Resilience of UK crop yields to changing climate extremes

Response to Reviewer Comment 2 (RC2):
'Comment on esd-2021-92', Corey Lesk, 13 Jan 2022

This paper seeks to understand historical links between climate and variability in UK wheat yields, and examine the implications of future climate change as projected using a convection-resolving climate model. It considers differential yield responses across growth stages, and tries to then aggregate these stages to assess compensating or amplifying impacts. This latter aspect is the main novelty of this research, which I think is useful and timely. I also appreciate the effort to consider compensating effects between growth stages and between heat and water via this aggregate climate scoring approach, and in Figures 4-5. There is increasing attention to these joint affects, so this paper has the potential to add some clarity here as well.

We would like to thank Corey Lesk for his very helpful review of our manuscript. We are pleased he finds the two main aspects novel and useful – i.e. assessing compensating/amplifying impacts across different growth stages, and considering heat and water extremes together. We are also pleased that the paper is seen as "timely". We address each of the comments and suggestions point-by-point in blue italic font below.

RC2.1 I have two main critiques that should be addressed. First, the statistical analysis is not adequately described, and based on what I can surmise from the sparse detail, it is probably not the strongest approach. Second, the assessment of future impacts is only driven by data on the climate side, and the crop impacts are only qualitatively discussed. This sells the historical climate-yield relationships short: why not use your historical results for a data-driven estimate of future impacts? Further, your results and other research show how multivariate climate variation/change could lead to compensating or compounding impacts on crops, the potential for which could be more robustly and objectively assessed through a more quantitative approach.

We appreciate this comment. First, we will make sure that our statistical analysis is fully described in the revised manuscript, and we will test the additional statistical approach suggested below in RC2.2 (a multivariate statistical model). Second, regarding the assessment of future climate impacts on crop yields, it is true that a multivariate statistical model using the historical observations could then be driven with the UKCP projections. We will explore this data-driven approach as suggested (e.g., temperature and precipitation variables for each growth stage all included in one yield model). We discuss this in more detail in response to the next comment.

RC2.2.1 On statistical analysis: The methods is missing any description of the statistical analysis, justification for model specification, etc. This makes it fairly hard to assess the reliability of the results, and what they mean. I gather that the analysis is pairwise two-variable Pearson correlations (yield vs. each climate variable). The authors then use these results to develop a scoring system to combine variables/growth stages, which is not necessarily a bad approach, and the results in Figure 6 seem pretty strong. But this is not a widely used approach, and given lack of detailed methods, it is hard to assess. **RC2.2.2** Rather, multivariate regression (i.e., temperature and precipitation variables for each growth stage all included in one yield model) is what is typical. There are both benefits and pitfalls to it, but it would improve confidence to try this more widely-vetted method and see if results are consistent, and would enable a more self-consistent way to assess compensations. **RC2.2.3** Further, this multivariate regression approach is more suited to then actually projecting yield based on multivariate projections from climate models. You may also consider non-linear yield responses. **RC2.2.4** Finally, only p-values are mentioned in the text, which only provide limited information. I see Pearson coefficients in a table, but their relative magnitudes are not discussed. And the effect size (i.e. slope coefficient) underlying these correlations also provide useful information (steepness of yield response to climate variable), so may be helpful to discuss.

AC2.2.1 *Yes, the statistical analysis in Table 2 was simply pairwise two-variable Pearson correlations (yield vs. each climate variable), as indicated in the caption. We will ensure the statistical analysis is fully described in the revised manuscript.* ***AC2.2.2*** *The Reviewer makes a very good suggestion about developing a multivariate regression model with the historical observations, and we will test this approach.* ***AC2.2.3*** *As suggested, we will use the same model to project future yield using the climate model projections. We will explore this approach in the revised manuscript.* ***AC2.2.4*** *Yes, we agree here too. Whether we keep the existing statistical analysis in the manuscript, or enhance it, we will ensure that it is thoroughly described and reproducible to a reader. We will include further statistical diagnostics, including the relative magnitudes of correlation coefficients and slope coefficients.*

RC2.3 Another methodological issue is reliance on interpreting specific years relative to statistical results, which often lead the paragraphs in the results. I actually really like this for its concreteness, but it is not a super robust method and seems prone to cherry-picking years that fit the narrative. I think this can be remedied by trying to frame these claims more as discussion points and reducing their prominence in the results. Alternatively, you could formalize your method for selecting key years, and describe it in the text.

This is a fair point, which was also raised by Reviewer 1. We will ensure the revised manuscript will have this alternative ordering, i.e. that the descriptions of individual years do not lead our results and instead are used more as discussion points, with less prominence in the results.

RC2.4.1 Another important limitation of this research is its use of only one climate model under only one climate forcing scenario. This leaves important uncertainties in emissions trajectories and climate responses unquantified. **RC2.4.2** The RCP8.5 scenario also is falling out of favor in some circles, as it assumes implausibly high emissions – the authors acknowledge this late in the paper, but don't strongly justify why we should nevertheless be focusing on an unlikely future. It would probably be useful to include RCP2.6 or 4.5, or at very least acknowledge that the paper doesn't address emissions uncertainty. **RC2.4.1 (similar point as above)** The implications of using one climate model should also be justified – is the HadGEM3/HadREM3 nested model particularly useful for the region? The use of a 12 member ensemble helps, but I notice that some years (often with important yield impacts) in Figures 4-5 fall outside the whiskers of the historical model data, raising questions of whether this model can reproduce these conditions (historically or in the future). We know models have such deficiencies –using more than one can help at least partly constrain uncertainty. **RC2.4.3** Small comment: impacts of rising CO2 on crop water use will be important in the future, as you mention in the intro. It's a huge uncertainty and hard to model, but should probably discuss its relevance for your projections.

AC2.4.1 *We understand the concern regarding the use of one climate model. However, the driving Earth System Model of UKCP Local is subjected to a range of plausible parameter variation (perturbed physics experiments). Hence the different ensemble members at least partially represent the range of uncertainty in climate models held in the CMIP ensembles (see last bullet point of page 5 of this document: https://www.metoffice.gov.uk/binaries/content/assets/metofficegovuk/pdf/research/ukcp/ukcp18-factsheet-local-2.2km.pdf). We acknowledge that we are not sampling other international climate models, and so likely underestimate climate modelling uncertainty (i.e. only sampling a small part of the range). This could perhaps be addressed in future work once CMIP5 driven UKCP Local projections become available. Additionally, as discussed in response to RC1.22, the UKCP Local* *projections are generally within the 5-95% probability levels of the UKCP Probabilistic projections, which include some multi-model information from CMIP5. We will more fully justify and explain why UKCP is particularly useful for the UK (e.g. it gives reduced biases in both summer and winter mean rainfall). We will also reiterate that the process representation of rainfall-based effects in UKCP Local are considered 'state-of-the-art', disaggregating large-scale changes accurately, as possible with a convection-permitting model.*

AC2.4.2 *We appreciate that the RCP8.5 scenario may not be the most likely scenario, but we will more clearly explain why it is used in our study. The first reason is that this is the only scenario for which UKCP Local projections were performed. RCP8.5 was deliberately chosen as the configuration for UKCP Local simulations to maximise the signal to noise, while still representing a plausible scenario. Using a high emissions scenario has the advantage that we can infer changes for other lower emissions scenarios using scaling approaches. We will clarify that the paper does not address emissions uncertainty, although a reasonable assumption, to first order, is that changes under lower emissions will broadly scale with change in GHG radiative forcing.*

AC2.4.3 *We agree that the impact of rising CO2 on crop physiological response and water use is an important uncertainty and will make sure that we discuss its relevance in the revised manuscript (e.g. Ewert et al. 2002 and other references). A key point of our manuscript is that we are likely to move outside of the climatic envelope which wheat farming in the UK has previously experienced and adapted to. Thus, the high levels of uncertainty around the effects of rising CO2 on crop growth and yield are only likely to increase the degree to which farmers may struggle to adapt to and mitigate against climate impacts.*

Ewert, F., Rodriguez, D., Jamieson, P., Semenov, M. A., Mitchell, R. A. C., Goudriaan, J., ... & Villalobos, F. (2002). Effects of elevated CO2 and drought on wheat: testing crop simulation models for different experimental and climatic conditions. Agriculture, Ecosystems & Environment, 93(1-3), 249-266. https://doi.org/10.1016/S0167-8809(01)00352-8

RC2.5 Finally, I think you could consider in a bit more depth the interactions between temperature and precipitation both in the climate and for crops. For instance, very hot conditions in the UK can often only be reached with a dry land surface (visible as apparent negative temp-precip correlations during production, Fig's 4-5). Miralles et al. 2019 is useful reference on these processes. Cool and wet conditions could also be linked physically, with implications for crop impacts. This raises questions about the independence of heat and moisture impacts, which is a problem here since they are only assessed one-at-a-time using Pearson's correlations (multivariate regression could help capture the interaction). Further, joint impacts of changes in temp and precip in the future could be discussed more, see line comments.

We agree with you that the interactions between temperature and precipitation and their impacts are important and should be further considered. We will explore these interlinkages (interdependence) and impacts using the multivariate approach suggested in RC2.2 - thank you for the suggestion. We will cite the suggested reference (Miralles et al. 2019), and we will also discuss potential joint impacts of changes in temperature and precipitation into the future as GHGs rise.

Thanks for the nice paper! I think it will be a useful publication once some issues are addressed.

Thank you very much for your positive and helpful comments on our manuscript!

Line comments:

RC2.6 Line 36: Could cite more recent papers on this: Ray et al. 2019, Ortiz-Bobea et al. 2021

Thank you. We will cite more recent papers, including these two that you suggest.

RC2.7 Line 55: Ainsworth and Long 2021 would be a useful reference here

Thank you for the suggested reference; we will include it.

RC2.8 Line 56: Soil moisture, precipitation intensity/distribution ref?

Sorry, this question isn't entirely clear but we can include a reference to the importance of soil moisture and rainfall intensity and their impacts for crop yields.

RC2.9 Line 80: Could be helpful to motivate this step. Presumably, you do this to remove long-term yield trends (due to technology, climate, co2) and isolate annual anomalies relative to this.

The Reviewer is referring to the fact we subtract this running mean from each annual value. Yes, indeed, we do this to remove the trend and isolate annual anomalies which we expect to be related to interannual climate variability rather than, say, long-term technological improvements. We will clarify this normalisation in the revised manuscript.

RC2.10 Line 100: This threshold for heavy rainfall should be justified and/or its influence should be tested. For instance, Lesk et al. 2020 found extreme rainfall impacts only at high intensities >50mm/hr for US maize and soy (how this maps to daily scale is unclear, but a 10mm/hr threshold would preclude these damaging intensities). Others have used more holistic distributional measures like the daily rainfall GINI coefficient (Shortridge 2019). I'm not aware of equivalent studies for wheat, but these could be good references to add to Zampieri et al. 2017 in line 56 to bring in studies in sub-seasonal rainfall distribution.

Thank you, this is helpful information. We will justify the choice of threshold: e.g. how it compares with the annual rainfall distribution over the British Isles; its relevance in the context of UK crop yields; and how it compares with the thresholds used in other studies.

RC2.11 Line 137: I think "1989-1960+1" was not intended to be included in text

Yes, thank you for noticing this typo, since removed.

RC2.12 Lines 159-161: I think the connection between temperature and precipitation is an issue worth discussing. The wet years with poor yields also tend to be relatively cool (especially during foundation). The dry years tend to be hot.

Thank you for the suggestion; we will discuss this point in the revised text. We also note how this fits well with your other queries about simultaneous changes or anomalies in temperature and precipitation.

RC2.13 Line 191: I don't see 1976 on the figure, and 2013 and 2018 don't seem particularly extreme.

Good spot, thank you; we will remove 1976 and adjust this statement accordingly.

RC2.14 Line 200: This somewhat undercuts your preceding results. You do find climate-yield relationships so I don't see strong basis for claiming they are masked by inputs. Further, it is not clear which inputs these would be. I do not know of any short-term adaptive solutions to excess moisture (farmers can improve drainage and soil texture over time, but not within a single season). Further, the usual adaptive management for heat or drought is irrigation, which is not widespread in the UK. Instead, what might be more important/interesting is analyzing (or at least speculating on) the role of inputs in raising mean yields (over decades), and how that may influence yield variability (which you are trying to attribute differentially to climate).

Thank you - this is a good point and we will adjust the text by editing the statement. (The reviewer is referring to the statement that “the relatively input-intensive nature of UK wheat production may be sufficient to mask crop responses to climatic variation”). Here we could replace "mask" with "dampen" (i.e. we still see effects by not as much as we might expect) and drop "inputs" (i.e. we refer to all management here, not just agrochemical inputs), i.e. “the relatively intensive nature of UK wheat production may be sufficient to dampen crop responses to climatic variation”.

We would argue that there is still a role for agronomic management in dampening apparent relationships with climate - these might not be as direct as irrigating in response to drought, but farmers can, for example, change fungicide regimes to response to increased fungal disease brought about by wetter conditions. Farmers can also change many other aspects of management, including wheat variety, tillage, sowing date, sowing rate, or harvest date, in response to forecast or current conditions. We agree that these are not inputs as such and will change the wording.

We will also add some discussion of the role of inputs in raising mean yields and the current yield plateau (e.g. Knight et al. 2012).

Knight, S., Kightley, S., Bingham, I., Hoad, S., Lang, B., Philpott, H., Stobart, R., Thomas, J., Barnes, A., Ball, B. (2012) Desk study to evaluate contributory causes of the current yield plateau in wheat and oilseed rape. https://projectblue.blob.core.windows.net/media/Default/Research%20Papers/Cereals%20and%20Oilseed/pr502-summary.pdf

RC2.15 Line 205: This claim is interesting and usefully motivates the next section, but needs work, and here’s one place using multivariate regression may be useful. In this more standard method, multiple climate variables together usually explains less than half of yield variation (full-model adjusted r2 < 0.5). Using individual pairwise correlations is less common, and so it’s unclear what would be high or low correlation. If the correlations are indeed low in a more robust assessment, it could be because of the myriad other environmental or social factors contributing to yield (climate explains less than half of yield variability).

Thank you. We will test the multivariate regression, as discussed in comment RC2.1, and include it if it proves logical to do so. These comments are helpful.

RC2.16 Line 257-259: Here’s a place you could mention multivariate change. Cool and wet foundation phases have been linked to poor yields, and these are connected because it is hard to warm up the surface when soils are wet, and hard to dry out wet soils when it is cool. The projected warmer and wetter conditions are orthogonal to this connection, and some of that warming may help dry out waterlogged soils. Question is whether the warming will suffice to offset the increased precipitation, and this is the kind of question that a multivariate regression model could help answer. See for instance Rigden et al. 2020, Lesk et al. 2021, Ortiz-Bobea et al. 2019.

Thank you for the suggestion and the references - we will include these citations and summarise their findings as points of discussion.

RC2.17 Line 265: Precipitation may not change much, but there is still warming, which will increase atmospheric vapour demand (all else being equal). So here’s a place where some acknowledgement or analysis of multivariate change would probably lead to more robust conclusions about the future. Zampieri et al. 2017 touches on some of this multivariate influence. See also Lobell et al. 2013 with detail on the evaporative role of temperature (it's for U.S. maize, but relevant to interpreting future warming).

Thank you for the helpful suggestions! We will discuss multivariate change here and consider using the model for future projections (as mentioned in our reply above to RC2.1). We will also include these suggested references.

RC2.18 Line 277-279: Yes, especially since temperature could have non-linear impacts, see Barlow et al. 2015, a useful reference for frost effects too.

Thank you for the reference!

RC2.19 Line 285-288: Great, this offsetting is coming to light as an important mechanism/uncertainty, I just think it could be discussed in more depth.

Thank you! We will indeed discuss it in more depth in the revised manuscript.

RC2.20 Line 300-301: Consider using term 'compound extremes' here and in the intro to link to emerging literature on this topic. E.g. Zscheischler et al. 2020.

Thank you for the helpful suggestion. We will refer to compound extremes in both places.

RC2.21 Figures 4-5: I like that this shows the bivariate temperature-precipitation distributions. It is hard to differentiate the grey circles from diamonds, however. It may be easier to see if the 95% confidence ellipses are removed – I'm not sure what they add and could be replaced by simple dots showing point-estimates of mean yield. Otherwise, perhaps the climate model data should be presented on separate axes.

Thank you for the suggestion. We will consider removing the ellipses and replacing them by simple dots, or alternatively using separate axes.

RC2.22 Figure 6: this is a pretty convincing figure notwithstanding my concerns above, but it's hard to understand why the black data are showing y-axis values and an increasing trend, as I don't see yield projection results or methods anywhere in the paper. I assume the points are different years, and aggregate climate scores evolve over time. If so, this data should probably be separate time axes. The black data also seem visually like trendlines on the yield/climate score scatters, but I don't think they are so this may mislead readers.

These comments are helpful - Figure 6 was evidently not clear enough. The black data only showed the projections of the combined climate score and not the projected yields. We will update this figure after having tested the multivariate model suggested in RC2.1. The idea of showing how the combined climate score might evolve as a time series is a particularly nice suggestion. This is a good way to merge contemporary data with the model projections.

References:

Ainsworth, E. A., & Long, S. P. (2021). 30 years of freeâair carbon dioxide enrichment (FACE): What have we learned about future crop productivity and its potential for adaptation?. Global Change Biology, 27(1), 27-49.

Barlow, K. M., Christy, B. P., O'leary, G. J., Riffkin, P. A., & Nuttall, J. G. (2015). Simulating the impact of extreme heat and frost events on wheat crop production: A review. Field Crops Research, 171, 109-119.

Lesk, C., Coffel, E., & Horton, R. (2020). Net benefits to US soy and maize yields from intensifying hourly rainfall. Nature Climate Change, 10(9), 819-822.

Lesk, C., Coffel, E., Winter, J., Ray, D., Zscheischler, J., Seneviratne, S. I., & Horton, R. (2021). Stronger temperature–moisture couplings exacerbate the impact of climate warming on global crop yields. Nature food, 2(9), 683-691.

Lobell, D. B., Hammer, G. L., McLean, G., Messina, C., Roberts, M. J., & Schlenker, W. (2013). The critical role of extreme heat for maize production in the United States. Nature climate change, 3(5), 497-501.

Miralles, D. G., Gentine, P., Seneviratne, S. I., & Teuling, A. J. (2019). Land–atmospheric feedbacks during droughts and heatwaves: state of the science and current challenges. Annals of the New York Academy of Sciences, 1436(1), 19.

Ortiz-Bobea, A., Wang, H., Carrillo, C. M., & Ault, T. R. (2019). Unpacking the climatic drivers of US agricultural yields. Environmental Research Letters, 14(6), 064003.

Ortiz-Bobea, A., Ault, T. R., Carrillo, C. M., Chambers, R. G., & Lobell, D. B. (2021). Anthropogenic climate change has slowed global agricultural productivity growth. Nature Climate Change, 11(4), 306-312.

Ray, D. K., West, P. C., Clark, M., Gerber, J. S., Prishchepov, A. V., & Chatterjee, S. (2019). Climate change has likely already affected global food production. PloS one, 14(5), e0217148.

Rigden, A. J., Mueller, N. D., Holbrook, N. M., Pillai, N., & Huybers, P. (2020). Combined influence of soil moisture and atmospheric evaporative demand is important for accurately predicting US maize yields. Nature Food, 1(2), 127-133.

Zscheischler, J., Martius, O., Westra, S., Bevacqua, E., Raymond, C., Horton, R. M., ... & Vignotto, E. (2020). A typology of compound weather and climate events. Nature reviews earth & environment, 1(7), 333-347.

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