Revision for egusphere-2025-1982 "Warmer growing seasons improve cereal yields in Northern Europe only with increasing precipitation"

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Dear Dr. Rammig

We hereby submit the revised version of our manuscript entitled '**Warmer growing seasons improve cereal yields in Northern Europe only with increasing precipitation**'' We previously provided a detailed, point-by-point response to the reviewers as stated below. The main changes made to the originally submitted manuscript can be summarized as follows:

1. We clarified our rationale for the selection of climate indicators and time periods by providing additional detail on both the indicators themselves and the selected temporal windows. This includes an expanded explanation of snow-depth–related indicator and modeling components. We also evaluated the selected indicators and periods using a Random Forest model; however, we did **not** comment on this analysis in the main text in order to avoid confusion and to maintain focus on the primary objectives of the study. As noted in our response to the reviewer, the results of the Random Forest analysis were consistent with our physiology-based selection approach.
2. We added a discussion of the potential effects of increasing atmospheric CO_2 concentrations on crop yields.
3. We refined figures 1 and 2, to improve their clarity and visual presentation.
4. We incorporated additional references and expanded the discussion to show that our results are consistent with previously reported historical yield responses to climatic conditions, motivated by the *community-member*'s suggestions.
5. We added the statement used in MatLab code to the Supplementary Information to illustrate how yield variability was modeled using both random and fixed effects, while the main text includes only a model with the fixed-effect parameters.
6. We substantially revised the manuscript to streamline the discussion, reduce repetition, and improve overall readability.

These revisions also include several minor improvements and clarifications that were not explicitly raised in the reviewers' comments. All changes to the manuscript are highlighted in **blue** using track changes.

We hope that you will find the revised manuscript suitable for publication in *Biogeosciences*.

Best regards,

Faranak Tootoonchi - PhD
On behalf of the (co-)author team

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Reply to reviewer #1 for on egusphere-2025-1982 "Warmer growing seasons improve cereal yields in Northern Europe only with increasing precipitation"

The reviewer's comments appear in black, our response in blue. Line numbers refer to the original submission.

This manuscript systematically evaluated the effects of different climate factors (temperature, precipitation) on crop yield before and during the growing season, focusing on winter and spring cereal yields in Sweden from 1965 to 2020. Using county-level yield data and a range of physiologically relevant climate indicators for growth stages, the study found that warmer temperatures only benefit yields if accompanied by increased growing-season precipitation. This study, aligned with the focus of Biogeosciences on climate-ecosystem interactions, and provides recommendations for yield management in the context of climate warming in Sweden's high latitudes. However, the manuscript requires further improvement in its variable selection strategy, model specification, and reproducibility of the results. The article's structure and language should also be refined.

We thank the reviewer for their detailed comments that are helping us to further improve the manuscript. In a revised manuscript, we will clarify our methodology for feature selection, discuss and compare other modeling schemes. We have also identified ways to improve the discussion, by re-organizing and shortening it. The detailed responses to the specific comments can be found below.

Specific Comments:

1. Table 1: Nearly all the selected climate indicators represent frequency of short-term or extreme events, omitting intensity metrics that are known to influence crop yields. Please justify this choice or include intensity-based indicators in Section 2.2.1.

We fully agree that selected indicators must be complementary in nature. We selected a broad range of indicators reflecting both average conditions during whole growing season or subperiod, e.g. precipitation sum and temperature averages, other indicators reflecting frequencies of potentially damaging conditions, e.g. number of days with precipitation above 10 mm. In the selection we also considered the duration of these conditions, extending from short-term intense events to those with effects over longer periods. We also selected indicators that could have had effects over varying periods e.g. maximum number of consecutive dry days. While we acknowledge that even shorter-term damaging conditions, e.g. intense precipitation of 15 mins can have an adverse effect, this data is not readily available for the spatiotemporal scale of our study and is naturally concealed through daily averages. We will further clarify the rationale of the chosen indicators and any aspect unaccounted for in L130.

2. Model formulation:

- Why the Best formula can only include two main climate variables?

We considered together variables that are expected to have interactive effects on crops for physiological reasons (Luan et al., 2022; Ortiz-Bobea et al., 2021; Ray et al., 2015). While methodologically possible, combining more variables is not physiologically backed up and leads to complex models where interpretability is limited. Moreover, certain combinations, for example mixing wet days and dry days are not necessarily meaningful.

Nonetheless, we acknowledge that top-down feature selection approaches such as LASSO and random forest would allow for selections beyond two and free from priori assumptions. For this reason, we checked selected features with random forest and will comment on the complementary nature of this method and the similar ones to our physiologically backed-up approach in section 2.2.1. We will consider whether to also add a sentence in the abstract to signal our bottom-up approach based on our physiological understanding.

- Pre-growing: why only consider DI, what about other indicators?

DI was chosen for the pre-growing period because this variable is the most likely one to capture effects that go beyond the inactive period of crop growth and extend into the main growing season for winter crops and the actual growing season for the spring crops. It is possible that also precipitation or extended dry periods alone could have an effect, as they also affect the amount of water available to the crop at least in the beginning of the main growing season. Average temperatures could also have an effect in defining the timing of snow melt and soil water evaporation and, in turn, soil water availability. However, precipitation and temperature before the main growing season are likely to affect crops together, by defining the soil water availability, making DI a superior choice. We will add a sentence to clarify this choice in L194.

- Rather than fitting pre- and post-flowering variables separately, perform LASSO selection on the full set of seasonal indicators simultaneously (as i*Zhu et al. The critical benefits of snowpack insulation and snowmelt for winter wheat productivity. Nat. Clim. Chang. 12, 485–490 (2022)*), then interpret the selected variables. Also you can try to put the average & short-term indicators together.

Thanks for this suggestion. We have chosen our candidate indicators and models as they strike a balance between feasibility, based on commonly available data, simplicity and interpretability in light of the eco-physiological understanding. In this way, we minimized the trial-and-error procedure of model selection and leaned toward a more process-oriented understanding.

However, we agree that our manuscript could benefit from further clarifications on our modeling approach. We are considering how to best compare our results with an automatic feature selection approach in section 2.2.1, bringing up the advantages/disadvantages with LASSO or random forest, also referring to Zhu et al. (2022) where we discuss the indicator representing the Sum of precipitation occurring when mean daily temperature is below 0 °C (P-T0), the proxy of snow amount, in L165.

NOTE: We evaluated the selected indicators and periods using a Random Forest model; however, we did not comment on this analysis in the final version of the main text in order to avoid confusion and to maintain focus on the primary objectives of the study. As noted in our response earlier, the results of the Random Forest analysis were consistent with our physiology-based selection approach.

- Many climate-crop studies use log-transformed yield as the dependent variable. Please clarify why raw yield Y was chosen. Will the result change if you use log(Y)?

This is typically done when the data is skewed and the linear mixed effect model assumptions are not satisfied. However, this was not the case for our data. Using untransformed yields has the further advantage that the fitted parameters are immediately interpretable, as changes in yields per unit change of conditions. We will clarify this in L204.

1. The potential role of snowfall on soil moisture and yield is also important in high latitudes regions. Please discuss or analyze snowfall indicators.

This is a very good point. While snowfall and ultimate snow-depth have a direct effect on winter crops and an indirect one on spring crops, looking at the snow would only explain the winter accumulation of moisture, because snow melts occur already by the end of March in the south and early May in north of Sweden. Furthermore, precipitation as rain nearer the main growing season, and whether that evaporates or not, matter as well. In other words, snow can contribute to soil water availability, but ultimately it is the early spring precipitation, combined with temperature, that defines water available early in the main growing season. Indeed winter crops could be directly affected by snow depth, but examining this direct effect would require several snow- and winter-related indicators, adding additional indicators. Since we consider both spring and winter crops, we believe adding such indicators would make our work too complex and potentially confusing.

We also note that quantifying the direct effect of snow requires a reliable snow product. At the spatiotemporal scale of the current study, spanning from 1965 to 2020 and at 0.1° resolution, only a few gridded data sets are available, for which the uncertainties of the trends and the actual accumulation of snow is considerable (Wood et al., 2025). Relying on a proxy of snow depth (P-T0, i.e. the precipitation sum for days with temperature below 0 °C), only required precipitation and temperature data that are quality checked and more readily available for impact modelers, also over periods extending far in the past. Our correlation analyses showed that P-T0 is highly correlated with DI, and this contributed to the selection of DI for periods outside the main growing season, and extending over the winter. We will further clarify this choice and explain the possibility to use snow depth as an important indicator, in case of accessible reliable data in L165.

2. Section 2.2.2 Periods of interest: how to estimate the date of flowering and maturity. Now you only explain the beginning of growing-season. Uncertainty analyses of estimated phenological dates are also needed (e.g. shift the phenological dates forward or backward by equal intervals of days)

We have estimated the timing of flowering and maturity based on the growing degree day (GDD) approach, a common approach (e.g., Akyuz et al., 2017; Aslam et al., 2017; Liu et al., 2025), complementary to using crop growing calendar (e.g., Caparros-Santiago et al., 2021; Minoli et al., 2022). Through GDD approach, year-to-year variation of flowering and maturity dates caused by temperature are taken into account. This is particularly useful when field-level information regarding these phenological stages is not available. When revising the manuscript, we will adjust the description of the methods (L80-190), to clarify the approach used and its parameters (first day of counting, base temperature, thresholds for flowering and harvest).

We agree with the reviewer that such estimated dates are inherently uncertain. We thus checked for both the uncertainty caused by selecting different GDD thresholds and if there would be a difference in the results when year-to-year variations were considered instead of averages. None affected the results. We will clarify the lack of effects of the uncertainties in phenological stage estimation in L185.

3. Line300: here you indicated the yield maximizing DI, but for people who are not familiar with DI definition, they do not know what's the meaning of this DI value. What's the threshold of DI that represents drought? It should be clear in Methods.

That is a very good point and it is true that we missed explaining what DIs below or above 1 mean. We will clarify this in L165 and will remind the reader of the implications of DI in L300.

4. The current Discussion part repeats too many results and lacks logical flow. Please rewrite this part following a more clear structure and only remain main results.

Motivated by the reviewer's comment, we have carefully checked the discussion and found parts that can be removed or merged and reordered for improved flow and to avoid repetitions. More specifically, we have identified L356-370, L400-409, L465-470 to be revised. As we proceed with the revisions, it is likely that we will find additional parts that can be improved without loss of clarity.

Technical Corrections:

1. Figure 1b-c: The spatial map in panels b and c do not march the extent of panels a and d. The geographical boundaries should be the same as others.

We used the limited boundary to show that spring and winter wheat are only grown up to mid latitudes. We will add lines representing the Swedish borders for enhanced clarity.

2. Figure 2: the inclusion of too many indicators obscures the main information. Consider focusing on the most influential metrics. And the Spearman correlation coefficients were calculated from variables in which period? Please specify the period.

We see the reviewer's point that the number of indicators is high and the figure is complex. Nevertheless, we note that evaluating correlations is one of the steps we undertook towards reducing the number of indicators. For this reason, we would prefer to maintain all the indicators in this figure. However, we will use curly brackets to group them in three separate ones being precipitation, temperature and combination of precipitation and temperature. The figure refers to the entire growing season for winter wheat, estimated from sowing to maturity derived from the GDD model. We will clarify this in the caption.

3. Figure 3: add the explanation of each indicator in the caption (like what's short-term).

The caption will be revised as suggested

4. Table 2: relocate it to the Supplement and reference it appropriately in the main text.

We prefer to keep the table of coefficients (Table 2,3) in the main text. These are important parts of the results and guiding the reader on the significance of the parameters in the best fitting models. To keep the table brief, we had the indicators with lower ranking in the supplementary materials.

5. The current equations now only include fixed effects, random effects (e.g. site, year) also should be shown in the equation.

We will critically revise the text regarding the model, making sure the random effects are clearly indicated and justified. We prefer for the sake of clarity to write only the fixed part of the model. However, we see the reviewer's point that lacking an equation that includes also the random factors might be problematic. We will thus add the MatLab statements relative to the models to the supplementary materials. These clearly show the random factor structure and can also make our results reproducible.

6. Line275-280: "Yields increased between 0.2 ton·ha-1 per decade for spring crops and 0.5 ton·ha-1 per decade for winter wheat (Table 2), i.e., 7% to 10% of the long-term average". The location of this paragraph is a bit abrupt.

Upon re-reading the text, we agree. We will merge this sentence with L289-294.

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Reply to reviewer #2 for on egusphere-2025-1982 "Warmer growing seasons improve cereal yields in Northern Europe only with increasing precipitation"

The reviewer's comments appear in black, our response in blue. Line numbers refer to the original submission.

This paper explores the meteorological drivers of observed variability in crop yields in Sweden, investigating statistical relationships between key weather / climate indices and the yields of the four most commonly grown crops in the country over 55 years (1965-2020). Given the common assertion that anthropogenic climate change is beneficial for crops in higher latitudes, the conclusion that the potential benefits of warming may be limited by lack of increased precipitation is a very important one. There are also a number of extremely useful insights in the manuscript regarding the relative explanatory power of different variables, so overall I am supportive of this work.

We thank the reviewer for their positive feedbacks and further comments that are helping us to improve the manuscript. As detailed below, in a revised manuscript, we will discuss the lengthening of the growing season, which however does not impact our conclusions. We will also mention the effect of increasing CO_2 concentrations.

I note that the manuscript has already received a review from a referee and also a community review, to which the authors have already responded. Here I will focus on two additional points that appear to have been overlooked, which I recommend are addressed in a revised manuscript.

1. As the authors note, climate change is expected to increase the length of the growing season, and indeed this has already happened. eg. in southern Sweden, the meteorologically-defined growing season length has been starting earlier by between 2 and 4 days per decade between 1950 and 2022 (Miś and Tomczyk, 2025 https://doi.org/10.1007/s00704-025-05382-6). So, over the period analysed in the current study, the growing season may have lengthened by over 20 days in some places. However, the authors conduct their analysis using an average growing season length over the study period. Is there a risk that the results may have been affected by including events or averaging periods outside of the growing season in the earlier part of the study period but excluding some within the growing season in the later part? This seems particularly pertinent in the context of the authors remark at lines 317-320: "We surmise this low performance is in part due to the infrequent occurrence of short-term potentially damaging conditions (e.g., few occurrences of days with average temperatures above 25 °C, or frost during sensitive developmental stages)". I would be reassured if the authors could demonstrate that their conclusions are not sensitive to the use of an average growing season length over a period when the length has changed by a non-trivial amount.

This is a valid point. In our dataset, the growing season length increases by approximately 10 days on average over the study period, the result of the advancement of the sowing date and a smaller advancement of the maturity date, as determined by the growing degree (GDD) model (**Figure 1**).

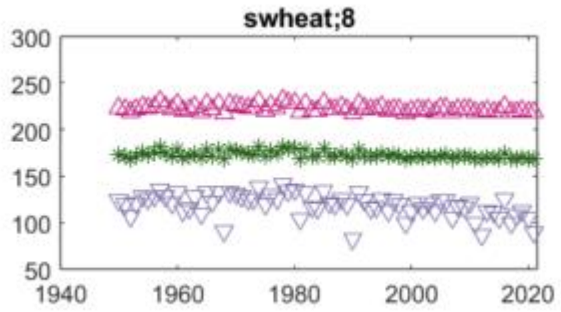

Figure 1: Example of time series of the day of the year (y-axis) corresponding to sowing (purple down-pointing triangles), flowering date (green stars) and maturity (pink triangles pointing upwards) for spring wheat in Kalmar County, in south-east of Sweden.

Motivated by the reviewer's concern, we tested the sensitivity of our results to the use of year and county-specific growing seasons, and hence length, instead of a fixed county-specific average, in determining the climatic indices. This had no meaningful effect on the number of extreme events identified or the average conditions or the resulting conclusions.

2. The authors do not mention the potential impact of rising atmospheric CO2 concentrations on photosynthesis, transpiration and yield - see, for example, Rezaie et al (2023 https://doi.org/10.1038/s43017-023-00491-0) for a recent review. If this is already having an influence then it will be included within the continuous variable representing the combined effects of time elapsed in since 1965 (as described in lines 197-200) so I don't think it will alter the findings regarding the relative importance of the different meteorological drivers during the period of observations. However, given the potential non-linear effects of CO2 effects in the future, especially in how they may affect crop responses to drought and high temperatures, the existence of these influences and their implications should be highlighted as an outstanding uncertainty in relation to the results here. Eg. it should be mentioned in line 199 alongside climate change and technological improvements, and also discussed in section 4.4 (Implications under climate change).

We agree with the reviewer that explicitly mentioning the role of atmospheric CO_2 concentration is helpful for a more complete description of conditions. However, as recognized by the reviewer, the role of the increase in CO_2 concentration cannot be disentangled by that of other trends, for example technological improvements. We will thus mention the physiological effects of CO_2 increase, referring to Rezaei et al. (2023) in L**70**, and explicitly mention that this is conflated with other changes in time in the coefficient of time in **L410** where we discussed implications under climate change. We note that all plotted results pertain to an intermediate time point (the year 1992, an intermediate year within the study period) and hence implicitly an intermediate atmospheric CO_2 concentration, among other changes occurred in the 55 years considered.