). An implicit assumption is that the authors think that temperature, precipitation and forest cover can largely explain the annual variation in drought, but why? I do not doubt the contribution of temperature and precipitation to the evaluation of drought. However, it remains unclear why the other human activities (e.g., aerosol emission) are not considered here. It is also feasible to either replace the forest cover change with other human forcing or combine the forest cover change with other human forcing to rebuild the statistical model. It is unclear how the main results shown in this manuscript would be modified if different independent variables are selected to build the model.

AR: Our primary focus is to analyse the impact of forest cover change on droughts, considering both natural and human-induced alterations. We do not differentiate between these two sources of change and instead focus on the overall change in the forest area. It is widely acknowledged that precipitation and temperature are key factors influencing drought conditions. Consequently, we aim to investigate the interactions between forest cover, precipitation, and temperature to gain a deeper understanding of their combined effects on droughts.

According to Tab. 1, these three factors exhibit a certain power in describing drought changes. From visual inspection and comparison of R^2_{adj}, drought indices in the equatorial region can be described best ($0.84 < R^2_{adj} < 0.97$). However, in the snow region, the model's performance is comparatively weaker ($0.23 < R^2_{adj} < 0.39$), suggesting that factors influencing drought indices in this region are likely more complex than the linear models considered in this study. In arid and temperate zones, the linear models incorporating forest cover, temperature, and precipitation yield results that are nearly as effective as those in the equatorial zone. Hence, linear models comprising these factors are well-suited to describe the drought indices in the equatorial, temperate, and arid regions, while the snow region requires more intricate considerations when examining the factors impacting drought indices.

6. From Figure 2 and Figure 3, I see that the drought indices show a clear decreasing trend in arid regions during the analysis period. I'm curious about whether such a trend is related to global warming. If so, this is not surprising to see a dominant contribution of temperature to the evolution of drought, as shown in Figure 5. In other words, the covariance of drought is dominated by its long-term trend, which is further related to the long-term temperature trend in arid

regions. This leads to another question: whether the drought indices, temperature and precipitation need to be detrended before regression? The authors do not detrend the variables and may confound the contribution of temperature, precipitation and forest cover changes to drought at multi-time scales.

AR: Thanks for this remark. Detrending might be indeed meaningful for some analyses. However, we do not consider it purposeful as we focus on a statistical description of drought indices as functions of temperature, precipitation and forest cover, independent on external drivers of these variables. We agree that the observed trend in drought indices may very well be a result of global warming but we expect it to be mediated by changes in regional patterns of precipitation and temperature, which we have both in our model. We do not expect a large effect of global warming on droughts which is not mediated via temperature and precipitation. Furthermore, we have included residual versus fits plots for all drought indices (scPDSI, SPEI03, SPEI06, SPEI12, SPEI24) across different regions (equatorial, arid, temperate, snow regions) in the Appendix section. These plots help us identify any underlying trends over time that may not be accounted for by the existing predictor variables (temperature and precipitation). If there were missing terms in the predictor or if heteroscedasticity (unequal variance) existed, it would likely manifest as noticeable patterns or structures in the residual plots. However, upon careful inspection of the residual plots, no evident structures or patterns are observed, indicating that there are no apparent missing terms or heteroscedasticity present in the model. Therefore, there is no extra trend.

7. In Figure 6, the authors show the responses of drought indices to forest cover changes at different precipitation (or temperature) levels with temperature (or precipitation) fixed at its median. It is unclear whether the main results would be modified if temperature or precipitation is fixed at other levels (e.g., maximum or minimum).

AR: Thank you for your asking here. In the 4.2 section of the study, the objective is to examine how the influence of forest cover change in droughts is conditioned by precipitation and temperature. In Figure 6, the first two rows depict scenarios where the temperature is fixed at its median value. The purpose is to observe how variations in precipitation affect the relationship between forest cover change and droughts for “normal” (i.e. median) temperature. In the last two rows of the figure, precipitation is held at a normal level, allowing for an examination of the interaction between temperature and forest cover change in relation to droughts. In Fig. 7 we can observe the effect of simultaneous extremes of precipitation and temperature for two extreme cases of forestcover. For complex relations, presentation on 2D plots is always a compromise. And additional figures that provide further insights and analysis when temperature or precipitation is fixed at maximum or minimum levels have been included in the Appendix section of the study.

8. In Figure 6 and 7, the authors only show the results for SPEI03 and SPEI24. It is fine to only show these two drought indices in the main text, but the results for the other indices (i.e., SPEI06, SPEI12 and scPDSI) should be provided, for example, in the supplementary material.

AR: Thank you for your advice. We have added the new figures in the Appendix part.

Minor:

1. Line 6: “forest fraction” -> “forest cover fraction”.

AR: modified.

2. Line 9: “The impact of forest cover” -> “The impact of forest cover changes”.

AR: modified.

3. Line 10-12: “forest cover’s impact” -> “the impact of forest cover changes”

AR: modified.

4. Line 38-39: “forests typically have a low surface albedo” -> “the typically low surface albedo of forests”.

AR: modified.

5. Line 39-42: I think that the large uncertainty in the temperature effect of afforestation/deforestation in the mid-latitude is MAINLY caused by the radiative (i.e., albedo) and nonradiative (i.e., roughness and evapotranspiration) effects being similar in magnitude but opposite in sign. The background climate, forest types or analysis methods, as mentioned by the authors, just further enlarge such an uncertainty.

AR: Thank you for your advice. I have reorganised this part. Rvised in the new manuscript.

6. Line 47-58: In this paragraph, the authors review the impacts of deforestation/afforestation on precipitation in previous studies. I find that most references cited here are either old (before 2010) or review articles (e.g., Bonan, 2008; Perugini et al., 2017). Numerous important studies have examined the impacts of deforestation/afforestation on precipitation based on observations (LeiteFilho et al. 2021; Smith et al. 2023) and simulations (Liang et al. 2022; Luo et al. 2022) in recent years. I recommend the authors to update the references in this paragraph.

AR: We sincerely appreciate the valuable comments. We have updated the references in the new version of the manuscript.

7. Line 60: “And it is” -> “Drought is”.

AR: modified.

8. Line 106-107: “…, which maps…”. What does “which” refer to? SPEI or SPI? Rephrase this sentence. When I first read this sentence, I interpreted “which” as “SPEI”. As such, I cannot understand why the authors say that the SPEI use precipitation as the only input but later they say that potential evapotranspiration is also used. I later realized that “which” refers to “SPI”.

AR: Revised.

9. Section 2.2: In this section, you should tell the readers what the magnitude and sign of the SPEI and scPDSI mean. For example, what are the possible ranges of the indices? What do the positive or negative values of the indices mean? What do higher or lower values of the indices mean?

AR: The explanation has been added in the new manuscript.

10. Figure 3: The description of figure caption is inaccurate. It should be the annual means of precipitation and temperature aggregated analogously to the aggregation level of the drought index, rather than the annual temperature and precipitation.

AR: Modified.

11. Line 193-194: Why not considering the interactions between X1 and X2 (i.e., X1:X2) and X1 and X3 (i.e., X1:X3)? Do you assume that X1 is independent of X2 and X3?

AR: Here is just an example to explain the direct effect factors (X_1, X_2, X_3) and the interaction of 2 factors (X_2, X_3). And the total effect of $X_2 \wedge X_3$ means $X_2 * X_3$, which means the $X_2 + X_3 + X_2 : X_3$, the direct effect and interaction of the two factors, which is shown in Eq. (4).

12. Line 199: Why are the fourth and fifth right-hand terms are the same in Equation 5?

AR: Modified.

13. Line 200-201: What do the annual mean precipitation (i.e., Xprecip) and temperature (i.e., Xtemp) refer to? Do they refer to the commonly used mean values of precipitation and temperature or the mean values of the precipitation and temperature aggregated to the aggregation level of the drought index (as mentioned in Line 172)? Clarify the "annual mean" here. Does Dτ also refer to the annual mean values of scPDSI or SPEI?

AR: For the linear model for scPDSI, X_{precip} and X_{temp} mean the commonly used annual mean, because the scPDSI cannot calculate the droughts for different time scales. For the linear models for SPEIs at different time scales, X_{precip} and X_{temp} should firstly aggregate analogously to the aggregation level of the SPEIs, then calculate the annual mean of precipitation and temperature. And D_τ is the annual mean value of drought indices. More explanations have been added in the new version.

14. Line 228: What does $\hat{y}_i$ denote?

AR: It should be $\hat{Y}_i$.

15. Line 275: "ominates" might be "dominates"?

AR: modified.

16. Line 320-321: High/low temperatures lead to a notable negative/positive response of SPEI03 to forest cover, instead of decrease/increase in forest cover.

AR: Changed

References:

Leite-Filho, A.T., et al. 2021: Deforestation reduces rainfall and agricultural revenues in the Brazilian Amazon. Nature Communications, 12, 2591.

Liang, Y., et al. 2022: Deforestation drives desiccation in global monsoon region. Earth's Future, 10, e2022EF002863.

Luo, X., et al. 2022: The biophysical impacts of deforestation on precipitation: results from the CMIP6 model intercomparison. Journal of Climate, 35(11), 3293-3311.

Smith, C., et al. 2023: Tropical deforestation causes large reductions in observed precipitation. Nature, 615, 270–275.

McCullagh, P. and Nelder, J. 1989: Generalized Linear Models, CRC Press, Boca Raton, Fla, 2 edn.