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Interactive comment on "Impacts of extreme precipitation and seasonal changes in precipitation on plants" *by* M. J. B. Zeppel et al.

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We appreciate the thoughtful comments about our manuscript. Several comments, such as those regarding our discussion of the role of soil water content as a key factor and our focus on manipulative experiments, highlight areas we agree are essential to understanding this issue. Although we sought to emphasise these points, we clearly did not reach our goal, and our revised manuscript more clearly addresses these issues.

More generally, we have earnestly attempted to address all raised issues and list our responses in the reply below. In our reply, we have repeated each comment (in italics), followed by our response. All referenced changes have been implemented in the revised manuscript. If there are any questions regarding our responses, please let us know.

Sincerely, Melanie Zeppel, Jessica Wilks, and Jim Lewis.

Short Comment, Y. Zhang COMMENT: This paper presents a new review on how altered precipitation patterns impacts vegetation of grassland and forest, mainly focusing on the studies of manipulative precipitation experiments. The key point of the impacts is how altered precipitation patterns drive the changes of soil water content, which is already supported in previous studies (e.g., Knapp et al. (2008)). Although the authors have reviewed many literature in this area, especially from the studies of experiments, the reviews is not completed. As we know, one of the strengths of manipulative experiments is that they permit the examination of any combination of precipitation dynamics one wants to explore. The problem with manipulation experiments is that they did not incorporate the entire micro- and macro- environmental aspects of variable weather, and that the scale of manipulation experiments is sufficiently small that border effects can alter the results from what might be expected of more pervasive, naturally-occurring weather phenomena. Hence, only reviews of experimental studies might be not sufficient. Some studies investigated in natural environments need be added. Natural experiments have more power to study the nuances of the problem than manipulations and rain exclusion, as the response functions are highly nonlinear and the results depend on which treatments are made and when the rain is applied or removed. In this case, long-term measurements of natural variability in field settings either from eddy covariance flux tower (e.g., Ross et.al., 2012, Biogeoscience, 007-10024) or remote sensing (e.g., Zhang et.al., 2013,J. Geophys. Res. Biogeosci., 118, 148–157) at ecosystem scale can be quite useful, in addition to the manipulative experiments.

As stated in the paper, two different types of altered precipitation patterns were used in their conceptual framework: 'reduced precipitation' and 'amount remained constant'. However, there is another type of altered precipitation patterns in the real world: annual precipitation amount increased with the increase of extreme events and longer dry periods because total rainfall amount and large storms are strongly interrelated in

natural settings (e.g., Zhang et. al., 2013). Therefore, only two assumptions of altered precipitation patterns are not sufficient and could not represent the 'real' response of vegetation to these changes.

RESPONSE: We agree that understanding the effects of any particular factor on natural systems requires an understanding of how that factor interacts with other factors. However, observational studies cannot establish cause and effect. As our focus in this review is on whether changes in precipitation regimes may affect vegetation, we focus specifically on manipulative experiments so that we can address cause and effect. Having said that, the realised effects of changes in precipitation regimes will reflect other drivers. We will revise the manuscript to more-clearly state that, while our goal was to review whether changes in precipitation regimes affect vegetation, the ultimate effects in natural systems will reflect interplay with other factors. And, as noted in this comment and the one that follows, a combination of manipulative studies and observational studies will be required to fully understand the effects of extreme precipitation on natural systems. Accordingly, we will broaden our discussion of the need for more observational studies, and will add the suggested references.

Referee Comment, Kate Holland

COMMENT: This paper reviews 16 seasonal and eight extreme rainfall manipulation experiments to draw conclusions about how altered rainfall patterns affects grassland, shrubland and forest vegetation. The review could be improved by using a consistent comparison metric such as the climate aridity index (PET/P) to compare sites. Mean annual precipitation (MAP) alone is not a good indicator of plant water availability. Comparison of seasonal or monthly PET/P ratios may also provide insight into the plant responses to seasonal and extreme precipitation patterns. Several of the studies showed that soil water content (SWC) was a driver of plant response, however there is little discussion of the role of soil type or description of site soils in determining soil responses to rainfall. The review is limited to experimental studies of rainfall manipulation, however this is not clearly stated in the title or introduction. Value could be gained

by inclusion of studies in natural ecosystems where the study period occurred during drought or altered rainfall seasonality. This could expand the review to include altered rainfall patterns where annual totals increase.

RESPONSE: This comment notes that effects of changes in precipitation will be mediated by soil characteristics; we agree, and sought to emphasise this point in the original manuscript. We will revise the manuscript to further emphasise that soil characteristics and effects on soil water content will regulate vegetation responses to extreme precipitation and seasonal changes in precipitation.

This comment also emphasises the importance of using a combination of manipulative and observational studies to develop a fuller understanding of the effects of extreme precipitation and seasonal changes in precipitation on vegetation. As noted above, we agree with this assertion, and will revise the manuscript to clarify that we focus on manipulative experiments (for reasons noted above), while also more clearly articulating that a combination of manipulative studies and observational studies will be required to fully understand the effects of extreme precipitation on natural systems.

Specific comments: COMMENT:It is not clear from where the hypotheses contained in Box 1 are derived. Are they from Brzostek et al. (2012)?

RESPONSE: The hypotheses in Box 1 are not from Brzostek et al. 2012, rather they are derived from Knapp et al. 2008 and other literature. We will clarify this in the revised manuscript.

COMMENT: The conclusions of the review appear to rely heavily on the six studies in Table 3 and Figure 2. Is there value in referring the reader to Box 1 during the conclusion section?

RESPONSE: This is an excellent suggestion and we will incorporate it – referring the reader to Box 1.

COMMENT: Could the studies in Tables 1 and 2 be summarised in a 3D plot of growth

response (+ or -), seasonal change and PET/P for each biome and climate classification? Even the qualitative nature of this plot would help the reader to compare these studies.

RESPONSE: This also is an excellent suggestion, and ideally each study would include PET and P for each site. However, we found that many of the studies not only omitted mean annual PET for the site, they also didn't provide mean annual rainfall – a key variable in understanding the vegetation's response to altered precipitation. Thus, we will revise the paper to suggest that each study reports both mean annual rainfall as well as potential ET.

COMMENT: Title, abstract, introduction: please emphasize that the review is limited to experimental rainfall manipulation studies.

RESPONSE: We agree this change will clarify the focus of the review, and will revise the manuscript accordingly.

COMMENT: Ln 69 change to 'individual droughts.'

RESPONSE: We will make this change.

COMMENT: Ln 78 change to 'links between soil'

RESPONSE: We will make this change.

COMMENT: Ln 92 change to 'knowledge of the'

RESPONSE: We will make this change.

COMMENT: Ln 139 please define SWC

RESPONSE: We will add this definition.

COMMENT: Ln 145 please clarify whether Box 1 is derived from Brzostek et al. (2012)

RESPONSE: The hypotheses in Box 1 are not from Brzostek et al. 2012, rather they are derived from Knapp et al. 2008 and other literature. We will clarify this in the

revised manuscript.

COMMENT: Ln 282-294 what role does soil type play at these sites?

RESPONSE: We will address this here. As noted above, we will also more generally revise the manuscript to further emphasise the role of soil characteristics in regulating the effects of extreme precipitation and seasonal changes in precipitation on vegetation.

COMMENT: Ln 301 change to 'in Africa reported'

RESPONSE: We will make this change.

COMMENT: Ln 339-341 sentence incomplete

RESPONSE: We will rewrite this so that it is a complete sentence.

COMMENT: Ln 343-344 could this also be due to their adaptation to drought?

RESPONSE: Potentially, yes. We will revise the manuscript to more clearly emphasise differential responses among plants due to differences in adaptation to drought.

COMMENT: Ln 369 change to 'particularly trees'

RESPONSE: We will make this change.

COMMENT: Ln 406 change to 'had a larger positive impact'

RESPONSE: We will make this change.

COMMENT: Table 3 MAP, Co and KS are not defined.

RESPONSE: We will add these definitions.

Referee Comment, Anonymous referee COMMENT: Synopsis: This is a well written manuscript that reviews prior studies of the impacts of redistributions of annual precipitation on plant productivity various biomes. In particular the authors consider changes in the seasonal distribution of precipitation as well as what they refer to as "extreme

precipitation". The article reviews numerous studies that have examined aspects of this topic, and identifies key knowledge gaps that are necessary steps for resolving the coupled impacts of vegetation, carbon and water resources given projected changes in precipitation redistributions for many parts of the globe under anthropogenic change. I highlighted a few items the authors might consider addressing including a couple items that warrant clarification or further explanation, as well as considering putting the discussion of changes in precipitation seasonality into a climatic water balance context.

RESPONSE: We appreciate the positive feedback and the suggested considerations. We have sought to adequately address these, and outline below our response to each suggestion.

Major Considerations: COMMENT: 1. Precipitation extremes can be defined in a number of ways. I believe the authors are focusing on timescales associated with individual weather systems, but this is not completely clear. It might be useful to discuss the different timescales of hydrologic extremes (e.g., multidecadal drought/pluvial, interannual, etc.) and responses of plants as a backdrop for the main focus of the article. While beyond the scope of the review, the authors might mention the potential for a confluence of extremes (e.g., multiyear drought + extended growing season dry spell) resulting in nonlinear impacts to ecosystems. Also, it might be worth to include the findings of Dreesen et al. (2014) who have examined the impact of repeated extremes on vegetation.

RESPONSE: We will mention the possibility of a confluence of extremes, and cite Dreesen et al 2014.

COMMENT: 2. It might be useful to consider contextualizing projected impacts of precipitation extremes, and in particularly seasonality, using climatic water balance and the parameters actual evapotranspiration and climatic water deficit as these will be connected to soil water content. Presumably some of the changes in precipitation seasonality discussed, such as increased/decreased spring/summer precipitation might

result in more water biologically available for plants during the growing season. However, the climatological seasonality in precipitation will play a significant role in determining the impacts. You might caveat that it challenging to definitively say that reduced spring precipitation may be detrimental to ANPP (e.g.,) unless moisture is a limiting factor during that particular season. For example, in Figure 2, the responses for the sites with higher MAP might be significantly different if precipitation were concentrated during the growing season, or instead during the winter months.

RESPONSE: We will further clarify that the impact of changed seasonality of precipitation also depends on when soil moisture is limiting.

COMMENT: 3. I recommend the authors consider some of the latest projections on changes in precipitation extremes as quantified as the magnitude of precipitation extremes and the duration of dry spells discussed in the IPCC WG1 (See Ch 12, WG1, Figure 12.26). Some regions of the globe may be subjected to both increases in precipitation extremes and dry spell length that might be worth emphasizing.

RESPONSE: Excellent suggestion - we will incorporate the latest IPCC projections.

COMMENT: 4. In Section 2.1.1 the example given is of the Colorado Plateau which does not strike me as a boreal or sub-alpine region, but rather a cold desert of the intermountain western North America. Also, the authors report species were sensitive to summer, rather than winter drought. Given the ambiguity of the meaning of "drought", it would be better to be specific.

RESPONSE: This is a good suggestion, we will clarify which season the drought occurred in, and rename the biome the study comes from.

COMMENT: 5. Soil water is also influenced by the phase of precipitation and delayed release of water from snowmelt in certain areas. Given the discussion on climate change and the large-scale changes anticipated in snowfall and snowmelt it might be useful to include a short discussion of snow as it does modify the seasonal availability

of water that might otherwise be masked when just examining precipitation seasonality.

RESPONSE: We will add text discussing how changing temperatures alter snowmelt, and thus modifies seasonal availability of water.

Minor Considerations: COMMENT: 1. Abstract, first sentence: The entire globe is not universally projected to see increases in precipitation extremes and longer dry spells. This statement might be relaxed somewhat.

RESPONSE: We agree our statement may come across as too strong; we will revise accordingly.

COMMENT: 2. Pg 16648, line 17-19: Do you mean to say that the total quantity of "precipitation" rather than "water" remains constant?

RESPONSE: Good question. This statement should refer to precipitation, and we will revise accordingly.

COMMENT: 3. Page 16652, line 4: Define ROS

RESPONSE: We will add this definition.

COMMENT: 4. Page 16655, Line 18: Africa, rather than African?

RESPONSE: Yes; we will revise accordingly.

COMMENT: 5. Anderegg and colleagues have done some good work examining the impacts of both short and long-term drought on tree mortality in the western United States. Some of their work has shown short-term extreme moisture deficits that limit shallow water reserves to be particularly important in mortality.

RESPONSE: This is an excellent point, and Anderegg and colleagues are leading the field in mortality research in the Western United States. We particularly enjoy their finding that there is a multi-year time lag between drought and final mortality. The suite of studies conducted by Anderegg et al. imposed droughts rather than altering

the timing of precipitation, thus, these studies were outside the scope of this review. However we will add text commenting that a drought in one year may not lead to final observed mortality until years later, and cite Anderegg.

[Listed references] Anderegg, W. R. L., J. Kane, and L.D.L. Anderegg (2013). Consequences of widespread tree mortality triggered by drought and temperature stress. Nature Climate Change. 3: 30–36 Anderegg, L.D.L., W.R.L. Anderegg, J. Abatzoglou, A. Hausladen, and J.A. Berry (2013). Drought characteristics' role in widespread aspen forest mortality across Col- orado, USA. Global Change Biology. 19: 1526–1537 Dreesen, F. E., De Boeck, H. J., Janssens, I. A., and Nijs, I. (2014) Do successive climate extremes weaken the resistance of plant communities? An experimental study using plant assembl.

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