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Peer Review Information

Journal: Nature Ecology & Evolution
Manuscript Title: Exacerbated drought impacts on global ecosystems due to structural overshoot
Corresponding author name(s): Yao Zhang, Trevor F. Keenan

Editorial Notes:

Reviewer Comments & Decisions:

Decision Letter, initial version:

12th March 2021

*Please ensure you delete the link to your author homepage in this e-mail if you wish to forward it to your co-authors.

Dear Dr Zhang,

Your Article, "Exacerbated drought impacts on global ecosystems due to structural overshoot" has now been seen by three reviewers. You will see from their comments copied below that while they find your work of considerable potential interest, they have raised quite substantial concerns that must be addressed. In light of these comments, we cannot accept the manuscript for publication, but would be very interested in considering a revised version that addresses these serious concerns.

We hope you will find the reviewers' comments useful as you decide how to proceed. If you wish to submit a substantially revised manuscript, please bear in mind that we will be reluctant to approach the reviewers again in the absence of major revisions. In particular, Reviewer 3 raises important concerns about the underlying data and analyses, which should be addressed with substantial revision.

If you choose to revise your manuscript taking into account all reviewer and editor comments, please highlight all changes in the manuscript text file [OPTIONAL: in Microsoft Word format].

We are committed to providing a fair and constructive peer-review process. Please do not hesitate to contact us if there are specific requests from the reviewers that you believe are technically impossible or unlikely to yield a meaningful outcome.

When revising your manuscript:

* Include a “Response to reviewers” document detailing, point-by-point, how you addressed each referee comment. If no action was taken to address a point, you must provide a compelling argument. This response will be sent back to the referees along with the revised manuscript.

* If you have not done so already we suggest that you begin to revise your manuscript so that it conforms to our Article format instructions at http://www.nature.com/natecolevol/info/final-submission. Refer also to any guidelines provided in this letter.

* Include a revised version of any required reporting checklist. It will be available to referees (and, potentially, statisticians) to aid in their evaluation if the manuscript goes back for peer review. A revised checklist is essential for re-review of the paper.

Please use the link below to submit a revised paper:

[REDACTED]

Note: This URL links to your confidential home page and associated information about manuscripts you may have submitted, or that you are reviewing for us. If you wish to forward this email to co-authors, please delete the link to your homepage.

If you wish to submit a suitably revised manuscript we would hope to receive it within 6 months. If you cannot send it within this time, please let us know. We will be happy to consider your revision so long as nothing similar has been accepted for publication at Nature Ecology & Evolution or published elsewhere.

Nature Ecology & Evolution is committed to improving transparency in authorship. As part of our efforts in this direction, we are now requesting that all authors identified as ‘corresponding author’ on published papers create and link their Open Researcher and Contributor Identifier (ORCID) with their account on the Manuscript Tracking System (MTS), prior to acceptance. This applies to primary research papers only. ORCID helps the scientific community achieve unambiguous attribution of all scholarly contributions. You can create and link your ORCID from the home page of the MTS by clicking on ‘Modify my Springer Nature account’. For more information please visit please visit www.springernature.com/orcid.

Please do not hesitate to contact me if you have any questions or would like to discuss the required revisions further.

Thank you for the opportunity to review your work.

[REDACTED]

Reviewer expertise:

Reviewer #1: Structural overshoot, forest ecology

Reviewer #2: Drought, effects on forests

Reviewer #3: Ecohydrology, remote sensing, machine learning

Reviewers' comments:

Reviewer #1 (Remarks to the Author):

The main hypothesis is that vegetation dynamics is driven not only by current climate, but also by memory-induced lagged responses. Previous climatic conditions could stimulate vegetation growth to surpass ecosystem carrying capacity, leaving an ecosystem more vulnerable to climate stresses. Although the concept of structural overshoot has been previously developed this is to my knowledge the first attempt to describe this phenomenon at a global scale and to explore the underlying spatial and temporal drivers. The authors undertake a novel approximation based on remote sensing, high-resolution climate data, and random forest analysis This paper is timely and topical and it is an innovative approach in global climate change climate inspired in the concept of anomaly and overshoot drought.
Authors address lagged effects with a Bayesian multivariate dynamic linear model (DLM) and use non parametric random forest (machine learning algorithms) to investigate factor driving occurrence and impact of overshoot drought events. They conclude that around 11.2% of drought events during the 1981-2015 period are linked to overshoot droughts. The DLM decomposes NDVI time series into several components (trend, seasonal, and de-seasonalized and de-trended anomalies) so the anomalies are linked to drought stress, temperature, and direct and lagged effects from past vegetation anomalies at different time scales. The idea is that it is possible to separate timescales of importance for all drought events globally. Then they link some of these anomalies to structural overshoot and quantify its contribution to timing, speed, frequency and impact of drought.
Altogether this is a potentially ground-breaking manuscript that can change the view of ecosystem responses to drought and generate a controversial but interesting scientific debate. I have however several important concerns. Mainly I have found the manuscript quite complex and hard to read for a plant ecologist audience and in its current form it seems more oriented for the remote sensing community. I encourage the authors to clarify how the main concepts link to plant community ecology and forestry so the validity of these findings can be properly evaluated and have a broader impact. Next, I suggest possible suggestions in this direction:

-Define ecosystem carrying capacity: it can be useful to know the classical description of soil water balance and the maximum plant canopy that can be maintained. See for example classical definitions i.e. Eagleson, Specht, Woodward (see references in the bottom). These ideas do not consider remote sensors neither lagged responses (with the exception of soil water dynamics) but depart from similar assumptions and are still the basis of current agronomy.
-Overshoot droughts are identified by a faster NDVI decline with respect to non-overshoot droughts. Authors argue that a faster decline is induced by environmental lagged effects that have created a disadvantageous structure to cope with concurrent climate. I am not convinced, however, that reported NDVI patterns can be referred to as structural overshoot as I explain next. Structural overshoot has been examined in two main contexts:
i) Regional forest mortality. Here drought effects can be clearly define and quantified in terms of mortality and forest decay. Because of lack of competition the population can grow surpass carrying capacity and because of phenotypic plasticity some individuals have a disadvantageous phenotype. Structural overshoot results in forest decay because competition intensifies and individuals cannot

cope with current water balance in part because of a disfunctional allocational strategy.
ii) Remote sensing studies targeting ecosystem level properties such as productivity. This approach is valid because the level of response and variable of interest is aggregated, this is, they quantify the aggregated ecosystem response without being interested in population dynamics, species composition, functional type, disturbances, etc.
The approximation in this paper based on NDVI claims that observed patterns are the result of structural overshoot, however functional adjustments reflected in NDVI patterns may reflect phenological changes in plant functional traits, functional types turnover, disturbance, competition etc. Specifically, a faster NDVI decline with respect to non-overshoot droughts may simply reflect changes in acclimation of physiological parameters or an adjustment or turn over in plant functional types, for example the ratio of grasslands and tree cover or a readjustment including disturbances such as fire. I am not sure if these patterns can be considered structural overshoot or should describe another concept related to plant community dynamics. Moreover, it is not evident that NDVI reflects a carrying capacity as defined in population ecology. Neither NDVI seems to describe a structural carrying capacity for example LAI (as implied in the classical views by Specht, Eagleson, Woodward etc) which might be better describe by Lidar or ground data.
In conclusion this is a very interesting study with a high potential but in its current form it seems more oriented towards a remote sensing and ecosystem modeller audience. The ms would greatly benefit by the clarification of key concepts such as carrying capacity, plant community structure, structural overshoot etc connecting them with plant ecology. A description of possible mechanisms underlying observed patterns in terms of functional groups, disturbances, competition, phenology etc would be clarifying. Some of these discussions are inherent to current DGVM development (see for example JEDI by Pavlick et al. 2013). Alternatively the description of NDVI anomalies, including lagged effects might be a very promising metric in climate change research but I am not convinced that it is adequately conceptualized as structural overshoot drought.

References

Eagleson PS (1978) Climate, soil, and vegetation: 1. Introduction to water balance dynamics. Water Resources Research. https://doi.org/10.1029/WR014i005p00705
Pavlick R-, D. T. Drewry, K. Bohn, B. Reu and A. Kleidon. 2013. The Jena Diversity-Dynamic Global Vegetation Model (JeDi-DGVM): a diverse approach to representing terrestrial biogeography and biogeochemistry based on plant functional trade-offs Biogeosciences, 10, 4137–4177, 2013 https://doi.org/10.5194/bg-10-4137-2013
Specht RL (in retrospective 2019)
https://www.royalsocietyqld.org/wp-content/uploads/documents/Members_Collections/Ray_Specht_Retrospective_Jan_2019.pdf

Woodward FI .Climate and Plant Distribution 1987. Cambridge Studies in Ecology

Reviewer #2 (Remarks to the Author):

I consider this study of high relevance for NEE readership given its ability to illustrate how vegetation and climate conditions prior to drought onset may constrain or predispose to responses during and after droughts. This is an important issue given the impact of such climatic extreme events on global vegetation productivity, ecosystem services (e.g. forest vigor) and human resources (e.g., crops).

I think that the drought definition is an open issue with some authors using only climatic criteria. However, I agree with authors on using both climatic and ecosystem (NDVI impact) criteria since droughts must have an impact on vegetation.

I prove below some minor comments on the ms:
Line 66: “The number of overshoot droughts generally follows the spatial distribution of droughts (r=0.54, p<0.001, t-test)”. Did you account for the effects of spatial autocorrelation on this overshoot-drought association? The existence of positive spatial autocorrelation could affect the calculated p value.

Line 128: “In contrast, soil characteristics (clay fraction), terrestrial water decay time (GRACEτ)”. I would explain before the meaning of “(GRACEτ)”.

Fig 2: First, in Fig 2e a better explanation of the abbreviations used in the x axis is lacking in the legend. Second, perhaps just plotting Figs 2n and 2o in the same plot would be enough to summarize this figure, whereas Figs 2a-m could be moved to the Appendix.

Line 152: please expand and discuss this “double growing season”. For instance, bimodal growth patterns with peaks in spring and autumn have been extensively studied in seasonally dry Mediterranean regions from the northern hemisphere.

Line 198: do you mean “across the globe “?

Line 210, Fig. 5: first reference to SPEI; you should explain it before.

Line 227: overshoots exacerbate….

Lines 280-282: I guess you can delete “ref”

Reviewer #3 (Remarks to the Author):

Review of Zhang et al., NATECOLEVOL-210112662
“Exacerbated drought impacts on global ecosystems due to structural overshoot“

This study is investigating the global role of increased vegetation productivity for subsequent droughts.
The authors show that it affects about 11% of the globally detected droughts, where it explains approximately a third of the drought-related greenness decreases. These so-termed vegetation overshoot droughts happen predominantly in cold and dry regions, and they are inducing warmer concurrent temperatures and faster drought-related vegetation greenness decreases than non-overshoot droughts.

Recommendation:
I think the paper requires major revisions.

The topic of this study is very timely. Droughts have multi-faceted impacts on ecosystems and society, and their magnitude and/or frequency might increase in many regions in a changing climate. Therefore, it is essential to understand the underlying drivers of drought, which consequently allows to improve anticipation and management of these events. This analysis is an important contribution in this context as it comprehensively characterizes the role of antecedent vegetation conditions for drought development and impacts. It shows that this role is not negligible and requires more attention by the eco-hydrological research community.
However, I have some important concerns regarding the model formulation and the employed indices and data to quantify drought and vegetation dynamics, which need to be addressed to illustrate the robustness of the reported findings.

General comments:

(1)
The SPEI index defining droughts, and the GIMMS NDVI dataset to capture vegetation dynamics are not convincing choices.
-- The GIMMS NDVI dataset is based on the AVHRR satellite data which is not the most accurate to estimate NDVI. Further, the dataset contains many gaps, and the authors do not describe how the analysis deals with this. I suggest to use MODIS NDVI or GOME-2 SIF (sun-induced fluorescence) data here; while the time periods covered by these datasets are admittedly shorter, the improved accuracy in estimating vegetation dynamics more than outweights this disadvantage in my opinion. Process understanding as intended to be established by this study requires most accurate
underlying data.
-- The SPEI index is not the best choice to capture vegetation-relevant water deficits. While vegetation physically relies on soil moisture supply, this information is not included in SPEI.
Further, the underlying model infers (potential) evapotranspiration in a too simplified way, for example
ignoring vegetation water stress, as also described by the authors. Therefore, I suggest to use soil moisture data in this study, which can for example be obtained from reanalyses such as ERA5 (Hersbach et al 2020) or machine learning products (O et al.).

(2)
In the dynamic linear model the authors do not consider important variables which are known to influence vegetation dynamics such as radiation and soil moisture. Therefore, these ignored controls might (partly) be erroneously attributed to antecedent NDVI by the model, which thereby overestimates the relevance of NDVI
overshoot. I do not really agree with the argument of the authors to leave out radiation as it is correlated with temperature - this correlation might not always and everywhere be very high, and at the same time precipitation and temperature as used in the model presently are also correlated.

(3)
Drought is not defined in the main text. This is important for understanding the manuscript and should be added. Furthermore, the authors nicely illustrate in the supplementary material how the overshoot results change with adapting the (necessarily arbitrary) thresholds in their drought definition. This sensitivity should also be documented more clearly in the main text, and correspondingly the exact

determined percentage results such as in line 19 in the abstract should be toned down or removed as this
is dependent on the chosen drought definition.

(4)
While the manuscript is clearly structured and overall easy to read, there are many small language and grammar errors such as missing articles, particularly in the methods part.
I recommend that the authors take special care of these when revising the manuscript.

I do not wish to remain anonymous - Rene Orth.

Specific comments:

line 3: Here you could cite Orth & Destouni 2018

lines 37-39: It is stated that several studies have investigated the phenomenon but the understanding is still limited. This is somewhat contradictory and requires additional details.

line 54: Not clear what is meant with "The anomalies" here.

line 80: "Contribution of overshoot component", please clarify.

line 106-108: Not sure if I would agree with this reasoning.

line 170" "Climatological mean temperature", this is only for drought events if I get it correctly, so it cannot be a climatological (~30-year) mean? Please clarify.

line 244: I think this should be overestimate rather than underestimate. If vegetation water stress is taken into account, this would reduce potential evaporation and consequently increase P-Epot which would therefore indicate reduced drought magnitude.

line 260: I think here you should apply a threshold higher than 0 degrees, as also with a monthly mean temperature slightly above zero snow and soil freezing can occur at least during parts of the month, and vegetation productivity is low.

lines 268/269: "Most reliable estimate", please add reference(s) or tone down this statement.

lines 332-334: Why did the authors decide to couple these two conditions with an "or" rather than using only the latter requirement of negative temperature sensitivity which seems quite relevant to me.

line 353: With "drought development speed" you refer to vegetation anomaly development speed I guess. Please clarify.

line 380-381: How is "overshoot" quantified as used here?

line 456-459: Also scenario (3) could induce an overshoot drought I think, for example if normal summer precipitation
is accompanied by hot temperatures inducing high evaporation and consequently drought and decreased vegetation dynamics.

Figure 5:
Please improve the labelling of the SPEI and NDVI axes to specify if there are decreases or increases.

References:

Hersbach, H. et al., The ERA5 global reanalysis. Q. J. R. Meteorol. Soc. 146(730), 1999-2049 (2020).

O, S. and R. Orth, Global soil moisture from in-situ measurements using machine learning - SoMo.ml, https://arxiv.org/abs/2010.02374

Orth, R., and G. Destouni, Drought reduces blue-water fluxes more strongly than green-water fluxes in Europe
Nat. Comms. 9, 3602 (2018).

Author Rebuttal to Initial comments

We thank the reviewers for their constructive comments. We have carefully considered and addressed each of the comments from the three reviewers. Below each of the original comments, our responses are given in blue. The page and line numbers referred to are for the clean version of the revised manuscript (non-track-change version).

Reviewers' comments:

Reviewer #1 (Remarks to the Author):

The main hypothesis is that vegetation dynamics is driven not only by current climate, but also by memory-induced lagged responses. Previous climatic conditions could stimulate vegetation growth to surpass ecosystem carrying capacity, leaving an ecosystem more vulnerable to climate stresses.

Although the concept of structural overshoot has been previously developed this is to my knowledge the first attempt to describe this phenomenon at a global scale and to explore the underlying spatial and temporal drivers. The authors undertake a novel approximation based on remote sensing, high-resolution climate data, and random forest analysis This paper is timely and topical and it is an innovative approach in global climate change climate inspired in the concept of anomaly and overshoot drought.

Response: We thank the reviewer for the positive comments on our manuscript.

Authors address lagged effects with a Bayesian multivariate dynamic linear model (DLM) and use non parametric random forest (machine learning algorithms) to investigate factor driving occurrence and impact of overshoot drought events. They conclude that around 11.2% of drought events during the 1981-2015 period are linked to overshoot droughts. The DLM decomposes NDVI time series into several components (trend, seasonal, and de-seasonalized and de-trended anomalies) so the anomalies are linked to drought stress, temperature, and direct and lagged effects from past vegetation anomalies at different time scales. The idea is that it is possible to separate timescales of importance for all drought events globally. Then they link some of these anomalies to structural overshoot and quantify its contribution to timing, speed, frequency and impact of drought. Altogether this is a potentially ground-breaking manuscript that can change the view of ecosystem responses to drought and generate a controversial but interesting scientific debate. I have however several important concerns. Mainly I have found the manuscript quite complex and hard to read for a plant ecologist audience and in its current form it seems more oriented for the remote sensing community. I encourage the authors to clarify how the main concepts link to plant community ecology and forestry so the validity of these findings can be properly evaluated and have a broader impact.

Response: We thank the reviewer for this clear summary, and highlighting the importance of our manuscript. We carefully considered the reviewer's suggestions and improved the manuscript so that it can be more accessible for the readers outside the remote sensing community.

Next, I suggest possible suggestions in this direction:

-Define ecosystem carrying capacity: it can be useful to know the classical description of soil water balance and the maximum plant canopy that can be maintained. See for example classical definitions i.e. Eagleson, Specht, Woodward (see references in the bottom). These ideas do not consider remote sensors neither lagged responses (with the exception of soil water dynamics) but depart from similar assumptions and are still the basis of current agronomy.

Response: Thank you for this suggestion. We agree that a clearly stated definition of carrying capacity would be helpful for readers, and now include one in the methods section (Page 15 Line 302-304). We follow the classical definition of ecosystem carrying capacity, based on the soil water balance and the maximum plant canopy that can be supported. However, considering the seasonal dynamics of vegetation (vegetation phenology), the carrying capacity is dynamically changing over time. We therefore identified overshoot drought events based on the de-seasonalized vegetation canopy indicator (represented by NDVI). This is because both vegetation and climate vary seasonally, and the normal seasonal dynamics of vegetation canopy is a long-term acclimation to this seasonally changing environment. For example, for a typical grassland ecosystem in the North Hemisphere that has one peak growing season, higher-than-usual vegetation activities in spring may not exceed its summer peak by absolute value. However, due to the extra soil water consumption in spring, summer soil moisture is lower and cannot support the normal vegetation canopy. In this case, the positive anomaly in spring, although lower than the maximum canopy coverage that an ecosystem can support, is still considered as overshoot.

It should be noted that we are not defining overshoot based on the lagged responses. Rather, the lagged responses are the criterion to identify the overshoot drought events because soil water dynamics in the real world cannot be directly observed at a global scale.

-Overshoot droughts are identified by a faster NDVI decline with respect to non-overshoot droughts. Authors argue that a faster decline is induced by environmental lagged effects that have created a disadvantageous structure to cope with concurrent climate. I am not convinced, however, that reported NDVI patterns can be referred to as structural overshoot as I explain next. Structural overshoot has been examined in two main contexts:

i) Regional forest mortality. Here drought effects can be clearly define and quantified in terms of mortality and forest decay. Because of lack of competition the population can grow surpass carrying capacity and because of phenotypic plasticity some individuals have a disadvantageous phenotype. Structural overshoot results in forest decay because competition intensifies and individuals cannot cope with current water balance in part because of a disfunctional allocational strategy.

ii) Remote sensing studies targeting ecosystem level properties such as productivity. This approach is valid because the level of response and variable of interest is aggregated, this is, they quantify the aggregated ecosystem response without being interested in population dynamics, species composition, functional type, disturbances, etc.

Response: We thank the reviewer for clarifying the definition of structural overshoot. We would like to first politely point out however that in our manuscript the overshoot drought is not identified by a faster NDVI decline. In our analysis, we first identify overshoot events and then assess the speed of NDVI declines during both overshoot droughts and non-overshoot droughts. In our study, overshoot drought is identified from all drought events when lagged adverse effects are found in the dynamic linear model (DLM).

We agree with the reviewer that structural overshoot is commonly examined with regard to forest mortality, and other ecosystem level properties. In this study, since we aim to investigate structural overshoot at a global scale, we took the second approach suggested by the reviewer. NDVI is a remotely sensed index based on the unique spectral characteristics of vegetation.

$$NDVI = \frac{\rho_{NIR} - \rho_{red}}{\rho_{NIR} + \rho_{red}}$$

where ρ_{NIR} and ρ_{red} represent the spectral reflectance of the near infrared (NIR) and red bands, respectively. Vegetation, unlike other land cover types (e.g., snow, bare land), have very low reflectance in the red band due to light absorption by photosynthetic pigments, and high reflectance in the near infrared band due to leaf structure properties. NDVI is designed based on this unique characteristic, and is found to be directly related to leaf area index, and photosynthetic rates (see a detailed description in Piao et al., 2020 Box 1). Therefore, NDVI represents the aggregated ecosystem response when drought stress happens. We realize that NDVI, and its relationship to productivity is currently not well explained in the paper and may lead to confusions, and have therefore added a more detailed explanation in the main text and the methods section (Page 3, Line 55-56; Page 11, Line 211-215). We hope this clarifies that we are using approach (ii) detailed by the reviewer above, and quantifying overshoot based on ecosystem level properties as suggested.

Piao, S., Wang, X., Park, T., Chen, C., Lian, X., He, Y., Bjerke, J.W., Chen, A., Ciais, P., Tømmervik, H., Nemani, R.R., Myneni, R.B., 2020. Characteristics, drivers and feedbacks of global greening. Nat Rev Earth Environ 1, 14–27. https://doi.org/10.1038/s43017-019-0001-x

The approximation in this paper based on NDVI claims that observed patterns are the result of structural overshoot, however functional adjustments reflected in NDVI patterns may reflect phenological changes in plant functional traits, functional types turnover, disturbance, competition etc.

Specifically, a faster NDVI decline with respect to non-overshoot droughts may simply reflect changes in acclimation of physiological parameters or an adjustment or turn over in plant functional types, for example the ratio of grasslands and tree cover or a readjustment including disturbances such as fire. I am not sure if these patterns can be considered structural overshoot or should describe another concept related to plant community dynamics. Moreover, it is not evident that NDVI reflects a carrying capacity as defined in population ecology. Neither NDVI seems to describe a structural carrying capacity for example LAI (as implied in the classical views by Specht, Eagleson, Woodward etc) which might be better describe by Lidar or ground data.

Response: We thank the reviewer for their comments on whether the results based on NDVI can reflect the vegetation responses to overshoot drought. First, we would like to clarify that NDVI is a very good proxy of LAI, and most global LAI products are based on NDVI (e.g., MODIS, GIMMS). This is because as LAI increases, the difference between reflectance in NIR and red bands also increases, which leads to an increase in NDVI. Previous studies have found a strong relationship between LAI and NDVI (Asrar et al., 1984; Chen and Cihlar, 1996; Running et al., 1986). MODIS LAI, one of the most widely used remotely sensed LAI products, uses NDVI as a backup algorithm for LAI retrieval (Knyazikhin et al., 1999).

We agree that multiple factors may cause the changes of NDVI, as the reviewer suggests (e.g., seasonal changes due to phenology, changes of the tree cover fraction or other disturbances). In this study, the seasonal and trend signal is modeled by the DLM separately, therefore, the seasonal changes of LAI (phenology) and potential trend caused by the tree cover fraction changes can be considered and will not be identified as overshoot drought. Fire, insect and other disturbances may induce a sudden change of ecosystem canopy structure (i.e., NDVI anomaly), but will not be considered as overshoot since drought is a prerequisite for structural overshoot drought events in our framework. Only if these disturbances happen during the drought period, and lagged adverse effects is detected through the dynamic linear model (DLM), are they considered as overshoot drought.

To clarify these points, we added a paragraph in the methods section (Page 15, Line 300-306), highlighting the rationale and approach of using DLM to identify structural overshoot. We hope our response has clarified that NDVI, through its relationship to LAI, does indeed describe a structural carrying capacity as implied in the classical views by Specht, Eagleson, Woodward and colleagues.

Asrar, G., Fuchs, M., Kanemasu, E.T., Hatfield, J.L., 1984. Estimating Absorbed Photosynthetic Radiation and Leaf Area Index from Spectral Reflectance in Wheat 1. Agron.j. 76, 300–306. https://doi.org/10.2134/agronj1984.00021962007600020029x

Chen, J.M., Cihlar, J., 1996. Retrieving leaf area index of boreal conifer forests using Landsat TM images. Remote Sensing of Environment 55, 153–162. https://doi.org/10.1016/0034-4257(95)00195-6

Y. Knyazikhin, J. Glassy, J. L. Privette, Y. Tian, A. Lotsch, Y. Zhang, Y. Wang, J. T. Morisette, P.Votava, R.B. Myneni, R. R. Nemani, S. W. Running, MODIS Leaf Area Index (LAI) and Fraction of Photosynthetically Active Radiation Absorbed by Vegetation (FPAR) Product (MOD15) Algorithm Theoretical Basis Document, *https://modis.gsfc.nasa.gov/data/atbd/atbd_mod15.pdf*, 1999.

Running, S.W., Peterson, D.L., Spanner, M.A., Teuber, K.B., 1986. Remote Sensing of Coniferous Forest Leaf Area. Ecology 67, 273–276. https://doi.org/10.2307/1938532

In conclusion this is a very interesting study with a high potential but in its current form it seems more oriented towards a remote sensing and ecosystem modeller audience. The ms would greatly benefit by the clarification of key concepts such as carrying capacity, plant community structure, structural overshoot etc connecting them with plant ecology. A description of possible mechanisms underlying observed patterns in terms of functional groups, disturbances, competition, phenology etc would be clarifying. Some of these discussions are inherent to current DGVM development (see for example JEDI by Pavlick et al. 2013). Alternatively the description of NDVI anomalies, including lagged effects might be a very promising metric in climate change research but I am not convinced that it is adequately conceptualized as structural overshoot drought.

Response: We thank the reviewer for their suggestions. We have improved the manuscript by providing clearer definitions of key concepts such as NDVI, ecosystem carrying capacity, and the underlying mechanisms, which more closely links the results to plant ecology. We have also clarified the direct link between NDVI anomalies and structural overshoot drought. However, considering the aim of this study is to evaluate overshoot drought at the global scale, it is not possible to analyze competition, and changes in functional groups in more detail. We have highlighted the potential importance of such processes (increased competition, changes in species composition and functional groups) and hope this analysis can provide a global overview of this important ecosystem phenomenon and stimulate further analysis at finer scales focusing on these ecosystem processes (Page 10 Line 195-197).

References

Eagleson PS (1978) Climate, soil, and vegetation: 1. Introduction to water balance dynamics. Water Resources Research. https://doi.org/10.1029/WR014i005p00705

Pavlick R-, D. T. Drewry, K. Bohn, B. Reu and A. Kleidon. 2013. The Jena Diversity-Dynamic Global Vegetation Model (JeDi-DGVM): a diverse approach to representing terrestrial biogeography and biogeochemistry based on plant functional trade-offs Biogeosciences, 10, 4137–4177, 2013 https://doi.org/10.5194/bg-10-4137-2013

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Woodward FI .Climate and Plant Distribution 1987. Cambridge Studies in Ecology

Reviewer #2 (Remarks to the Author):

I consider this study of high relevance for NEE readership given its ability to illustrate how vegetation and climate conditions prior to drought onset may constrain or predispose to responses during and after droughts. This is an important issue given the impact of such climatic extreme events on global vegetation productivity, ecosystem services (e.g. forest vigor) and human resources (e.g., crops).

I think that the drought definition is an open issue with some authors using only climatic criteria. However, I agree with authors on using both climatic and ecosystem (NDVI impact) criteria since droughts must have an impact on vegetation.

Response: We thank the reviewer for the positive comments on our manuscript. We also appreciate the suggestions for improvement, which we have incorporated into the revised manuscript as detailed below.

I prove below some minor comments on the ms:

Line 66: “The number of overshoot droughts generally follows the spatial distribution of droughts (r=0.54, p<0.001, t-test)”. Did you account for the effects of spatial autocorrelation on this overshoot-drought association? The existence of positive spatial autocorrelation could affect the calculated p value.

Response: Thank you for this suggestion. We agree that spatial autocorrelation may potentially affect the correlation between two spatial patterns, and if present in our analysis could affect the statistical power of the results. To test this effect on our study, we first built a general linear model to predict the relationship between the number of overshoot events and the number of droughts. If the model performance is affected by a positive spatial autocorrelation, the semivariance (in our case, residual) would increase as a function of increasing distance between observations. This can be tested using a semivariogram (Fig. R1). The semivariogram shows that there is no obvious tendency of semivariance along the distance axis, although an increasing trend can be observed when distance (x-axis) is below 40 pixels, which may suggest a local autocorrelation. However, considering the spatial correlation is calculated globally, and the local autocorrelation is weak, this local autocorrelation has limited effects on the correlation coefficient and p-value we presented here. We therefore do not consider spatial autocorrelation further in our analysis. We now add discussions about this issue in the main text (Page 4, Line 74-76), and also add details of the method and figure R1 to the supplementary information.

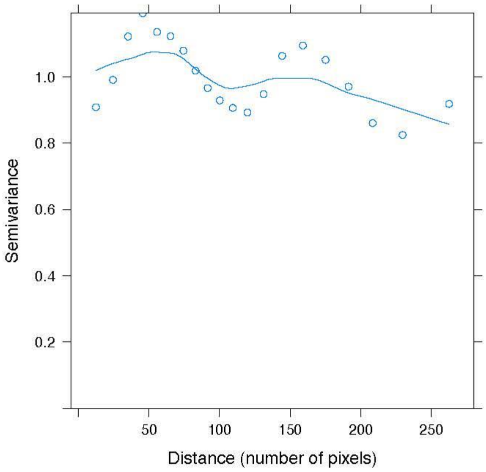

Fig R1. A semivariogram showing the relationship between semivariance and distance. The y-axis shows the normalized variance of residuals from the regression model between overshoot droughts and droughts, and the x-axis shows the distance between the observations (in number of pixels). If a positive spatial autocorrelation affects the model performance, that is, the model performs better (low residual) in part because the samples are closer to each other (shorter distance). This will be shown as an increasing trend of semivariance of the residual along the distance axis.

Line 128: "In contrast, soil characteristics (clay fraction), terrestrial water decay time (GRACEτ)". I would explain before the meaning of "(GRACEτ)".

Response: We agree this abbreviation can be confusing for many readers. We have revised the sentence to read:

"In contrast, soil characteristics (clay fraction), terrestrial water decay time estimated from Gravity Recovery and Climate Experiment satellites (GRACEτ, Methods),"

Since the definition of the water decay time is relatively complex, we therefore refer to the methods section for detailed descriptions.

Fig 2: First, in Fig 2e a better explanation of the abbreviations used in the x axis is lacking in the legend. Second, perhaps just plotting Figs 2n and 2o in the same plot would be enough to summarize this figure, whereas Figs 2a-m could be moved to the Appendix.

Response: Thank you for your suggestion, we have added the full names of the biome codes in the figure legend. While we understand the reviewer's concern that there is a lot of information in the current figure, and their suggestion to move panels a-m to the appendix, we have the following reason to keep them together in the main text. This figure shows the results from the prediction of the number and impact of overshoot droughts using machine learning. While we care about the importance of the variables that drive the variation of overshoot numbers and impacts, we are more interested in how these factors affect the occurrence and impact of overshoot. This is also why we use two paragraphs to discuss these relationships. This information is important to help us understand the driving factors of overshoot and how to better represent these processes in Earth system models. We therefore prefer to keep these subplots in the main text figure.

Line 152: please expand and discuss this "double growing season". For instance, bimodal growth patterns with peaks in spring and autumn have been extensively studied in seasonally dry Mediterranean regions from the northern hemisphere.

Response: Thank you for pointing this out. We agree that in Mediterranean climates where there are also bimodal growth patterns, the overshoot droughts may be more likely to happen in either peak growing season, similar to those of the water limited regions in Southern Hemisphere. We therefore added a sentence discussing this (Page 7, Line 138-140).

"This is also likely to occur in parts of dry Mediterranean climate regions in the Northern Hemisphere, where overshoot drought may happen in either peak growing season."

Line 198: do you mean "across the globe "?

Response: Thank you. We have revised the statement accordingly.

Line 210, Fig. 5: first reference to SPEI; you should explain it before.

Response: We have added the full name in the figure legend.

Line 227: overshoots exacerbate….

Response: Revised.

Lines 280-282: I guess you can delete "ref"

Response: Revised as suggested.

Reviewer #3 (Remarks to the Author):

Review of Zhang et al., NATECOLEVOL-210112662 “Exacerbated drought impacts on global ecosystems due to structural overshoot”

This study is investigating the global role of increased vegetation productivity for subsequent droughts.

The authors show that it affects about 11% of the globally detected droughts, where it explains approximately a third of the drought-related greenness decreases. These so-termed vegetation overshoot droughts happen predominantly in cold and dry regions, and they are inducing warmer concurrent temperatures and faster drought-related vegetation greenness decreases than non-overshoot droughts.

Recommendation:
I think the paper requires major revisions.

The topic of this study is very timely. Droughts have multi-faceted impacts on ecosystems and society, and their magnitude and/or frequency might increase in many regions in a changing climate. Therefore, it is essential to understand the underlying drivers of drought, which consequently allows to improve anticipation and management of these events. This analysis is an important contribution in this context as it comprehensively characterizes the role of antecedent vegetation conditions for drought development and impacts. It shows that this role is not negligible and requires more attention by the eco-hydrological research community.

However, I have some important concerns regarding the model formulation and the employed indices and data to quantify drought and vegetation dynamics, which need to be addressed to illustrate the robustness of the reported findings.

Response: Thank you for highlighting the importance of our study. We appreciate the suggestions on model structure and indicators used by the DLM, and have conducted additional analyses to assess and improve the robustness of the results. Please find them in the detailed responses below.

General comments:

(1) The SPEI index defining droughts, and the GIMMS NDVI dataset to capture vegetation dynamics are not convincing choices.

-- The GIMMS NDVI dataset is based on the AVHRR satellite data which is not the most accurate to estimate NDVI. Further, the dataset contains many gaps, and the authors do not describe how the analysis deals with this. I suggest to use MODIS NDVI or GOME-2 SIF (sun-induced fluorescence) data here; while the time periods covered by these datasets are admittedly shorter, the improved accuracy in estimating vegetation dynamics more than outweights this disadvantage in my opinion. Process understanding as intended to be established by this study requires most accurate underlying data.

Response: We agree that the GIMMS NDVI dataset has its limitations in terms of data quality. We took several steps to minimize this effect through (1) applying a temperature threshold to eliminate potentially snow-covered pixels; and (2) aggregating the good quality data both spatially (1/12 degree to 1/2 degree) and temporally (15-day to monthly) to get the most reliable estimates. The resultant missing values are set to NA and will be properly handled by the DLM. As the reviewer notes, we chose GIMMS NDVI because it provides the longest observational record of global vegetation. For most regions, drought is infrequent. And based on our current results, overshoot droughts are much less frequent. Using a short-term dataset may therefore not fully capture the spatial patterns of droughts and overshoot droughts. In addition, effects of orbit drift and shifts between satellites likely have a limited effect on overshoot identification since NDVI is relatively more robust to these changes (as compared to NIR_v, for example (Frankenberg et al., 2020)) and the DLM only uses the information from de-seasonalized and de-trended anomalies.

We agree however that MODIS retrievals are of higher quality and have followed Dr. Orth’s suggestions and tested the results based on MODIS NDVI. To do so, we first checked the MODIS quality assurance layer and used only good quality observations. The overshoot number and impact from MODIS show similar spatial patterns as compared to those from GIMMS NDVI (Fig. R2). For example, the hot spot regions in central US, north India, northern China plain are clearly identified. Although some differences also noticeable, these do not qualitatively change our conclusions and are likely due to the much shorter MODIS record and differences in the obversion period. We have added this result to the supplementary information as additional support for this study.

We did not test GOME-2 SIF because the SIF dataset is relatively short, and has rather large noise (Joiner et al. 2014). These characteristics makes it unsuitable for this study.

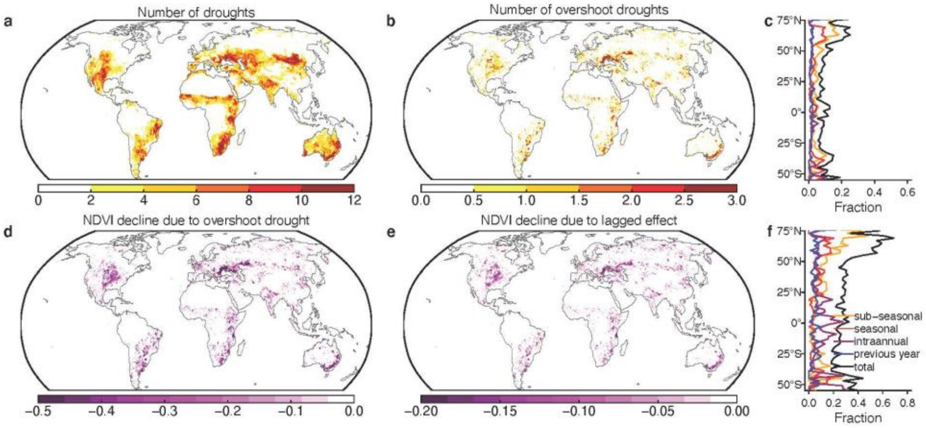

Fig. R2. Similar as Fig. 1. But uses the MODIS NDVI dataset during 2000-2018 instead of GIMMS NDVI during 1981-2015. The model considers temperature and 3-month precipitation as the major climate driver.

Frankenberg et al., Comment on “Recent Global Decline of CO2 Fertilization Effects on Vegetation Photosynthesis”, EarthArXiv, https://doi.org/10.31223/X5K89V

Joiner, J., Yoshida, Y., Vasilkov, A.P., Schaefer, K., Jung, M., Guanter, L., Zhang, Y., Garrity, S., Middleton, E.M., Huemmrich, K.F., Gu, L., Belelli Marchesini, L., 2014. The seasonal cycle of satellite chlorophyll fluorescence observations and its relationship to vegetation phenology and ecosystem atmosphere carbon exchange. Remote Sensing of Environment 152, 375–391. https://doi.org/10.1016/j.rse.2014.06.022

-- The SPEI index is not the best choice to capture vegetation-relevant water deficits. While vegetation physically relies on soil moisture supply, this information is not included in SPEI. Further, the underlying model infers (potential) evapotranspiration in a too simplified way, for example ignoring vegetation water stress, as also described by the authors. Therefore, I suggest to use soil moisture data in this study, which can for example be obtained from reanalyses such as ERA5 (Hersbach et al 2020) or machine learning products (O et al.).

Response: We agree that SPEI is an index widely used for describing meteorological drought, which may not directly reflect the drought stress that vegetation experiences. For this reason, we used a combination of SPEI and NDVI to identify drought events in our study. We chose this index because it is the most widely used index to assess drought impacts on ecosystems and, despite its shortcomings, has proven very effective (e.g., Schwalm et al., 2017; DeSoto et al, 2020; Babst et al., 2019).

Actually, one key point of this study is to highlight the mismatch between drought severity (climatological stress) and drought impact (vegetation response), which can be in part explained by structural overshoot. SPEI is an ideal indicator for this purpose as it captures the climatological anomaly. We agree that soil moisture is a more direct index to quantify the drought stress on vegetation. However, soil moisture is an integrated indicator that is not only driven by climate (precipitation, PET, etc.), but also affected by vegetation dynamics due to the changes in water consumption (increased ET when vegetation activity is higher).

Another advantage of using SPEI is that it is an observation-based indicator. Root zone soil moisture cannot be directly obtained at a global scale, and the resulting estimates of stress on vegetation are therefore affected by assumed soil characteristics and assumptions regarding vegetation rooting depth. Reanalysis dataset such as ERA5 may provide global root zone soil moisture, but the uncertainty is large and potential bias exists (Li et al., 2020).

That said, we have followed the reviewers' suggestions and examined both ERA5 and SoMo.ml soil moisture. Specifically, we have evaluated whether overshoot drought can induce greater soil moisture declines as compared to normal drought event using both ERA5 and SoMo.ml soil moisture (Fig. R3). Overshoot drought, compared to non-overshoot drought also shows greater declining speed of soil moisture, but the difference is less pronounced than the changes of vegetation. We have added these results to the Extended Data together with some discussion on the soil moisture changes in the main text (Page 11, Line 158-164).

"Using soil moisture data from ERA5 reanalysis[24] *and a machine learning approach*[25]*, we also find faster soil moisture decline for overshoot drought than non-overshoot drought (P<0.0001, paired two-sided t-test) (Extended Data Fig. 7). However, the differences in soil moisture changes are much smaller than the differences in vegetation declines (P<0.0001, unpaired two-sided t-test), likely because these datasets do not consider the interannual variations of vegetation and their effects on soil moisture."*

Due to the conflict of interest, we feel it is inappropriate to offer authorship to Dr. Orth for using the SoMo.ml soil moisture data as is suggested by the SoMo.ml data use agreement. We have instead added a statement in the acknowledgements, and thank Dr. Orth for providing the SoMo.ml data.

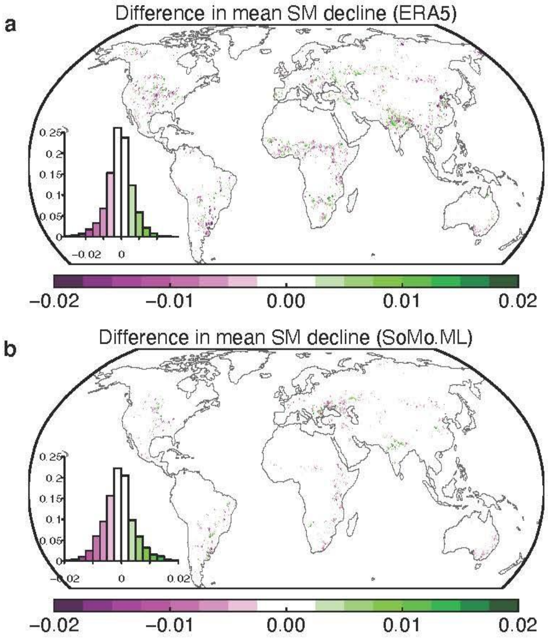

Fig. R3. Differences in soil moisture declining speed between overshoot drought and non-overshoot drought. (**a**) Using ERA5 reanalysis soil moisture between 1981-2015. (**b**) Using a machine learning based soil moisture dataset (SoMo.ml) between 2000-2018. For ERA5, we used overshoot droughts derived from GIMMS NDVI; For SoMo.ml, we used overshoot droughts derived from MODIS NDVI. Both soil moisture datasets were de-seasonalized and de-trended first so that we only focus on the soil moisture anomalies. The insets show the histogram of the differences, with negative values indicating soil moisture declining speed is greater (more negative) for overshoot drought than non-overshoot drought. Units are in $m^3 m^{-3} mon^{-1}$.

DeSoto, L., Cailleret, M., Sterck, F., Jansen, S., Kramer, K., Robert, E.M.R., Aakala, T., Amoroso, M.M., Bigler, C., Camarero, J.J., Čufar, K., Gea-Izquierdo, G., Gillner, S., Haavik, L.J., Hereş, A.-M., Kane, J.M., Kharuk, V.I., Kitzberger, T., Klein, T., Levanič, T., Linares, J.C., Mäkinen, H., Oberhuber, W., Papadopoulos, A., Rohner, B., Sangüesa-Barreda, G., Stojanovic, D.B., Suárez, M.L., Villalba, R., Martínez-Vilalta, J., 2020. Low growth resilience to drought is related to future mortality risk in trees. Nat Commun 11, 1–9. https://doi.org/10.1038/s41467-020-14300-5

Li, M., Wu, P., Ma, Z., 2020. A comprehensive evaluation of soil moisture and soil temperature from third-generation atmospheric and land reanalysis data sets. Int J Climatol 40, 5744–5766. https://doi.org/10.1002/joc.6549

Schwalm, C.R., Anderegg, W.R.L., Michalak, A.M., Fisher, J.B., Biondi, F., Koch, G., Litvak, M., Ogle, K., Shaw, J.D., Wolf, A., Huntzinger, D.N., Schaefer, K., Cook, R., Wei, Y., Fang, Y., Hayes, D., Huang, M., Jain, A., Tian, H., 2017. Global patterns of drought recovery. Nature 548, 202–205. https://doi.org/10.1038/nature23021

Babst, F., Bouriaud, O., Poulter, B., Trouet, V., Girardin, M.P., Frank, D.C., 2019. Twentieth century redistribution in climatic drivers of global tree growth. Science Advances 5, eaat4313. https://doi.org/10.1126/sciadv.aat4313

(2) In the dynamic linear model the authors do not consider important variables which are known to influence vegetation dynamics such as radiation and soil moisture. Therefore, these ignored controls might (partly) be errorneously attributed to antecedent NDVI by the model, which thereby overestimates the relevance of NDVI overshoot. I do not really agree with the argument of the authors to leave out radiation as it is correlated with temperature - this correlation might not always and everywhere be very high, and at the same time precipitation and temperature as used in the model presently are also correlated.

Response: We thank Dr. Orth for this insightful comment. Radiation and soil moisture are indeed not considered as driving factors in the DLM. The reasons we did not include radiation is that (1) radiation can be correlated with other climate variables, (2) the inter annual variation in radiation is relatively small compared to temperature and precipitation. We did not use soil moisture in the DLM because (1) soil moisture, compared to precipitation, is a more direct factor that affects vegetation growth. Actually, soil moisture should be considered as a response variable (like NDVI) rather than a driving variable for dynamic modeling. Overshoot droughts are mostly caused by the excessive usage of soil water by plants in the previous period, such that soil moisture is lower than usual when drought happens, and the impact is greater. Therefore, the dynamic changes of soil moisture can directly reflect the overshoot relationship. (2) there is no direct observation of root zone soil moisture available. Soil moisture datasets either come from reanalysis, model data fusion, or machine learning and may not adequately represent the vegetation processes in regulating soil moisture dynamics. For example, as the reviewer suggested, the vegetation water stress is currently not well modeled, which directly affects the water fluxes and soil water balance. In this study, we prefer to use observational based variables for the DLM so that it is less affected by the model uncertainties.

Using shortwave downward radiation from the CRU-NCEP dataset, we tested the correlation between radiation and other climate variables. Fig. R4 shows the correlation between (a) temperature (T) and radiation (R), and (b) between precipitation (P) and radiation. All variables are de-seasonalized since the DLM only uses the anomalies of these variables. There is a positive correlation between T and R and a strong negative correlation between P and R. It is therefore reasonable not to include radiation in the DLM in order to reduce the collinearity.

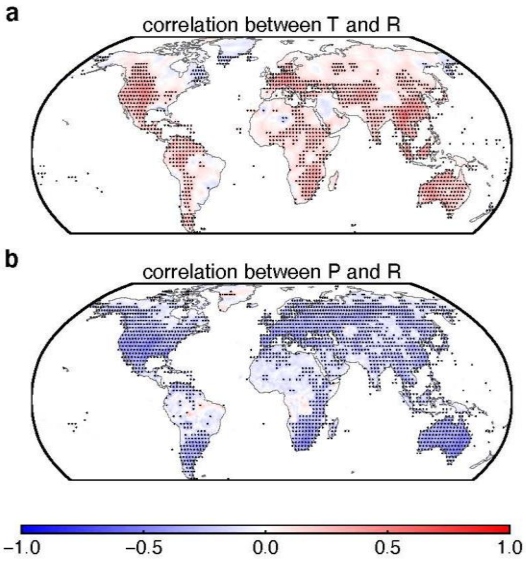

Fig. R4. Correlation between (**a**) temperature and radiation and (**b**) precipitation and radiation. All climate variables are de-seasonalized anomalies. Dotted regions indicate correlations are significant at a p-value <0.01.

We further calculated the relative interannual anomaly of the three climate variables. Precipitation shows largest interannual variability relative to the annual mean (Fig. R5a,c,e) and the seasonal variation (Fig. R5b,d,f). The interannual variability only contribute 3.3% of the annual mean value. Although the variability relative to the seasonal variability is slightly larger (13.5%), they are mostly contributed by the tropical regions, where the radiation seasonality is small. This suggests that although radiation may be important for ecosystems, its interannual variation is relatively small. Considering the DLM only uses de-seasonalized anomalies, and radiation is correlated with precipitation, we find it reasonable not to use it in the base model.

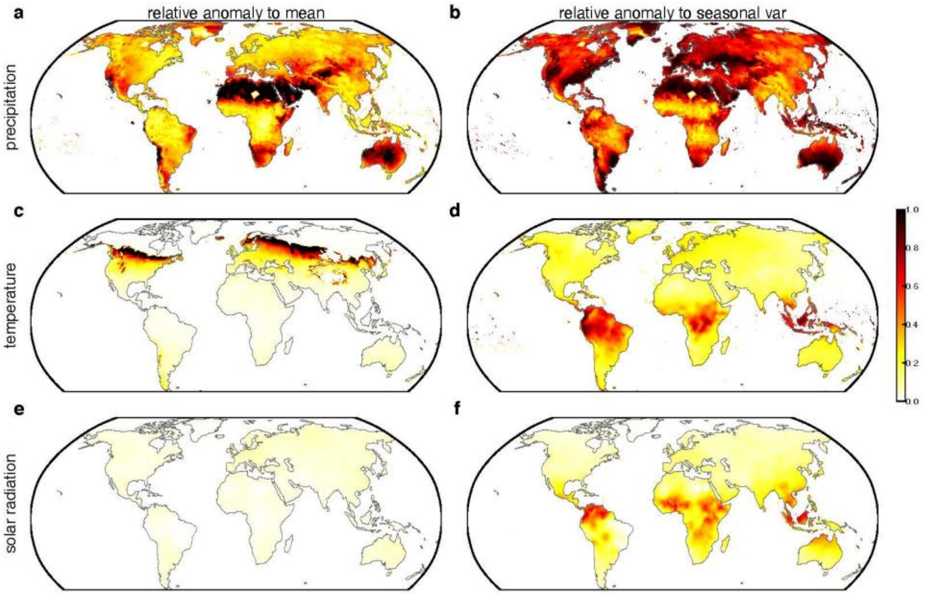

Figure R5. Relative variance of precipitation (a,b), temperature (c,d) and solar radiation (c,d). Left column shows the standard deviation of de-seasonalized anomalies (equivalent to the monthly interannual variation) relative to the annual mean. Right column shows the standard deviation of de-seasonalized anomalies relative to the seasonal variation (standard deviation of mean seasonal cycle).

To test how including radiation would affect our results, we set up an "extended experiment", which uses temperature, precipitation, and radiation as the climate drivers. The results are very similar to those that only use temperature and precipitation (Fig. R6). We have now added this result to the supplementary information for uncertainty analysis.

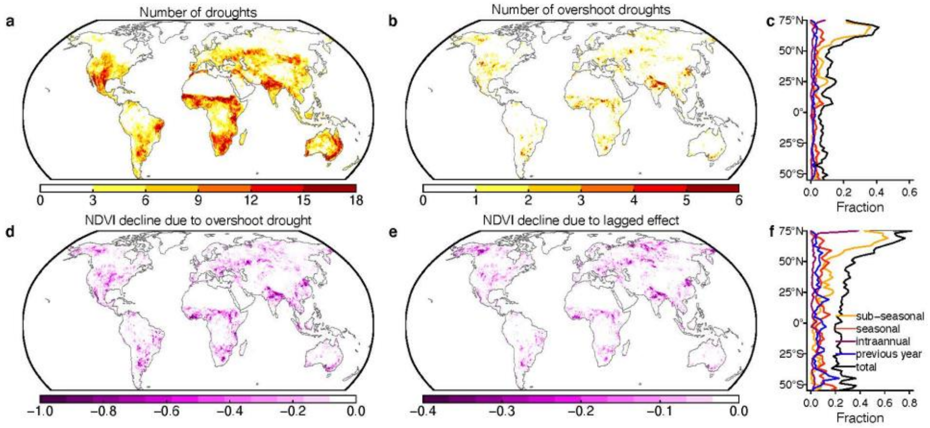

Fig. R6. Overshoot number and impact from the extended model (using temperature, precipitation, and radiation for environmental limitation) during 1982-2015.

(3) Drought is not defined in the main text. This is important for understanding the manuscript and should be added. Furthermore, the authors nicely illustrate in the supplementary material how the overshoot results change with adapting the (necessarily arbitrary) thresholds in their drought definition. This sensitivity should also be documented more clearly in the main text, and correspondingly the exact determined percentage results such as in line 19 in the abstract should be toned down or removed as this is dependent on the chosen drought definition.

Response: We agree with the reviewer that the definition of drought is important and should be mentioned in the main text. We therefore highlighted in the introduction that drought in this study is defined by a combination of a climatological drought index and vegetation greenness decline (Page 3, Line 54-56).

We also agree that the number of overshoot occurrence is dependent on the threshold being used for both the drought definition and the overshoot definition. In the revised text (Page 15, Line 318-323), we provided an ensemble range from various experiments and clearly stated that this fraction depends on model structure and threshold being used.

(4) While the manuscript is clearly structured and overall easy to read, there are many small language and grammar errors such as missing articles, particularly in the methods part. I recommend that the authors take special care of these when revising the manuscript.

I do not wish to remain anonymous - Rene Orth.

Response: We appreciate the reviewer's suggestion and have carefully gone through the manuscript and corrected language and grammar mistakes.

Specific comments:

line 3: Here you could cite Orth & Destouni 2018

Response: I assume Dr. Orth means line 31? This paper investigates the impact of drought on runoff and evapotranspiration, which is relevant to this statement, we have added the reference as suggested.

lines 37-39: It is stated that several studies have investigated the phenomenon but the understanding is still limited. This is somewhat contradictory and requires additional details.

Response: Here we highlighted that several previous studies have investigated this phenomenon, but they are either focusing on individual drought event or for small regions. A global understanding is, however, limited.

line 54: Not clear what is meant with "The anomalies" here.

Response: It refers to the "de-seasonalized and de-trended anomalies" in the previous sentence. We agree that this may not be very clear, and have therefore revised it to "anomaly components", which is easier to follow.

line 80: "Contribution of overshoot component", please clarify.

Response: We understand the reviewer's concern because we did not mention "overshoot component" in the main text. This sentence now reads:

"colored lines indicate the fraction of overshoot happening at sub-seasonal to interannual scales (see Methods)"

line 106-108: Not sure if I would agree with this reasoning.

Response: We have revised this statement as below:

"This is likely due to the fact that soil water is mostly low and has limited buffering capacity in dry regions, ecosystems are therefore more responsive to concurrent precipitation anomalies and relatively less dependent on the lagged effect[16]"

line 170" "Climatological mean temperature", this is only for drought events if I get it correctly, so it cannot be a climatological (~30-year) mean? Please clarify.

Response: The climatological mean temperature represents the long term mean temperature for each month for each pixel. Here we aim to compare the baseline temperature for overshoot and non-overshoot droughts, that is, whether overshoot droughts are more likely to happen in warmer months, as compared to the non-overshoot drought. Whether a month is warm or not is determined by the climatological mean temperature. We agree the presentation of this aspect was not clear and have revised it as:

"Red bars indicate the mean climatological temperature difference for overshoot (T_OD) and non-overshoot (T_NOD) drought events. Climatological temperature for each month is calculated during 1981-2015 for each pixel."

line 244: I think this should be overestimate rather than underestimate. If vegetation water stress is taken into account, this would reduce potential evaporation and consequently increase P-Epot which would therefore indicate reduced drought magnitude.

Response: Thanks for raising this interesting question. We agree that due to the vegetation responses to drought stress, the actual evapotranspiration (AET) would be smaller than the potential evapotranspiration. However, this mismatch in water balance calculation happens for all drought events and contributes to the actual relationship between drought severity (as indicated by drought index) and drought impact (on vegetation). This relationship is considered as the baseline.

Under overshoot drought conditions, in addition to this AET PET difference, there is an additional underestimation of AET. This is because excessive vegetation growth in the past can promote AET, which affects the soil water balance and breaks the baseline of drought severity-impact relationship. Our statement here refers to this underestimation of AET due to the ignorance of excessive vegetation activity in the past. This underestimation breaks the baseline relationship and only happens for the overshoot drought.

line 260: I think here you should apply a threshold higher than 0 degrees, as also with a monthly mean temperature slightly above zero snow and soil freezing can occur at least during parts of the month, and vegetation productivity is low.

Response: Thank you for your suggestion. We use this temperature threshold to remove NDVI observations that may be potentially contaminated by snow. Snow cover will greatly decrease NDVI and create a negative anomaly which will further affect the DLM results.

However, this anomaly does not reflect actual changes of vegetation. We agree that soil freezing can occur when monthly mean temperature is close to 0℃, and vegetation productivity is low, however, as long as the Earth surface is not covered by snow, the NDVI can still represent the status of vegetation.

We also agree that droughts are not likely to happened during these early or late growing season. However, since we are using a time-series Bayesian analysis, it is important that we use as many observations as possible to reduce the uncertainty. Using a higher threshold reduces the number of observations and may therefore undermine the model performance.

To demonstrate 0℃ is adequate to remove the possible snow contaminated observations, we select 6 sites in the northern high latitude representing 6 major biome types in this region. A snow contaminated observation can be identified as an abnormally low value compared to other observations in the same month. For example, very low values in October in Fig. R7(e,g). The red circles can identify most of these low values, while the orange circles are mostly in the normal range of other observations within the same month. This suggests that using 0℃ temperature threshold is adequate in identifying these potentially snow-covered observations. Using a higher temperature threshold, however, can greatly reduce the number of valid observations, especially in the high latitude regions.

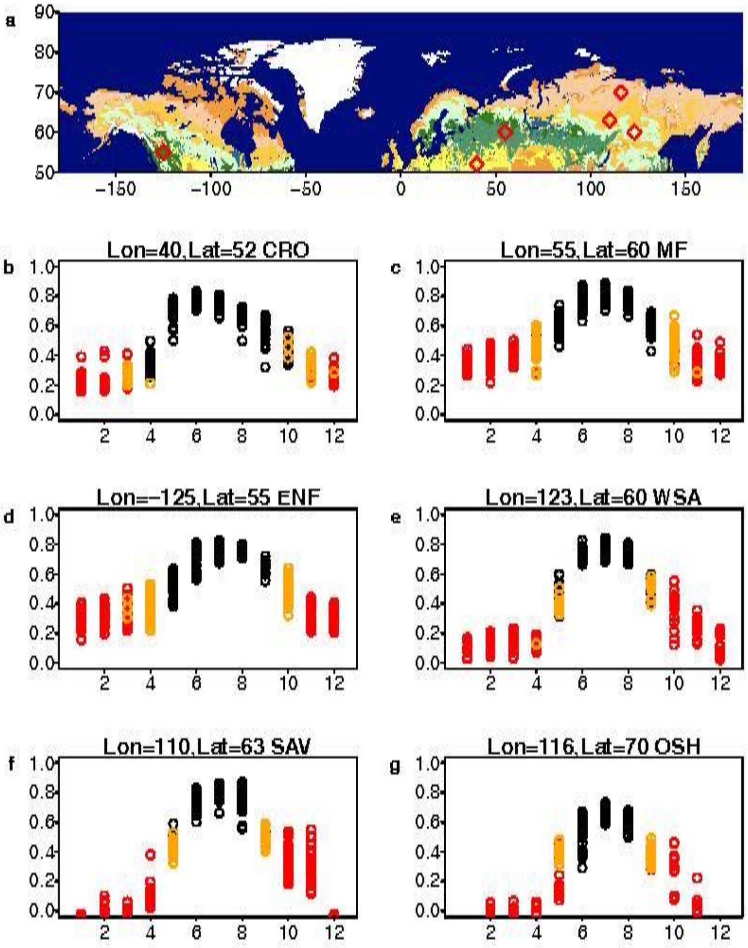

Fig. R7. NDVI time series for multiple sites with different temperature threshold. (a) land cover map from MODIS MCD12. Red diamonds indicate selected sites shown in b-g. (b-g) NDVI time series for the selected sites during 1982-2015. Black circles indicate all NDVI observations with temperature greater than 5 °C, orange circles indicate observations between 5°C and 0°C, red circles indicate observations below 0°C.

lines 268/269: "Most reliable estimate", please add reference(s) or tone down this statement.

Response: Thank you for pointing this out. We have toned down this statement and added a reference to support it. It now reads "…is often considered as a more reliable estimate of precipitation at global scale (Sun et al., 2018)"

Sun, Q., Miao, C., Duan, Q., Ashouri, H., Sorooshian, S., Hsu, K., 2018. A Review of Global Precipitation Data Sets: Data Sources, Estimation, and Intercomparisons. Rev. Geophys. 56, 79–107. https://doi.org/10.1002/2017RG000574

lines 332-334: Why did the authors decide to couple these two conditions with an "or" rather than using only the latter requirement of negative temperature sensitivity which seems quite relevant to me.

Response: We use this combination based on two concerns: (1) Although drought is usually accompanied with positive temperature anomalies, there are chances that temperature change during drought is minimal and the sensitivity is close to zero (either positive or negative). Under this circumstance, the vegetation decline is mostly due to a water deficit and should still be considered as a drought event. (2) In northern high latitude regions where temperature is mostly low, an increase in temperature during a drought period may be beneficial for vegetation growth. During a water deficit period, as long as the negative effect of water deficit is greater than the positive effect of warmer temperature (the first condition before "or" in our original statement), it should still be considered as a drought event.

Using the latter requirement exclusively may rule out some drought events, so a combination is used here.

line 353: With "drought development speed" you refer to vegetation anomaly development speed I guess. Please clarify.

Response: Thanks for pointing this out. We do mean the vegetation anomaly (drought impact) development speed, this has been corrected throughout.

line 380-381: How is "overshoot" quantified as used here?

Response: Overshoot is a categorical variable with only two values, 0 and 1. For each pixel, there are multiple drought events. Each drought event has three quantities, namely, NDVIz, SPEI3 and overshoot. A multivariate regression is used to quantify the coefficient for each variable. For Eq. (4), whether a drought is overshoot related or non-overshoot related will only affect the intercept by *b*. For Eq. (5), overshoot drought will not only change the intercept by *b*, but also change the slope of SPEI3 by *c*.

line 456-459: Also scenario (3) could induce an overshoot drought I think, for example if normal summer precipitation is accompanied by hot temperatures inducing high evaporation and consequently drought and decreased vegetation dynamics.

Response: Thank you for your suggestion. We agree that scenario (3) may potentially induce an overshoot drought event, but it highly depends on the vegetation response to soil moisture. This is because there is a negative feedback between vegetation and soil moisture, i.e., increased vegetation will decrease soil moisture, but low soil moisture will reduce evapotranspiration and counteract the further depletion of soil moisture. When there is no sudden reduction in precipitation, this feedback may operate at a timescale that only involves the plant physiological regulation, with no sudden changes of canopy structure. There are also chances that plants are very aggressive in using water and this negative feedback may not fully mitigate the declining soil moisture, which can lead to a change in canopy structure. Whether it can induce an overshoot drought is ecosystem dependent.

In our experiment, since the simple model did not predict a decline of NDVI during the summer months, we do not consider this specific event as an overshoot drought event. However, we added some discussion highlighting that whether this scenario is considered as overshoot can be ecosystem dependent. It should also be noted that these experiments are not structured to examine which scenarios are overshoot droughts, instead, they are used to test whether the DLM method can correctly identify the lagged relationship and overshoot events based on the synthetic data.

Figure 5: Please improve the labelling of the SPEI and NDVI axes to specify if there are decreases or increases.

Response: Thank you for your suggestion, we have added a sentence in the legend indicating that directions of arrows indicate a decrease for both (i.e., stronger drought severity and impact).

References:

Hersbach, H. et al., The ERA5 global reanalysis. Q. J. R. Meteorol. Soc. 146(730), 1999-2049 (2020).

O, S. and R. Orth, Global soil moisture from in-situ measurements using machine learning - SoMo.ml, https://arxiv.org/abs/2010.02374

Orth, R., and G. Destouni, Drought reduces blue-water fluxes more strongly than green-water fluxes in Europe Nat. Comms. 9, 3602 (2018).

Decision Letter, first revision:

14th July 2021

*Please ensure you delete the link to your author homepage in this e-mail if you wish to forward it to your co-authors.

Dear Professor Zhang,

Your manuscript entitled "Exacerbated drought impacts on global ecosystems due to structural overshoot" has now been seen again by three reviewers, whose comments are attached. Reviewers 1 and 2 now endorse publication, but Reviewer 3 continues to raise some concerns which must be addressed in a revision before we can reach a final decision regarding publication.

We therefore invite you to revise your manuscript taking into account all reviewer. Please highlight all changes in the manuscript text file.

We are committed to providing a fair and constructive peer-review process. Do not hesitate to contact us if there are specific requests from the reviewers that you believe are technically impossible or unlikely to yield a meaningful outcome.

When revising your manuscript:

* Include a “Response to reviewers” document detailing, point-by-point, how you addressed each reviewer comment. If no action was taken to address a point, you must provide a compelling argument. This response will be sent back to the reviewers along with the revised manuscript.

* If you have not done so already please begin to revise your manuscript so that it conforms to our Article format instructions at http://www.nature.com/natecolevol/info/final-submission. Refer also to any guidelines provided in this letter.

* Include a revised version of any required reporting checklist. It will be available to referees (and, potentially, statisticians) to aid in their evaluation if the manuscript goes back for peer review. A revised checklist is essential for re-review of the paper.

Please use the link below to submit your revised manuscript and related files:

[REDACTED]

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Please do not hesitate to contact me 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.

[REDACTED]

Reviewers' comments:

Reviewer #1 (Remarks to the Author):

The authors have satisfactorily addressed my main concerns. The changes in the ms have clarified key concepts. The global scope of this work makes impossible to link these patterns to community-level processes, yet the results presented open interesting questions and research avenues to understand the interplay between climate and vegetation structure from remote sensing products.

Reviewer #2 (Remarks to the Author):

A minor spelling mistake is found in line 679: "standardized precipitation evaporation index" should be written as "standardized precipitation evapotranspiration index" .

Reviewer #3 (Remarks to the Author):

Second review of Zhang et al., NATECOLEVOL-210112662A
“Exacerbated drought impacts on global ecosystems due to structural overshoot‟

The paper has overall improved as the authors have addressed some of the concerns raised in the first review.
However, at the same time some important issues remain insufficiently addressed:

-- regarding main comment (1) from my previous review
I appreciate that the authors have repeated their analysis with the more reliable MODIS NDVI data and can demonstrate similar conclusions.
Also I understand the arguments for employing SPEI in this study as stated in the rebuttal,

which, however, are not yet sufficiently reflected in the main text for all readers.

-- regarding main comment (2) from my previous review
I appreciate the effort of the authors to test the inclusion of radiation in the dynamics linear model. As for the soil moisture, I understand that it can (to some extent) be seen as a response variable of, rather than a predictor for, NDVI changes. However, I am not sure I fully agree with this because soil moisture dynamics are of course impacted by many other factors than vegetation such as precipitation and runoff dynamics, and in my opinion are key to fully understand and predict vegetation dynamics. Moreover, following your argument also precipitation and temperature can be classified as response variables as vegetation influences temperature (via evaporative cooling) and precipitation (via moisture supply and affecting boundary layer stability). In terms of (insufficient?) soil moisture data quality I want to point out that direct observations of root-zone soil moisture are indeed available and used in for example the derivation of the SoMo.ml product. Further, also precipitation data which is employed in the dynamic linear model comes with significant uncertainty.
Anyway, if the authors still do not want to include soil moisture into the linear model, I suggest at least they should include precipitation at different time intervals (e.g. 0 months, -1 month, -2 months) rather than summarizing this, because this can mitigate the precipitation signal and thereby lead to an overestimation of the NDVI importance in the linear model, resulting in an overestimation of overshoot droughts.

-- regarding main comment (3) from my previous review
It is good to see that the authors have given some more detail on the employed drought definition in the main text. However, the SPEI is still not introduced at all in the text while the authors instead use the general term "climatological drought index".

lines 168/169: The SoMo data does consider inter-annual vegetation variability as it is based on training a machine learning algorithm with in-situ soil moisture measurements which carry the imprint of vegetation variability.

Reference #25 can be updated to
O, S. & Orth, R., Global soil moisture data derived through machine learning trained with in-situ measurements,
Scientific Data, doi: 10.1038/s41597-021-00964-1 (2021).
[the manuscript is in press and should be published soon]

I do not wish to remain anonymous - Rene Orth.

*******************END*******************

Author Rebuttal, first revision:

We thank the reviewers for their constructive comments. We have carefully considered and addressed each of the comments from the reviewers. Below we provide each of the original comments, with our responses in blue. The page and line numbers referred to are for the clean version of the revised manuscript (non-track-change version).

Reviewers' comments:

Reviewer #1 (Remarks to the Author):

The authors have satisfactorily addressed my main concerns. The changes in the ms have clarified key concepts. The global scope of this work makes impossible to link these patterns to community-level processes, yet the results presented open interesting questions and research avenues to understand the interplay between climate and vegetation structure from remote sensing products.

Response: We thank the reviewer for supporting our study and appreciate the constructive comments in this process.

Reviewer #2 (Remarks to the Author):

A minor spelling mistake is found in line 679: "standardized precipitation evaporation index" should be written as "standardized precipitation evapotranspiration index" .

Response: We appreciate the reviewer’s time and efforts in improving the manuscript. We have corrected this mistake in the revised version.

Reviewer #3 (Remarks to the Author):

Second review of Zhang et al., NATECOLEVOL-210112662A
“Exacerbated drought impacts on global ecosystems due to structural overshoot“

The paper has overall improved as the authors have addressed some of the concerns raised in the first review. However, at the same time some important issues remain insufficiently addressed:

Response: We thank Dr. Orth for the constructive suggestions on the previous version of the manuscript. In this revision, we have followed Dr. Orth’s suggestions and tested the overshoot patterns using precipitation from previous months separately. The results show that doing so does not quantitively change our conclusions.

-- regarding main comment (1) from my previous review
I appreciate that the authors have repeated their analysis with the more reliable MODIS NDVI data and can demonstrate similar conclusions.
Also I understand the arguments for employing SPEI in this study as stated in the rebuttal, which, however, are not yet sufficiently reflected in the main text for all readers.

Response: We are glad that Dr. Orth supports our use of GIMMS NDVI and SPEI. We now better discuss the rationale behind the choice of SPEI in this study and its advantages in the method section.

“We also use a standardized precipitation evapotranspiration index (SPEI[40]) dataset for drought identification and drought severity assessment. SPEI is a widely used climatological drought index that calculates the standardized water balance anomalies (precipitation minus potential evapotranspiration) at different time scales. It is therefore an optimal index to evaluate the drought severity-impact relationship and the role overshoot plays in this process.”

“We use a combination of SPEI and NDVI together with outputs from the DLM to identify drought events. Both indices are directly calculated from observations and represent the climatological drought severity and the drought impact on vegetation, respectively.”

-- regarding main comment (2) from my previous review
I appreciate the effort of the authors to test the inclusion of radiation in the dynamics linear model. As for the soil moisture, I understand that it can (to some extent) be seen as a response variable of, rather

than a predictor for, NDVI changes. However, I am not sure I fully agree with this because soil moisture dynamics are of course impacted by many other factors than vegetation such as precipitation and runoff dynamics, and in my opinion are key to fully understand and predict vegetation dynamics. Moreover, following your argument also precipitation and temperature can be classified as response variables as vegetation influences temperature (via evaporative cooling) and precipitation (via moisture supply and affecting boundary layer stability). In terms of (insufficient?) soil moisture data quality I want to point out that direct observations of root-zone soil moisture are indeed available and used in for example the derivation of the SoMo.ml product. Further, also precipitation data which is employed in the dynamic linear model comes with significant uncertainty. Anyway, if the authors still do not want to include soil moisture into the linear model, I suggest at least they should include precipitation at different time intervals (e.g. 0 months, -1 month, -2 months) rather than summarizing this, because this can mitigate the precipitation signal and thereby lead to an overestimation of the NDVI importance in the linear model, resulting in an overestimation of overshoot droughts.

Response: We are happy that Dr. Orth agrees with our analysis on soil moisture in ED Fig. 7. We also fully agree that soil moisture plays a predominate role in regulating vegetation growth especially during drought periods. We do not mean soil moisture should not be considered to predict vegetation dynamics, on the contrary, our study highlights the importance of soil moisture, which may be the key to understand why overshoot would happen.

However, in this specific study, soil moisture should not be considered an input variable for the DLM. We include the vegetation anomalies from previous periods in the DLM to implicitly account for their effects on soil moisture, which provides the lagged linkages between past and current vegetation. Including soil moisture in the DLM may mask out these lagged linkages, which directly undermines our algorithm for overshoot identification.

We agree with Dr. Orth that there are root-zone soil moisture observations available, but those are mostly site-level obversions and are not suitable for this global scale analysis. Precipitation dataset, like other observations, inevitably have uncertainties, we therefore use the GPCC precipitation dataset which uses largest number of weather stations globally (>20000-50000 sites).

Nevertheless, we followed Dr. Orth’s suggestion and used precipitation from three previous months separately (0 month, -1 month, -2 month) in the DLM. This DLM also considers previous month NDVI and other climate factors including temperature and radiation. The fraction of overshoot drought numbers is slightly lower (10.7% as compared to 11.2% in Figure 1), the spatial patterns of overshoot number and impact obtained from this model, however, are very similar to the ones we show in the main text (Fig. R1). This analysis demonstrates the robustness of our method and results. We regard this analysis as additional experiment and add it in the Supplementary Information as Fig. S7. Descriptions about this experiment is also added in Supplementary Information Text S2.

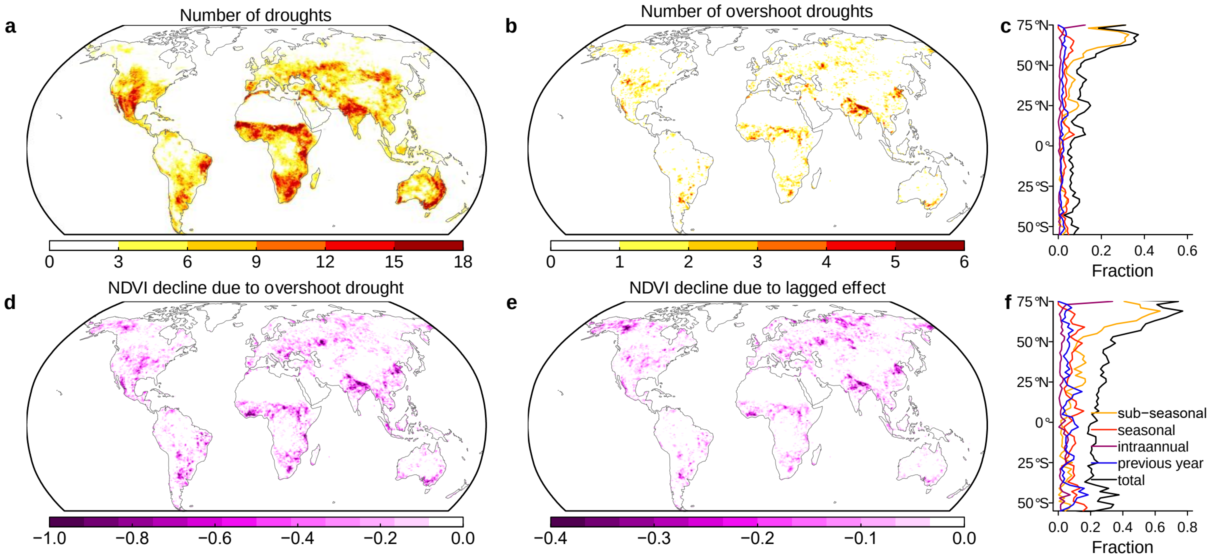

Fig. R1. Drought and overshoot drought patterns from the “discrete precipitation model”. Same as Fig. 1, but uses the “discrete precipitation model” that does consider the climate variables including temperature, radiation, and precipitation from current month and previous two months separately.

-- regarding main comment (3) from my previous review
It is good to see that the authors have given some more detail on the employed drought definition in the main text. However, the SPEI is still not introduced at all in the text while the authors instead use the general term "climatological drought index".

Response: We appreciate Dr. Orth’s suggestion and agree that SPEI should be better explained in the main text to improve readability. In this revision, we added additional explanations of SPEI when we evaluate how overshoot affects the drought severity and impact relationship (Line 175-177). Understanding what SPEI represents is helpful to the interpretation of Fig. 5. We did not mention and explain SPEI in the last paragraph of introduction, since here is just a very brief summary of the method.

"…as shown by a more negative NDVI anomaly compared to the standardized precipitation evapotranspiration index (SPEI) anomaly (Extended Data Fig. 9). SPEI is a widely used drought severity indicator which calculates the standardized surface water balance anomaly from meteorological variables."

lines 168/169: The SoMo data does consider inter-annual vegetation variability as it is based on training a machine learning algorithm with in-situ soil moisture measurements which carry the imprint of vegetation variability.

Response: We thank Dr. Orth for pointing this out. We agree that soil moisture carries the imprints of vegetation activity, since vegetation is not only affected by soil moisture, but also provides feedbacks to it by modifying evapotranspiration and related processes. However, since vegetation is dynamically changing all the time, its effect is also time-varying and may not be well represented by the data assimilation technique or LSTM.

We therefore revised the statement, it now reads "…, potentially because the interannual variation of vegetation is not used as a forcing in these datasets, and their effects on soil moisture may thus be underestimated."

Reference #25 can be updated to
O, S. & Orth, R., Global soil moisture data derived through machine learning trained with in-situ measurements,
Scientific Data, doi: 10.1038/s41597-021-00964-1 (2021).
[the manuscript is in press and should be published soon]

Response: We have revised the reference as suggested.

I do not wish to remain anonymous - Rene Orth.

Decision Letter, second revision:

28th July 2021

Dear Dr. Zhang,

Thank you for submitting your revised manuscript "Exacerbated drought impacts on global ecosystems due to structural overshoot" (NATECOLEVOL-210112662B). I'm happy to say that we have assessed the revision editorially (without going back to reviewers) and we are happy in principle to publish it in Nature Ecology & Evolution, pending minor revisions to comply with our editorial and formatting guidelines.

If the current version of your manuscript is in a PDF format, please email us a copy of the file in an editable format (Microsoft Word or LaTex)-- we can not proceed with PDFs at this stage.

We are now performing detailed checks on your paper and will send you a checklist detailing our editorial and formatting requirements in about a week. Please do not upload the final materials and make any revisions until you receive this additional information from us.

Thank you again for your interest in Nature Ecology & Evolution. Please do not hesitate to contact me if you have any questions.

[REDACTED]

Our ref: NATECOLEVOL-210112662B

30th July 2021

Dear Dr. Zhang,

Thank you for your patience as we've prepared the guidelines for final submission of your Nature Ecology & Evolution manuscript, "Exacerbated drought impacts on global ecosystems due to structural overshoot" (NATECOLEVOL-210112662B). Please carefully follow the step-by-step instructions provided in the attached file, and add a response in each row of the table to indicate the changes that you have made. Please also check and comment on any additional marked-up edits we have proposed within the text. Ensuring that each point is addressed will help to ensure that your revised manuscript can be swiftly handed over to our production team.

We would like to start working on your revised paper, with all of the requested files and forms, as soon as possible (preferably within two weeks). Please get in contact with us immediately if you anticipate it taking more than two weeks to submit these revised files.

When you upload your final materials, please include a point-by-point response to any remaining reviewer comments.

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In recognition of the time and expertise our reviewers provide to Nature Ecology & Evolution’s editorial process, we would like to formally acknowledge their contribution to the external peer review of your manuscript entitled "Exacerbated drought impacts on global ecosystems due to structural overshoot". For those reviewers who give their assent, we will be publishing their names alongside the published article.

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Final Decision Letter:

10th August 2021

Dear Professor Zhang,

We are pleased to inform you that your Article entitled "Exacerbated drought impacts on global ecosystems due to structural overshoot", has now been accepted for publication in Nature Ecology & Evolution.

Before your manuscript is typeset, we will edit the text to ensure it conforms to house style.

Once your manuscript is typeset you will receive a link to your electronic proof via email, with a request to make any corrections as soon as possible. If you have queries at any point during the production process then please contact the production team at rjsproduction@springernature.com. Once your paper has been scheduled for online publication, the Nature press office will be in touch to confirm the details.

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