Reply to community comment by Martin Skoglund 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.

General comments

This study addresses a highly relevant and timely topic, and I find the authors' attempt to integrate short-, medium-, and long-term climatic influences on crop yields both commendable and innovative. The analysis represents a significant step forward compared to previous work by systematically evaluating multiple climatic indicators across different time-scales and their interactions across different crop types and periods.

We thank Martin Skoglund for their comments and suggestions.

However, I have several concerns regarding the model specification, which may substantially affect the results and their interpretation. These issues primarily concern how the models account for spatial heterogeneity in climatic responses across Sweden. In addition to this, I have some other smaller concerns regarding the interpretation of the results when using relative yield indicators as well as the formulations of the model equations.

1. **Model specification**

My main concern is that the models do not properly account for the well-known spatial differences in the temperature–precipitation dependency of crop yields between northern (N) and central/southern (C/S) Sweden. These regional contrasts were already formally identified by Wallén (1917, 1918) and have been confirmed in subsequent studies dealing with both historical and recent periods (e.g., Edvinsson et al. 2009; Skoglund 2022, 2023; Sjulgård et al. 2023).

In short:

- In northern Sweden (Norrland and Dalarna), higher summer temperatures are positively associated with yields, whereas increased precipitation often has a negative, albeit small, effect.
- In central/southern Sweden (counties south of Dalarna/Gävleborg), the relationship is generally the opposite: higher temperatures tend to reduce yields, while greater precipitation tends to increase them.

These contrasting relationships imply that aggregating N and C/S counties into a single model (this article) or time-series (see Holopainen et al. 2012), without explicitly accounting for these systematic differences, introduces biases and will underestimate the true climatic sensitivity of year-to-year yield variability.

This issue is especially relevant for spring-sown crops, such as barley, which are cultivated across the entire country, but also potentially for winter crops and wheat to a lesser extent (see Sjulgård et al. 2023). For winter crops and wheat, the shift from positive (negative) or negative (positive) relationships with temperature (precipitation) tend to occur only in the southernmost counties, if at all.

In the Discussion, the authors write:

"The explanatory power of climatic conditions were lower for oats and spring barley yields compared with spring and winter wheat … A possible explanation is that wheat yield data refer to southern Sweden only, whereas spring barley and oats are grown under a wider range of latitudes and hence climatic conditions …"

Here the authors themselves imply that there is a possible aggregation bias, that lowers the explanatory power for oats and barley. The issue is less relevant for (spring and winter) wheat that is mainly grown in C./S. Sweden with a more homogenous climatic signal (see also the results for barley and wheat yields in Holopainen et al. 2012 where the same type of aggregation error is made). In an analysis where relationships are estimated at the county-level, where the systematic difference between N. and C./S. is largely accounted for (except perhaps when considering border counties such as Dalarna/Värmland/Gävleborg), it can clearly be seen that year-to-year climatic fluctuations have a much greater explanatory power in N. Sweden compared to C./S. Sweden (Sjulgård et al. 2023; Skoglund, 2022; 2023). In your model, this is mainly introduced as a random effect, which brings the oat and barley models to similar levels of explanatory power as the wheat models. However, because the random effects model assumes that group-level differences are uncorrelated with the explanatory variables, this treatment is inappropriate when the between-county differences are themselves driven by climate–yield dependencies.

Possible alternatives that address the aggregation bias:

- Including an interaction between region (N, C, and S or N and C/S) and key climatic variables.
- Fit separate models for N, C and S or N and C/S.
- A random-slope model that allows the effects of temperature and precipitation to vary by county.

We acknowledge that Sweden exhibits climatic differences across its parts. However, we disagree that the model must be split into separate subregions. We explain here our rationale.

We explicitly include aspects of the local climatic conditions, as summarized by the different climatic indices. In other words, the regional scale differences in climatic conditions are accounted directly, and not indirectly via a subdivision of the country. Of course, different parts of the country might experience different conditions, i.e., not being subject to all conditions represented in the contour plots.

The climatic indices we considered refer to the main growing season or the 30-60-90 days preceding that. Although annual climate averages differ substantially across Sweden, the temperature conditions relevant to crop development show less spatial variation. This is because the growing season occurs in partially different periods, depending on the location. This is the case not only in Sweden, but also across larger latitudinal gradients: for example, the growing season average temperature from northern Sweden to southern Italy and Spain has been shown to be substantially aligned (Costa et al., 2024), despite the clear difference in annual average temperature. Lacking specific information on sowing date for spring crops and the release of dormancy for winter crops, we have used a Growing Degree Day (GDD)–based growing season. This approach explicitly adjusts the start and end of the main growing season according to the local temperature conditions. The GDD adjustment therefore normalizes much of the climatic contrast between north and south.

County is included as random effect, i.e., we control for that and hence, implicitly, for the three regions mentioned above. We set county as random factor as we are interested in the crop response to the climatic conditions directly, not the location, which in turn affects the climatic conditions. We recognize that we set as random just the intercept though, i.e., we do not consider county-specific responses.

However, motivated by the comment received, we have now evaluated an alternative structure for the random factor, and specifically: Yield ~ ClimateVars + (Temperature | County). This allows each region to have its own temperature–yield slope. This model including the random slopes did not improve model fit i.e., AIC did not decrease, and the estimated random slopes for temperature were very close to zero for most regions. This indicates that the effect of temperature on yield does not vary meaningfully across counties. In other words, the model itself provides evidence against the idea that climate–yield relationships are region specific, thus calling for separate models. A similar conclusion is reached if considering a random slope for the precipitation variable, i.e., Yield ~ ClimateVars + (Precipitation | County).

Taken together, these points justify using single mixed-effects models across all cultivated regions of Sweden. The model effectively accounts for spatial and climatic heterogeneity while avoiding arbitrary regional divisions and maintaining statistical coherence. For these reasons, we will not change the model. However, we will add a sentence around section 2.3.3 (Linear mixed effect models) to better justify our modeling choice, while acknowledging the north-south climatic gradient and the ultimate yield differences, with reference to Sjulgård et al. (2023) and Skoglund (2022).

Relevance of results: Another issue, that is related to the model specification but only becomes an issue in regards to the interpretation of the results is that since you are treating yield as a relative variable (i.e., tonnes per hectare), instead of absolute production levels, the lumping together of N. and C./S. Sweden also obfuscates the social relevance of the results as the overwhelming majority of grain production occurs in C./S. Sweden.

We see that it is production, not productivity, having the ultimate implication in terms of locally produced cereal availability. However, we have chosen to focus on productivity, because we are primarily interested in the ecophysiological response of the different crops to a range of climatic conditions. In this way we can separate this effect from the combined effects of ecophysiological response and past and current spatial distribution of cultivated areas. We also note that the latter is less impacted by the year to year variation in climatic conditions compared with the productivity.

Equations: As a previous reviewer mentioned, in your model equations (eq. 1–3), you describe yield as, $Y_{,}$ when it should in fact be indexed as time- and location-variant, Y_{it}. Furthermore, all explanatory variables should also include $_{it}$ since they describe a given variable at time $_t$ and location $_i$. I do not believe the choice to make it only Y makes it clearer as the authors suggests as we now are several reviewers who had the same objection.

We will add the subscripts for clarity.

References:

Costa, A., Bommarco, R., Smith, M. E., Bowles, T., Gaudin, A. C. M., Watson, C. A., Alarcón, R., Berti, A., Blecharczyk, A., Calderon, F. J., Culman, S., Deen, W., Drury, C. F., Garcia y Garcia, A., García-Díaz, A., Hernández Plaza, E., Jonczyk, K., Jäck, O., Navarrete Martínez, L., Montemurro, F., Morari, F., Onofri, A., Osborne, S. L., Tenorio Pasamón, J. L., Sandström, B., Santín-Montanyá, I., Sawinska, Z., Schmer, M. R., Stalenga, J., Strock, J., Tei, F., Topp, C. F. E., Ventrella, D., Walker, R. L., and Vico, G.: Crop rotational diversity can mitigate climate-induced grain yield losses, Glob. Change Biol., 30, e17298, https://doi.org/10.1111/gcb.17298, 2024.