Interactive comment on "Quantifying the Impacts of Compound Extremes on Agriculture and Irrigation Water Demand" by Iman Haqiqi et al.

Comments and Responses to Anonymous Referee #2 ***(Reviewer comments in italics)***

Overall: *The paper is about a well-designed study aiming to elaborate individual and compound extreme event impacts on corn yields in the USA using statistical approach. The significance of extreme events on yield anomalies were studied using various indicators of soil moisture (representing water stress) as well. The outcomes of the paper can be insightful for further studies of predicting crop yield anomalies and assessing impacts of extreme weather conditions to crop yields. Consequently, the paper is worth for publishing with some revisions.*

We would like to thank the referee for his/her helpful comments that helped to improve the manuscript. We have revised the paper accordingly and provided overall and specific answers below. Also, many thanks for the positive feedback on the technical details and the significance of the paper.

As the majority of the comments are around the organization of the paper, we have revised the flow of the paper and transitions within the sections. We have dropped the sections identified less relevant by the referees. This has resulted in a substantial re-ordering of the material presented, and these changes have substantially shortened the paper as requested by the reviewer. Now, the paper is focused on the main messages. The manuscript introduces the problem by stating the research gap as "current statistical models of crop yield prediction ignore the compound extreme". And we establish the discussion around the main finding that "statistical models ignoring compound hydroclimatic extremes will significantly underestimate the yield response to water in hot days while they will significantly overestimate the yield response to water in moderate days". The referee's comments also helped us identify the unclear terms and less critical ideas. They helped us to improve the cohesion of the writings by providing clarifying definitions for unfamiliar terms and by removing the ideas not critical for the argument. The background information has been moved to the Supplementary Materials. We have also clarified the methods, moved some parts of the appendix to the text, and moved some parts of the Methods section to the Supplementary. These are major changes:

Introduction: We have included some of the text from the section "Empirical concerns" to provide adequate background on the models and metrics of individual and compound hydroclimatic extremes for predicting corn yields. We limited the text on the state of the art in the statistical prediction of corn yields to highlight current shortcomings. We kept the text on the description of the objectives to give a clear view of the originality of the research. We have removed the sentences more relevant to the Results and Conclusion.

Empirical concerns: A shortened version of this section has been merged into "Methods" and "Introduction" sections as follows. The sentences regarding the Schlenker and Roberts (2009) model are moved to the Methods section making the base for our model with individual extremes. The sentences regarding spatial aggregation are removed, we only kept our method for spatial aggregation in the Methods section. The sentences regarding average versus extreme metrics of water availability are moved to the introduction as they show the shortcomings in the current literature and how we are going to address them in the paper. The sentences regarding "interaction of soil moisture and heat" are shortened, rephrased, and moved to the introduction as they are base for our arguments about compound extreme. We have also clarified the meaning of the statistical term "interaction" when it first appeared in the manuscript. Finally, the sentences regarding measurement errors and endogeneity concerns are moved to Supplementary.

Methods: This section has some minor changes. We re-order the sub-sections introducing the data before the models. Also, technical terms are described including the “panel fixed effect” method, “daily interaction of heat and soil moisture”, and “conditional marginal impact”. Figures 1-3 are improved to support definitions and methods.

Results: The results from Model 1 (individual extremes) and Model 2 (compound extremes) have not changed. However, we added a couple of sentences to provide a comparison with previous studies. We added two critical subsections here. A new sub-section on “Model comparison” compares the performance of each model in predicting yields and to illustrate why we have estimated different models with different assumptions and different water metrics. It clearly shows the advantages of using a model with compound extremes. Also, a new sub-section on “Robustness checks” describes why we do these checks and what we learn. Figures 4-6 are moved to the Results section with more details.

Discussion: This section is substantially shortened. We dropped contents about methods and results. The section on “implications for climate studies” and the related text is dropped. The section on “implications for irrigation water demand” and the related text is dropped. Based on our findings we argue that “As we find that the coefficient on extreme heat is significantly different when considering soil moisture, it is possible that previous statistical studies have over- or under-estimated the yield impacts”. The revised Discussion section is provided below.

In the following sections, we offer detailed responses to each comment.

My major comments on the paper are:

1- *The paper needs to be re-structured/re-written. First, it is too lengthy including textbook information (e.g. Figure 1b, and Figure 2) which are not necessary for the reader (peer knowledge). Second, its structure is chaotic: the introduction chapter includes results and discussions points etc; it is like a short summary of the whole paper; the discussion section includes equations, methods, results and data sources. The authors claim to include results/conclusions which are too diverse and out of scope of the analysis (e.g. irrigation, farm soil management, marginal value, decision making as specified in the abstract). The framework of analysis do not support to make conclusions about these topics. The authors should revise their goals and associated conclusions accordingly. The paper is about compound vs individual extreme events on crop yield and comparison of different soil moisture indicators. Other conclusions not taken from this analysis can be excluded. Furthermore, the empirical concerns are relevant however too lengthy for readers. It can be reduced and can be removed to SI.*

Overall response: Thanks for these excellent suggestions. These comments helped us to improve the organization of the paper. To minimize redundancies and maximize the audience engagement, we re-organized the manuscript. We omitted the less relevant parts in order to focus on the main message. This has resulted in a substantial re-ordering of the material presented, and substantially shortened the paper.

Comment: “it is too lengthy”

Response: Regarding the length of the paper, we have shortened the paper substantially from 52 pages (around 19,000 words) to 29 pages (around 10,000 words).

Comment: "including textbook information (e.g. Figure 1b, and Figure 2) which are not necessary for the reader (peer knowledge)"

Response: Regarding the textbook information, we have dropped panel b from figure 1. Figure 2 and 3 are revised to illustrate the critical concepts and definitions necessary for this study.

Comment: "*the introduction chapter includes results and discussions points etc; it is like a short summary of the whole paper"*

Response: The flow of the Introduction section has been revised as you will see from the following responses. We have omitted the contents related to conclusion, discussion and summary from the Introduction. The first paragraph and the last paragraph are omitted too.

Comment: "*the discussion section includes equations, methods, results and data sources"*

Response: The Discussion section has been revised substantially as you will see below. We have omitted the equations, methods, and results type of content from it.

Comment: "*The authors claim to include results/conclusions which are too diverse and out of scope of the analysis (e.g. irrigation, farm soil management, marginal value, decision making as specified in the abstract). The framework of analysis do not support to make conclusions about these topics. … Other conclusions not taken from this analysis can be excluded."*

Response: We agree that some of the discussions required further details and their relevance to the main message were not well-defined. Hence, we have focused on the main message and omitted the discussions about marginal value, farm soil management, supplemental irrigation. Below we have included the shortened and revised Discussion section.

Comment: "*The authors should revise their goals and associated conclusions accordingly. The paper is about compound vs individual extreme events on crop yield and comparison of different soil moisture indicators."*

Response: Thanks for this very helpful comment. We have revised the flow of the paper focusing on the significance of compound extreme metrics and their advantage over the individual extreme metrics.

Comment: "*Furthermore, the empirical concerns are relevant however too lengthy for readers. It can be reduced and can be removed to SI".*

Response: Thanks for highlighting the relevance of this material. The content of this section is shortened and moved to SI and other relevant sections. Below, we will describe the changes in more details.

2- The authors claim that "marginal value of water" will be calculated and utilized in the paper. There is nothing about it in the method and result section (only shown in the discussion section – a short paragraph without any substantial info). I think having this goal of economic analysis is not relevant and beyond the scope the. It is better to exclude this part of the analysis so that the paper is coherent and consistent with its framework.

It is true that the paper does not provide details on the implications for irrigation water demand. While the paper could potentially talk about economic and agronomic water demand, it only briefly discussed the economic demand. To improve the flow of the paper and to focus on the main message, we decided to cut the "irrigation demand" section.

3- Discussion sections were boldly written (e.g. like for climate change discussion and farmer management). I recommend drawing conclusions only if it is supported by the data and analysis.

Thanks for this comment that helped us focus on the critical findings. We omitted the climate change implications. We have omitted the contents are not critical to our main message. Also, we have revised the conclusion and discussion to only draw the conclusions supported by our analysis. This is the revised Discussion:

> "In this paper, we have identified new water availability metrics that improve the predictive power of statistical corn yield models. While predictive power is an important outcome of this analysis, the insights gained from incrementally adding higher temporal-resolution metrics of water extremes to the models are also valuable for understanding the drivers of corn yield variability, and for revealing the resolution of water availability data required to capture future extremes under climate change scenarios. Statistical crop models have been used to both elucidate drivers of crop yield trends and variability, and to evaluate potential climate change impacts on crop production in the future (Diffenbaugh et al., 2012; Lobell and Burke, 2010) . However, these models typically use seasonally averaged water availability metrics (e.g., total growing season precipitation), and utilize precipitation more often than soil moisture. Generally, if the location of the study does not expect a significant change in the within-season distribution of the soil moisture, a mean soil moisture index will work. However, if there is an expected change in this distribution, using the mean variable will create biased yield projections. Because climate models project significant changes in the frequency and intensity of both extreme precipitation and temperature (Zscheischler et al., 2018; Manning et al., 2019; Bevacqua et al., 2019; Poschlod et al., 2020; Potopová et al., 2020; Wehner, 2019), the results presented here show that the mean metrics of water availability – especially mean precipitation - are not sufficient to capture the impacts on yields. It is necessary to consider the metrics of extreme events as illustrated in Figure 1. As we find that the coefficient on extreme heat is significantly different when considering soil moisture, it is possible that previous climate impact studies have over- or under-estimated the yield impacts. Further, farm management practices can alter soil moisture – and therefore yields – independent of precipitation. Supplemental irrigation, as well as no-till farming, cover cropping, and soil conservation can increase soil moisture. These adaptations may occur in places predicted to face higher mean precipitation coupled with more extreme water events. The results of these management practices cannot be captured by statistical models looking at precipitation metrics alone. Such precipitation-based studies could potentially lead to over-

estimation of yield damages under future climate extremes by not accounting for human adaptations designed to conserve soil moisture."

References:

Bevacqua, E., Maraun, D., Vousdoukas, M. I., Voukouvalas, E., Vrac, M., Mentaschi, L. and Widmann, M.: Higher probability of compound flooding from precipitation and storm surge in Europe under anthropogenic climate change, Science Advances, 5(9), eaaw5531, doi:10.1126/sciadv.aaw5531, 2019.

Diffenbaugh, N. S., Hertel, T. W., Scherer, M. and Verma, M.: Response of corn markets to climate volatility under alternative energy futures, Nature Climate Change, 2(7), 514–518, doi:10.1038/nclimate1491, 2012.

Lobell, D. B. and Burke, M. B.: On the use of statistical models to predict crop yield responses to climate change, Agricultural and Forest Meteorology, 150(11), 1443–1452, doi:10.1016/j.agrformet.2010.07.008, 2010.

Manning, C., Widmann, M., Bevacqua, E., Loon, A. F. V., Maraun, D. and Vrac, M.: Increased probability of compound long-duration dry and hot events in Europe during summer (1950–2013), Environ. Res. Lett., 14(9), 094006, doi:10.1088/1748-9326/ab23bf, 2019.

Myhre, G., Alterskjær, K., Stjern, C. W., Hodnebrog, Ø., Marelle, L., Samset, B. H., Sillmann, J., Schaller, N., Fischer, E., Schulz, M. and Stohl, A.: Frequency of extreme precipitation increases extensively with event rareness under global warming, Scientific Reports, 9(1), 1–10, doi:10.1038/s41598-019-52277-4, 2019.

Poschlod, B., Zscheischler, J., Sillmann, J., Wood, R. R. and Ludwig, R.: Climate change effects on hydrometeorological compound events over southern Norway, Weather and Climate Extremes, 28, 100253, doi:10.1016/j.wace.2020.100253, 2020.

Potopová, V., Trnka, M., Hamouz, P., Soukup, J. and Castraveț, T.: Statistical modelling of drought-related yield losses using soil moisture-vegetation remote sensing and multiscalar indices in the south-eastern Europe, Agricultural Water Management, 236, 106168, doi:10.1016/j.agwat.2020.106168, 2020.

Wehner, M.: Estimating the probability of multi-variate extreme weather events, in Workshop on Correlated Extremes, Columbia University., 2019.

Zscheischler, J., Westra, S., Van Den Hurk, B. J., Seneviratne, S. I., Ward, P. J., Pitman, A., AghaKouchak, A., Bresch, D. N., Leonard, M. and Wahl, T.: Future climate risk from compound events, Nature Climate Change, 8(6), 469–477, 2018.

For more-detailed comments:

1) Abstract

- which crops were addressed in the article? Please specify. It is important to mention corn here.

The paper is focused on corn in the US, we have added this in the revised abstract.

- "the value of water experiences a four-fold increase on hot days": not clear, what do the authors refer to by "value of water"? Is this volume? Value of water is generally associated with significance, importance, true cost etc.

This sentence is omitted from the abstract. This term was used to refer to economic value, but the related section and discussions are removed from the revised paper.

- This paper also improves our understanding of the conditional marginal value (or damage)". Which way? And what is conditional marginal value? It is important to provide necessary descriptions in the text as well.

This sentence is related to a section which is omitted from the revised paper. However, the concept of conditional marginal value has been defined in the paper. This is added in the text:

> "Marginal impact and conditional marginal impact are two statistical concepts equivalent to partial derivatives in mathematics. When the partial derivative of one variable does not depend on other variables, we use the term "marginal impact". When it depends on other variables, we use "conditional marginal impact". A conditional marginal impact shows the impact of a compound extreme. A non-conditional marginal impact can show the impact of individual extremes."

2) Introduction

- The first paragraph was written like a conclusion section (after line 26). It includes a short summary, reminding "an abstract". This part needs revision or can be completely excluded (or moved to discussion/conclusion sections).

This paragraph is excluded in the revised paper.

- Ln 33: there can be other factors affecting crop yield significantly such as soil, management, nutrients etc.

This is completely right. The word "variation" was missing. We revised the sentence to the following:

> "In agricultural production, water and heat extremes are key determinants of yield variations".

- Ln 37-38: "Other metrics of extreme water conditions", please specify.

We revised the sentence as:

> "While soil moisture is a more appropriate measure of water availability for crops, extreme water indicators based on soil moisture have been only minimally explored".

- Ln 38-39: "Current statistical studies had limited success in statistically capturing the yield response to soil moisture metrics", please explain why.

We added the following explanation:

> "There are several potential reasons for the limited success of previous statistical studies in capturing yield response to soil moisture. Direct measures of soil water availability include complex biophysical and hydrological processes that are difficult to capture in a rather simple statistical model. On the other hand, seasonal mean soil moisture is highly correlated to seasonal precipitation. Thus, including an average of soil water content may not add value to a statistical model."

- Ln 43: "the impact of climate change on soil moisture". The paper is about individual extreme response of yield vs compound. It is not clear why the authors refer to CC studies.

This is omitted. The climate change section is dropped now, so this sentence is no longer relevant.

- Ln 46: "conditional marginal impact". Please explain what this means.

See explanation above.

- Ln 50: please explain "wet-heat stress"

Wet heat stress or moist heat stress are the terms have been used in different disciplines to talk about hot and humid or moist conditions (Buzan and Huber, 2020). Soil water can exacerbate the heat stress under conditions of high humidity. This is not a prevalent condition. However, it can arise in the context of complex meteorological, hydrological, and agronomic interactions. In the US Midwest, a combination of heatwave and corn sweat can create "moist heat stress" which is dangerous for people, animals, and plants.

Reference:

Buzan, J. R. and Huber, M.: Moist heat stress on a hotter Earth, Annual Review of Earth and Planetary Sciences, 48, 2020.

- Ln 55-60: this part is an outcome of the study. Please remove it to another section (e.g. discussion).

This part has been shortened and moved to Methods and Results.

- What are exactly marginal and conditional marginal impacts? It is better if definitions are given for readers.

See explanation above.

- Ln 64-79: this part is related to discussion/conclusion. I recommend deleting these parts or move to the other relevant sections.

In order to shorten the length of the paper, this part has been removed.

- Ln 77/78: the authors claim that they will show how the results can be used to economically quantify the marginal value of water, in the form of soil moisture, for corn production in the US under different hydroclimatic conditions. I couldn't see this in the rest of the paper. Please clarify.

This topic has now been omitted as it is tangential to the main theme of this paper.

3) Empirical concerns

- This section is mostly about discussion of the method and assumptions taken for the study. It can be presented as supplementary information, rather than in the main text. That can help reader to focus on the results of the paper and its wider implications. In its current form, it is too lengthy.

Thanks for your suggestion. To improve the flow of the paper, we have shortened the content of this section and moved them to the Supplementary, Methods, or other relevant sections. Here are some of the major changes:

Line 84-92: shortened and moved to the Methods.

Line 93-116: omitted.

Line 117-126: shortened and moved to the Introduction.

Line 127-130: moved to the Methods.

Line 131-147: shortened and moved to the Introduction.

Line 148-163: shortened and moved to the Introduction.

Line 164-171: shortened and moved to the Introduction.

Line 172-177: shortened and moved to the Methods.

Line 178-189: shortened and moved to the Introduction.

Line 190-217: omitted.

- Equation 1: please describe what exactly each letter in the equation refers to? For example please refer last variable in the equation as error and describe g(h) function?

Thanks for catching this. We have added the description for the missing variables. Here, g(h) is a general function showing the yield growth as function of heat.

- Ln 126: "measure the value of water". Not clear what the authors refer to as "value of water". Please clarify.

This part is omitted in the revised version.

- Figure 1: this is nothing new, a known information– like a textbook. Excluding this figure does not change anything about the paper. I recommend not to include it.

We have dropped panel b of the Figure 1. We believe that Figure 1-a illustrates the concepts that are central to the Methods. While illustration itself might look like textbook information, it helps us to define the metrics of soil moisture extremes. To distinguish this from a common-knowledge figure, we have modified it as follows:

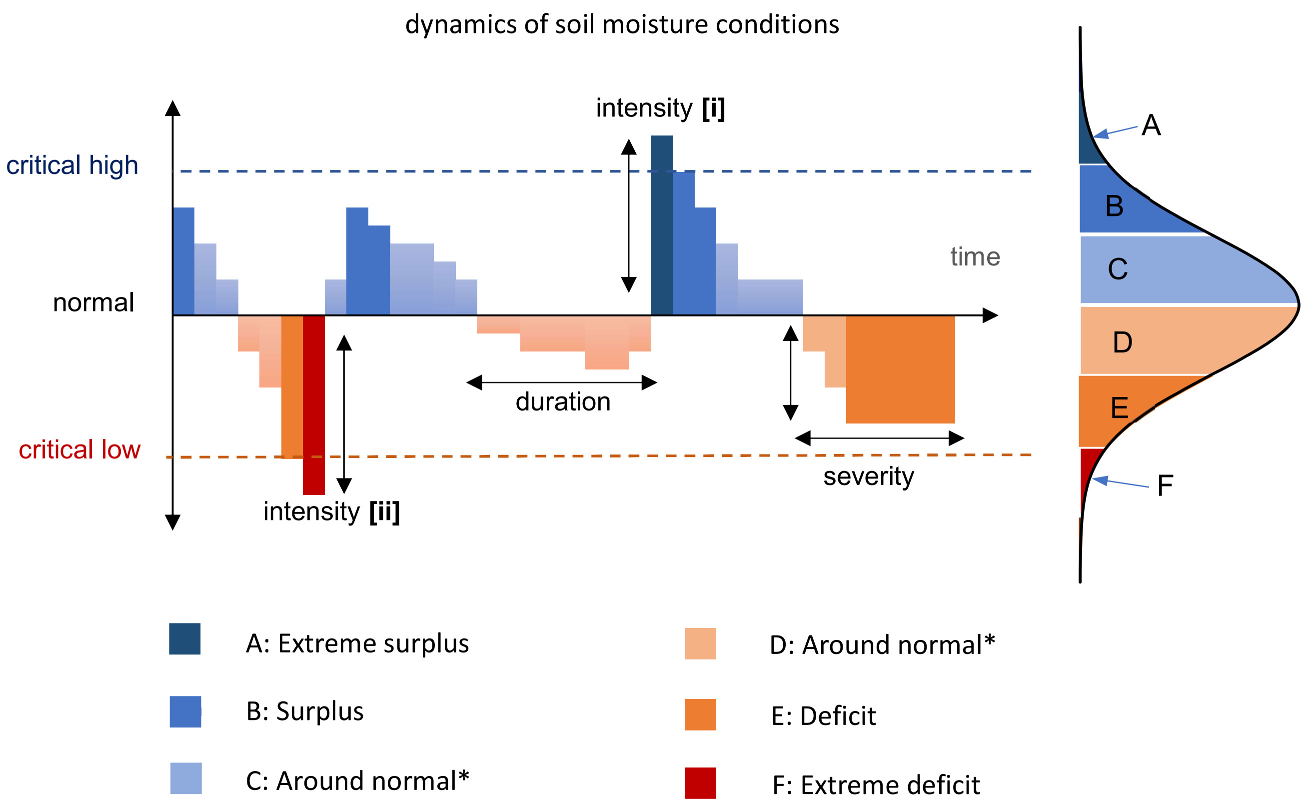

Figure 1. Soil moisture dynamics within a typical growing season. Some soil moisture conditions can be harmful to crops including excess wetness [i], moisture stress intensity[ii], duration of moisture stress [iii], and severity of soil moisture stress [iv]. Normal level of soil moisture is defined as the historical average of volumetric soil moisture within the growing season.

- Ln 134: "Many researchers have acknowledged the need for soil moisture data to predict the response of crop yields to variations in water availability." Please provide references to those researchers.

This sentence has been omitted in the revised version.

- Ln 171: please provide references to those studies.

This sentence has been rephrased and moved to the introduction:

"It has become a standard practice either to focus on a limited geographical area (Rizzo et al., 2018; Wang et al., 2017) or to employ a proxy variable like precipitation, evapotranspiration, or vapor pressure deficit estimates (Comas et al., 2019; Roberts et al., 2013)."

References:

Comas, L. H., Trout, T. J., DeJonge, K. C., Zhang, H. and Gleason, S. M.: Water productivity under strategic growth stage-based deficit irrigation in maize, Agricultural Water Management, 212, 433–440, doi:10.1016/j.agwat.2018.07.015, 2019.

Rizzo, G., Edreira, J. I. R., Archontoulis, S. V., Yang, H. S. and Grassini, P.: Do shallow water tables contribute to high and stable maize yields in the US Corn Belt?, Global Food Security, 18, 27–34, doi:10.1016/j.gfs.2018.07.002, 2018.

Roberts, M. J., Schlenker, W. and Eyer, J.: Agronomic Weather Measures in Econometric Models of Crop Yield with Implications for Climate Change, Am J Agric Econ, 95(2), 236–243, doi:10.1093/ajae/aas047, 2013.

Wang, R., Bowling, L. C., Cherkauer, K. A., Cibin, R., Her, Y. and Chaubey, I.: Biophysical and hydrological effects of future climate change including trends in CO2, in the St. Joseph River watershed, Eastern Corn Belt, Agricultural Water Management, 180, 280–296, doi:10.1016/j.agwat.2016.09.017, 2017.

4) Method

- This section is too long. Please shorten it and provide detailed information in SI.

We have substantially revised the organization and transitions within the Methods section. The section is re-organized to focus on the critical parts of the methods and to improve the flow of the paper. Here is the new order:

2.1. Data

2.2 Model (1): individual extremes

2.3 Model (2): compound extremes

2.4 Estimation strategy

- Equation 2: please define each variable and function used in the equation.

Thanks for pointing to the missing definitions. We have corrected it.

"where y_{it} is the crop yield, $g(h,m)$ is the yield response function to each combination of soil moisture level, m, and temperature (heat), h; $\varphi(h,m)$ is the distribution of soil moisture and heat; $\overline{m}$ and $\underline{m}$ are maximum and minimum soil moisture; $\overline{h}$ and $\underline{h}$ are maximum and minimum temperature; and c_i is a time-invariant county fixed effect. Here, we do not separate the impact of heat from water. In other words, the marginal impact of heat depends on water; and the marginal impact of water depends on heat."

- Ln 230: "some indicators", please clarify which indicators.

We have clarified this as:

> "In Model (1-c), we consider the number of days that soil moisture is either too high or too low. The model with these metrics of soil moisture extremes further improves the fit, revealing a negative marginal relationship associated with the number of days with low/high soil moisture."

- Please provide numbers to the equations.

Thanks for your comment. We added equation numbers in the revised version.

- Ln 277: g(Ws), please define the parameter

This description has been added to the text: "and $g(W_s)$ is 1 for all crops, while it is an exponential function of soil moisture depth for non-crop soil areas."

- Ln 290-295: this is a result of the analysis, not related to data/method or assumptions.

Thanks for your comment. We have moved this figure to the Supplementary Material. This information is important to ensuring that soil moisture is a different metric than precipitation. This information is added, and the statement re-contextualized and rephrased.

> "In a statistical study, a natural first step is to look at the correlation between these variables. To show that mean soil moisture is a different metric than mean precipitation, we have plotted the annual mean soil moisture versus annual cumulative precipitation in Fig. S1. This figure is a scatter plot for US counties for the growing season from 1981 to 2015. The simple correlation coefficient between them is 0.44. This rejects the hypothesis that soil moisture is highly correlated with precipitation. As mean precipitation has a linear relationship with cumulative precipitation, the results show that mean soil moisture is a different metric than cumulative or mean precipitation."

- Figure 4,5 and 6 are outcomes of the model/analysis. They can be presented in the result section.

These figures have moved to the results section. We have also added more explanations about the figures and their messages.

> "The overall simulation results from WBM are illustrated in Fig. 4-6, showing the gridded historical mean for the cultivated continental US, average annual variations for the cultivated continental US, and bivariate distribution of soil moisture and heat for the corn growing grid cells. To illustrate the spatial heterogeneity, Fig. 4 shows the growing season mean soil moisture content (in mm in 1000 mm topsoil) as calculated based on daily root-zone soil moisture level from Apr-Sep for 1981-2015 at 2.5 x 2.5 arcmin grids excluding non-cultivated area. Average growing season soil moisture is

heterogeneous across the Continental US, with distinct regional patterns (see Fig. 4). For the corn belt, the soil moisture level is relatively high compared to other regions. The mean of volumetric soil moisture ranges from below 50 mm in southern California to above 250 mm in the Corn Belt and around Mississippi.

To compare the variation of simulated soil moisture and precipitation, Fig 4 illustrates the weighted average soil moisture and precipitation over the cultivated US for 1981-2015. In general, variation in soil moisture average is higher than in that of precipitation (Fig. 5), showing how this new water metric is different from previous approaches. One interesting finding is that for some years the mean precipitation and the mean soil moisture move in opposite directions. For example, in 1990 the mean precipitation declined by around 5% while mean soil moisture increased by around 13%.

To show the dynamics of soil moisture and heat, Fig. 6 shows their bivariate distribution by month based on daily information for all the cultivated grid cells in the US Corn Belt for 1981-2015. Heat and soil moisture combinations vary through the growing season (Fig. 6) The data shows significant month-to-month variation, with the second half of the season facing hotter and dryer days. Also, July has the highest variation in soil moisture deviation with high probability of compound extremes as the distribution moves toward the lower right. "

5) Results

- Ln 363/364: "We will discuss the implications of these results in Sect. 5." The authors use lots of cross references between the sections as seen in here. This is not necessary, since discussion section means discussion of the results by definition. Please through the entire text and remove unnecessary cross-section references.

Good point. By cutting the length of the manuscript an improved flow of the paper, there is no need to these references. Thus, the superfluous section cross-references have been removed.

- Table 2: note section is repetition of the previous sections, thus it is not necessary.

The table notes have been removed or shortened for all the Tables.

- Ln 404: "This indicates that water is up to four times more valuable in hot weather." The authors can consider revising the sentence and be more explicit, "value of water" may mean several things.

As we omitted the value of water section, we have revised this as follows:

"The estimated parameters show the yield response to changes in soil water content. Comparing the parameter values can show the difference in yield response to soil moisture in hot weather and moderate weather…. This indicates that the average yield response to water is up to four times higher in hot weather."

- Model (2-a) and Model (2-b) were mentioned here for the first time. Please describe the differences between these models in method/data section.

The Methods section is revised to consider this comment. We have introduced the models in the relevant subsections on the Methods section. Here is the new order:

3.1. Model (1): predicting yield responses to individual extremes

3.2 Model (2): predicting yield responses to compound extremes

3.3 Model comparison

3.4 Decomposing the variation in US corn yields

3.5 Robustness checks

6) Discussion

- Ln 410/411: this is related to differences between model 1 & 2, right? Please clarify which model outcome supports (or all?) the statement.

These lines are omitted. The clarification has been added in subsection 3.2 “Model (2): predicting yield response to compound extremes”.

- Performance: does this mean best correlation between indicators of extreme events yield anomalies? Please clarify.

For comparing the models, we have Looked at statistical criteria. We have added Table 5 to compare the performance metrics of the models.

Table 5: Performance metrics for Models 1(a-d) and 2(a-d).

Model	Water metric	Extreme metric	R-squared	AIC (Akaike’s information criterion)	BIC (Bayesian information criterion)
1-a	Avg. precipitation	Precipitation sqr	0.469	-21,238	-21,201
1-b	Avg. soil moisture	Soil moisture sqr	0.471	-21,612	-21,576
1-c	Avg. soil moisture	Number of days with low/high soil moisture	0.480	-22,697	-22,660
1-d	Avg. soil moisture	Avg soil moisture deficit/surplus	0.491	-24,303	-24,267
2-a	Avg. soil moisture	T binned by extreme deficit/surplus	0.492	-24,402	-24,328
2-b	normal soil moisture x T	extreme deficit/surplus x T	0.501	-25,582	-25,509

- First paragraph: what about model 1-c ?

This section is omitted. We have presented the results from model 1-c in subsection 3.1 " Model (1): predicting yield response to individual extremes".

"Regarding Model (1-c), the coefficient on the number of days with low moisture is also significant and negative. Our estimation sample shows on average 26 days of high soil moisture and 27 days of low soil moisture. The implication is that eliminating 25 days of high soil moisture and 25 days of low soil moisture can improve the corn yields by up to 12.6%."

- Model 2 a-b were not defined in the previous parts of the paper. Please check consistency.

The Methods section is revised to consider this issue. As mentioned above, we have introduced the models in the relevant subsections on the Methods section.

"First, we construct a binning estimator based on daily interaction on heat and soil moisture in model (2-a). …. We estimate a coefficient for each combination of excess heat and soil moisture; i.e., we estimate a model with metrics of degree days while controlling for soil moisture. The model provides the conditional marginal impact of excess heat as:

$$y_{it} = \alpha D_{it}^{10-29} + \left\{ \sum_{m} \beta_m D_{mit}^{29} \right\} + \delta M_{it} + \delta' M_{it}^{2} + \lambda_s t + \lambda'_s t^2 + c_i + \varepsilon_{it} \qquad \text{(2-a)}$$

where *i* is the county index, *t* is the time index, *m* is an index of soil moisture condition (high, low, normal), *s* is an index for states, *y* is average corn yields, *D* represents conditional growing degree day variables, *M* shows the seasonal mean soil moisture content, *T* stands for the time trend variable, c_i is a time-invariant county fixed effect. Here, *β* is indexed by *m*; i.e., the marginal impact of heat is conditional to soil moisture conditions. *α, β, δ, λ* are the regression parameters showing the marginal impacts.

Second, we estimate a model with metrics of soil moisture while controlling for temperature in model (2-b). We define an index of soil moisture when the temperature is above the threshold and an index of soil moisture when the temperature is below the threshold. In this model, the soil moisture is separated by a temperature threshold *H**.

$$y_{it} = \alpha D_{it}^{10-29} + \beta D_{it}^{29} + \left\{ \sum_{m} \delta_m M_{mit}\big|_{H<H^*} + \delta'_m M_{mit}\big|_{H>H^*} \right\} + \lambda_s t + \lambda'_s t^2 + c_i + \varepsilon_{it} \qquad \text{(2-b)}$$

where *i* is the county index, *t* is the time index, *m* is an index of soil moisture condition, *s* is an index for states, *y* shows average corn yields, *D* represents growing degree day variables, *M* shows conditional seasonal mean soil moisture, *t* stands for the time trend variable, *H* is the average daily temperature, *H** is the temperature threshold, and c_i is a time-invariant county fixed effect. Here, we define *δ* and δ' to test whether the marginal impact of soil moisture depends on heat. The soil moisture metrics are calculated from daily gridded data and aggregated to county and growing season. This includes the index of normal soil moisture (*SM* 0-25+ mm around normal) when $H > H^*$, the index of normal soil moisture when $H < H^*$, the index of moisture deficit (*SM* 25+ mm below normal) when $H > H^*$, index of moisture deficit when $H < H^*$, the index of moisture surplus (*SM* 25+ mm above normal) when $H > H^*$, and the index of moisture surplus when $H < H^*$. $\alpha, \beta, \delta, \lambda$ are the regression parameters showing the marginal impacts. "

- Ln 416-421: These are newly introduced topics. None of these research goals (including why to have them), methods and results were mentioned in the previous sections of the paper (e.g. new interaction model, why do you have that and this was never mentioned in the paper). It is like Appendix is another paper with its own results, methods and goals. Please revise the paper accordingly.

We have substantially shortened and revised the Discussions and Appendix sections. The paper has been revised to focus on the main contribution and major messages. Thus, we dropped Model 2-c and 2-d as well as the discussions on "Implications for irrigation water demand and subsurface drainage" and "Implications for climate studies."

- Ln 424-428: Is this an outcome supported by the results? If so, please indicate how. It is more like a general knowledge.

This paragraph is omitted. We have revised the discussion section around the advantages of using the metrics of individual and compound extremes.

- Ln 429-430: Please provide supporting data/result from the analysis.

We have removed this paragraph as it requires further investigations which are not related to the main message of the paper.

- Ln 433: what are the other metrics suggested in the literature?

This section is omitted in the revised version.

- Ln 434-438: Is this a conclusion related to compound vs individual extreme weather event analysis? Can we say the same if we use other metrics of water stress than soil moisture?

Thanks for your helpful question. This section is omitted in the revised version. However, we used your suggestion in revising the paper. We focused on comparing models with individual extremes and models with compound extremes. This has improved the flow of the paper and highlighted the significance of this study.

- Ln 465-469: I question that the authors' research is critical for climate change studies. First, their analysis was based on historical data and says nothing about counterfactual analysis. This is not the first time impacts of a compound event was researched and like other studies this paper shows stronger impact of a compound event. It does not bring anything to climate change impact studies.

We have omitted this subsection in the revised version and briefly talked about it in the revised manuscript. However, we believe that the findings are critical for climate impact studies for several reasons. First, the current literature follows methods like Schlenker and Roberts (2009) by modelling yield response functions looking only at average water conditions. They ignore individual and compound extremes related to water. As we find that the coefficient on heat stress variable is significantly different when considering soil moisture and compound extremes, it is possible that previous climate impact studies have over- or under-estimated the yield impacts of climate change. Second, we are introducing simple but operational metrics of individual and compound extremes that can be constructed using hydroclimatic models for the future. These metrics can improve the prediction of crop yields. We are not aware of any other study suggesting such a simple yet powerful prediction framework.

- Ln 472: please clarify benefit of this collaboration. In which way it helps to solve the challenge.

We believe that collaboration between hydrologists, climate scientists, and statisticians can improve data generating processes and leads to better models and metrics to help better decisions among people and policymakers. Here is the revised text:

> "Applying this framework to climate impact studies will face a key challenge —namely projecting the future compound extremes with the high temporal resolution of Model 2. It requires collaboration between hydrologists, climate scientists, and statisticians (Zscheischler et al., 2020). For future yield projections, we need reliable future projections of daily temperature (maximum and minimum) and soil moisture. Unfortunately, to the best of our knowledge, available data sets including predictions of future soil moisture have a relatively coarse spatial and temporal resolution, and rely on climate model projections with known difficulties representing daily temporal resolution events (Hempel et al., 2013). Further research is required to improve the ability of climate models and impact models in projecting the bivariate distribution of heat-moisture (Sarhadi et al., 2018)."

References:

Zscheischler, J., van den Hurk, B., Ward, P. J. and Westra, S.: Multivariate extremes and compound events, in Climate Extremes and Their Implications for Impact and Risk Assessment, pp. 59–76, Elsevier., 2020.

Sarhadi, A., Ausín, M. C., Wiper, M. P., Touma, D. and Diffenbaugh, N. S.: Multidimensional risk in a nonstationary climate: Joint probability of increasingly severe warm and dry conditions, Science Advances, 4(11), eaau3487, doi:10.1126/sciadv.aau3487, 2018.

- Ln 479-ln 483: this recommendation is not related to the sub-section heading. The authors stated a discussion point which is out of scope of their analysis and not supported with the overall goal of the paper. Recommendations can be given to farmers etc; however their model/research is not aimed for decision - support guidance. Please remove this section of revise it.

Thanks for your comment. We have omitted this part.

- Section 5.4: This section includes literature, method, data and equation related to an estimation. This is not a discussion section. Please previse it accordingly. This additional analysis doesn't bring anything to the value of the paper. I would recommend excluding this analysis from the paper in order to keep its coherence and consistency.

Thanks for your comments which helped to improve the flow of the paper. We have omitted this subsection.

- Ln 501: "We find that the average damage from excess heat has been up to four times more severe when combined with water stress" what is the damage, yield losses?

Thanks for your comment. Originally benefits and damages were considered from an economics point of view. In the revised version, we removed the economic analysis of the value of soil moisture. Now we have revised and clarified the sentence as:

> "Finally, the marginal impact of heat index on crop yields depends on the soil moisture level. We show the average yield damage from heat stress is up to four times more severe when combined with water stress; and therefore the value of water in maintaining crop yield is up to four times larger on hot days."

- Line 517-525: the CC knowledge and analysis were not included in previous parts (method, data, results) section of the paper. Please include info about this analysis in adequate sections.

To improve the flow of the paper and reduce the redundancy, the climate change material is omitted.

- Line 525- 535: There is almost no economic analysis thus the paper does not contribute to CC economics. No policy analysis or research were provided either; also paper does not say/bring anything to regional resilience of agroecosystems, global food security, and as well as future climate impacts. These two paragraphs have to be re-written. These claims are bold and cannot be taken from the research as described in the paper.

Thanks for your comment. As we have dropped the subsection, theses paragraphs are also omitted.