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Heat, drought, and compound events: Thresholds and impacts on crop yield variability

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ABSTRACT

Food security is threatened by compound events (extreme events like heat and drought occurring together), intensifying with climate change. Crucial for studying their impact on crop yield variability is the setting of temperature and precipitation thresholds. While relative thresholds (e.g., the 95th percentile) can hardly be justified concerning plant physiology, absolute thresholds (e.g., 30 °C) are expected to differ substantially between plant-level and large-scale assessments. As this contradiction has not yet been addressed, suitable relative and related absolute thresholds for the prominent crops grain maize and winter wheat are examined in this study. With these, it is analyzed whether extreme or compound events explain yield variability better and which development phase is sensitive to them. Also novel in the approach is to compare defining heat with daily mean and maximum temperatures and drought over 10 and 30 days. The analysis covers the years 1983 to 2021 and the 96 administrative districts of Bavaria, Germany, which are located in central Europe and exhibit a considerable precipitation gradient. Relative thresholds vary over this gradient, yet lead to similar absolute thresholds. This indicates that absolute thresholds are more suitable to explain crop yield variability. The discovered thresholds for daily maximum temperatures are at least 28 °C for grain maize and 24 °C to 25 °C for winter wheat, being lower than in plant-level analyses. Compound events have more impact on grain maize compared to individual extreme events. Yet, this effect was not revealed for winter wheat yields, showing the greatest sensitivity to individual heat events. During the vegetative phase, grain maize was most sensitive to heat. During the reproductive phase, grain maize was most sensitive to drought and winter wheat to heat. These results can be used in the methodology of further studies and for developing measures that buffer the impact of compound events on crop yields.

1. Introduction

Global food security is threatened by increasing variability of crop yields, which is largely associated with climate variability (Ray et al., 2015). Climate change harms crops mainly through the extreme events of heat and drought, with an increasing frequency of especially heat (Hao et al., 2022). When these extreme events occur together in space and time, they can be defined as compound events, with the potential for interaction and an amplified impact on crop yields (Hao et al., 2022). For defining these extreme and compound events, a wide range of incoherent thresholds exist, often applied without justification (McPhillips et al., 2018).

Grain maize and winter wheat, two important crops for human consumption, face yield variability due to climate change in almost all regions of the world (Neupane et al., 2022; Ray et al., 2015). Even with high mean yields, this variability endangers global food security (Ray et al., 2015). Fahad et al. (2017) list yield losses for maize of 42 % in years with heat and 63–87 % in years with drought, while these losses are for wheat 31 % and 57 %. These values were discovered for maize during field studies in Canada and Nigeria, for wheat in a climate chamber experiment in Hungary (Badu-Apraku et al., 1983; Balla et al., 2011; Kamara et al., 2003). Neupane et al. (2022) reported losses for different world regions that are in a similar range. Heat affects both crops, particularly during their reproductive phase, because of pollen

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sterility and, therefore, reduced grain numbers (Porter and Gawith, 1999; Sánchez et al., 2014). Drought also affects maize during the reproductive phase via pollen sterility (Daryanto et al., 2017). Wheat is affected during the vegetative phase as well because it invests more into roots instead of leaves during droughts early in their phenological development (Daryanto et al., 2017). When heat and drought occur together as compound events, they can have stronger negative effects than the sum of individual extreme events (Rezaei et al., 2023). One reason is that during heat, crops open their stomata to increase transpiration for cooling down, which is not possible under droughts (Shan, et al., 2024a). Rezaei et al. (2023) report yield losses of 60 % for compound events compared to 30 % for heat only and 40 % for drought only. However, they also emphasize a lack of quantified evidence for this phenomenon (Rezaei et al., 2023).

While their importance for crop yields is known in research, defining extreme events remains difficult (Stephenson, 2008). Most studies define heat as temperature above a certain threshold and drought as precipitation or soil moisture below a certain threshold (Hao et al., 2022). Thresholds are commonly set with relative values (via percentiles, standard deviation, or return periods) or absolute values (e.g., maximum temperature above 30 °C, daily precipitation below 1 mm) (Hao et al., 2022). Relative thresholds are appealing from a meteorological point of view, as they can be directly derived from the weather data in different study regions. Yet, from a plant physiological point of view, absolute thresholds are more suitable, as they can be set to values that are known to cause stress for the plant (Siebert et al., 2017). The problem with setting these values is that harmful temperature thresholds found empirically for larger study areas are typically 5 °C to 10 °C lower than in studies conducted on a plant-level, possibly because of the amplifying effect of water scarcity (Lesk et al., 2022).

Although this contradiction in setting relative or absolute thresholds is crucial for defining and studying extreme and compound events, it has, to our knowledge, not yet been addressed in the literature. Therefore, the first aim of this study is to find the relative and their related absolute temperature and precipitation thresholds that explain crop yield variability. Defining heat, drought, and compound events this way, their impact on grain maize and winter wheat is compared. This allows, as the second aim, analysis of whether compound events explain yield variability better than individual extreme events. It also identifies which crop and development phase is especially sensitive to them.

The approach to reach these aims is to quantify through linear regression how well different relative and related absolute thresholds can explain yield variability. The relative thresholds are calculated via percentiles of the values during a reference period. They are applied separately for each district and development phase and lead, therefore, to different absolute thresholds. This is the first study to compare the use

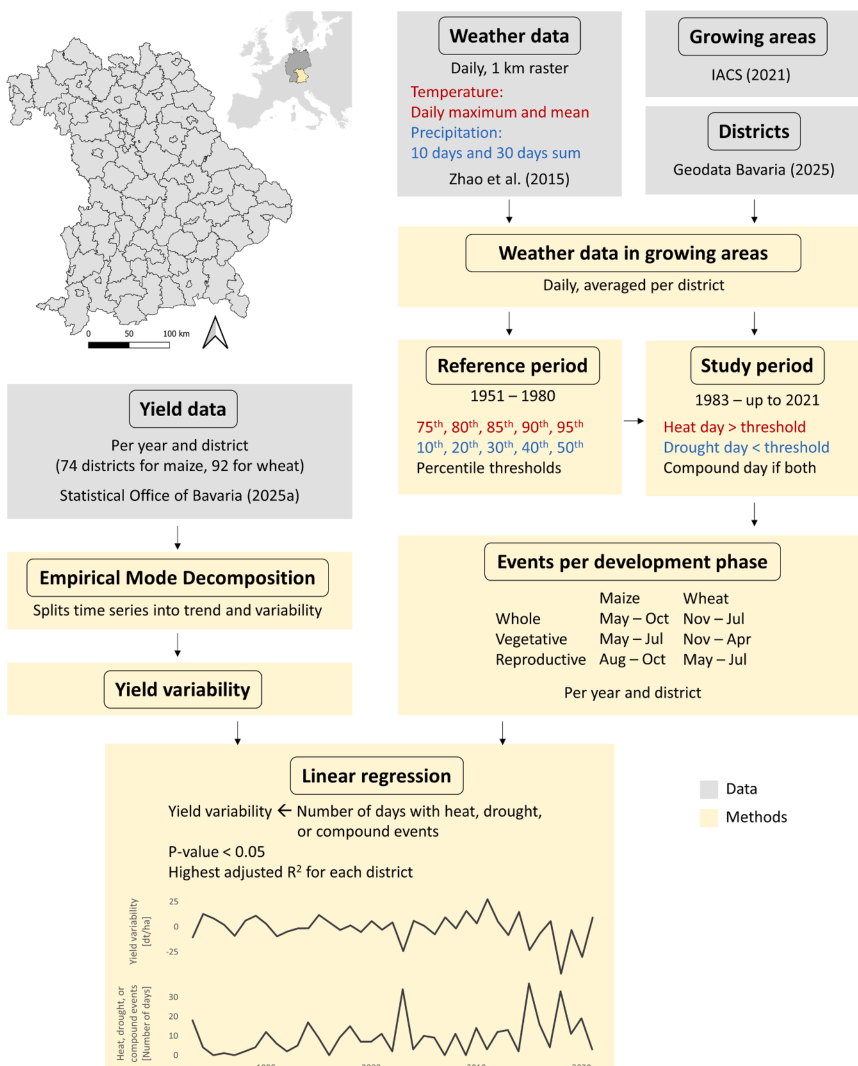

Fig. 1. Location of the study area Bavaria within central Europe with its 96 districts. The flowchart shows how the yield variability was calculated from the yield data and the extreme and compound events from the weather data, growing areas, and districts. In the last step, their relation was quantified in linear regressions.

of daily mean versus daily maximum temperatures for defining heat and precipitation over 10- and 30-day periods to characterize drought. The analysis was conducted for the years 1983 to 2021 and the 96 administrative districts of Bavaria, Germany, which have a gradient in precipitation and climatic conditions representative for continental Europe. The detected thresholds and metrics can be applied in further research. Additionally, the results on maize and wheat in their development phases can be used to adjust agricultural practices and policies. This can contribute to increasing the stability of yields and food security under climate change.

2. Methods

2.1. Study area and target crops

The study area is the federal state of Bavaria, Germany, which is located in central Europe (Fig. 1). It covers an area of 70 550 km^2, with almost half of it used for agriculture and one-third for forestry (Statistical Office of Bavaria, 2025b). It has a temperate climate with an average temperature of 7.9 °C (16.3 °C on average in summer, -0.5 °C in winter) for the period 1971 to 2000. Between 1951 and 2019, a temperature increase of 1.9 °C was reported. The average annual precipitation sum was 941 mm, with 700 mm in the north-eastern climatic region of the river Main, 800 mm in the central region of the river Danube (Donau), 1000 mm in the south-Bavarian hill region until almost 2000 mm in the South at the Alps (StMUV, 2021; Fig. S1). This precipitation gradient makes the area suitable for studying the effect of differing weather conditions. Weather and yield data were analyzed on the spatial level of up to 96 administrative districts of Bavaria. As target crops, grain maize and winter wheat were chosen, as they are two of the most prominent crops for human consumption globally (Neupane et al., 2022). To differentiate the impact of extreme and compound events on the crops during their phenological development, it is split into two phases: The vegetative phase is set from May to July for grain maize and from November of the sowing year to April of the harvest year for winter wheat. The reproductive phase is set from August to October for grain maize and from May to July for winter wheat (DWD, 2025; Gornott and Wechsung, 2016). Yield data for these two crops for the period 1983 to 2021 were extracted from official agricultural statistics at the district level (Statistical Office of Bavaria, 2025a; Fig. 1).

2.2. Calculation of yield variability

To remove long-term trends in yields caused by the use of improved technology, new management practices, or breeding progress, the raw yields had to be detrended first (Ceglar et al., 2016). The annual yield time series available for the two crops and the period 1983–2021 has data gaps in some districts, especially for the period after 2015. To have sufficiently long time series for the analysis, only districts with a complete time series from 1983 to at least 2015 (up to 2021 for districts with more available data) were included. After filtering, this resulted in grain maize data for 74 districts and winter wheat data for 92 districts. For each district, a separate "ensemble Empirical Mode Decomposition" was conducted to differentiate the raw yield time series into its trend and variability (Z. Wu and Huang, 2009; Tab. S1). The initial time series is decomposed into "intrinsic mode functions" and a residue (Z. Wu and Huang, 2009). All modes with a periodicity above 20 years were assigned to the trend, all equal to or below 20 years to the variability (Tabs. S2 and S3). The temporal and spatial characteristics of the yield data are summarized in Figures S2 and S3. The yield variability was used as the dependent variable to be explained by extreme and compound events, of which the calculation is described in the following section.

2.3. Detection and quantification of extreme and compound events

The extreme events heat and drought, as well as their compound events, were derived from published daily weather data for mean temperature, maximum temperature, and precipitation sum. This data set was available at 1 km resolution for the entire study region and study period (Zhao et al., 2015). It was developed by combining weather station data and gridded time series obtained from the observation network of the German Meteorological Service (Zhao et al., 2015). The weather data were aggregated to the level of the Bavarian districts by calculating the arithmetic mean of the values from all grid cells falling in an area that is suitable for growing grain maize or winter wheat. To delineate the suitable areas, all grids were selected in which the respective crop was grown according to the Integrated Administration and Control System (IACS) of the European Union in the available period 2005 to 2021 (IACS, 2021; Fig. S4). The shapefile of the Bavaria districts was obtained from Geodata Bavaria (2025).

To derive the extreme events in each district from the weather data, percentile-based thresholds were applied. Temperatures above their threshold are defined as heat, and precipitation sums below them as drought. To test which thresholds explain yield variability best, the 75th, 80th, 85th, 90th, and 95th percentiles were used for temperatures and the 10th, 20th, 30th, 40th, and 50th for precipitation values (Feng et al., 2020). Heat was calculated with daily mean as well as with daily maximum temperatures. Drought was calculated from precipitation sums for 10 and 30 days, to account for the distinct water storage potential of the soils in the study region. For each day, the precipitation of that day and the 9 and 29 preceding days was summed up to receive its 10- and 30-day precipitation sum. The historic reference period from 1951 to 1980 was chosen, as it is reported to have comparably stable climatic conditions (He et al., 2022). To compare the effect of different reference periods, a modern one matching the study period from 1983 to 2021 was used in addition. With percentiles of the values in the reference period, absolute thresholds were calculated and applied to the study period. The thresholds were calculated and applied within each district separately, allowing for the comparison of the influence spatial differences have on the definition of thresholds. On a temporal scale, they were calculated for the whole phenological development, the vegetative development phase, and the reproductive development phase of the two crops (Fig. 1). For example, the 184 daily maximum temperatures of the whole development phase of grain maize in one district for the 30 reference years resulted in 5520 values. Their 95th percentile resulted in an absolute threshold of 28 °C and each day in the study period for the same district and development phase with a maximum temperature above it was defined as a heat day. Compound events are defined within each district for days on which both heat and drought occur. The days with heat, drought, or compound events were then summed up for each development phase to obtain one value per year. Consequently, the values per year and district for the extreme and compound events were on the same temporal and spatial resolution as the yield variability data.

2.4. Analyzing the relationship between extreme or compound events and yield variability

Linear regression was used to quantify the effect of extreme and compound events on crop yield variability. Yield variability of grain maize and winter wheat was considered as the dependent variable. For individual extreme events, the independent variable was the number of heat days defined with daily maximum or daily mean temperatures and the number of drought days defined with precipitation sums of 10 or 30 days. Each of them was calculated for the whole, vegetative, or reproductive development phase. A separate univariate linear regression model was set up for each of the extreme events calculated after these definitions. For each district, five linear regression models were set up, always with the number of heat or drought days defined according to one of the above-mentioned percentile-based thresholds. This approach of modeling each district separately resulted in datasets with 33 to 39 observations. Because of this small sample size, linear regression was chosen over machine learning models (Rajput et al., 2023). To assess the suitability of the linear regression, the residuals of each model were tested for normal distribution with the Shapiro-Wilk test (Tab. S4). Additionally, a Durbin-Watson test was conducted to verify that the residuals show no positive temporal autocorrelation. And the regression coefficients with their confidence intervals were calculated to determine whether the effect on yields is positive or negative (Tabs. S5 to S10).

All models with a p-value above 0.05 were considered not significant and were removed. From the remaining of the five models, the one with the highest explanatory value (adjusted R^2) was taken, assuming that events defined with this threshold explain the yield variability best. This was first done for heat and drought individually to find suitable thresholds to be applied for compound events. Concerning the percentiles, heat showed a tendency towards a certain threshold which explains yield variability best, while drought was explained best in different districts by different thresholds. Therefore, one best threshold was selected for heat and combined with the five potential thresholds for precipitation. This resulted in again five threshold combinations, from which the ones explaining yield variability best in each district were selected. The spatial distribution of explanatory values was illustrated in maps. The related absolute thresholds, together with their percentile-based relative thresholds, were illustrated in histograms and maps.

3. Results

3.1. Individual extreme events

3.1.1. Heat impact and thresholds

Associations between yield variability and heat have almost equal strength when heat days were calculated based on daily maximum temperatures and daily mean temperatures. As the use of daily maximum temperatures is more common in the literature and easier to interpret in terms of plant physiology, their results are described first (Figs. 2 and S6, Tabs. S5 and S6). For grain maize, heat explains 23 % (adjusted R^2) of the yield variability in the whole phase (as the median value of the 52 districts with a significant effect) and 16 % in mostly the same districts in the vegetative phase. In the reproductive phase, they explain 17 %, but in only 35 districts. In this phase, the difference to calculations with daily mean temperatures is largest, with an explanation of 14 % in 21 districts. For winter wheat, the explanatory value is in the whole phase with 18 % from 59 districts slightly lower compared to grain maize and shows the same explanatory value and pattern of districts in the reproductive phase. During the vegetative phase, heat events have a significant effect in only three districts with a median explanatory value of 11 % (7 districts and 10 % for mean temperature heat events; Fig. 2). While for all other regression models only single exceptions of districts with a positive effect of heat are captured, around half of the districts concerning the vegetative phase of winter wheat show a positive effect (1 of 3 and 4 of 7). However, not much effect of heat during the phase from November to April was expected because of the generally low temperatures.

The thresholds that led to the highest explanatory values for grain maize are for almost all districts calculated with the 95th percentile. The respective absolute thresholds for daily maximum temperatures are around 28.5 °C during the whole and vegetative phase and with 27 °C to 28 °C slightly lower during the reproductive phase. For winter wheat during the whole phase, the absolute thresholds in at least one district for daily maximum temperatures have a wide range between 16.5 °C and 27 °C because the long period from November to July contains different seasons and temperatures. The explanatory values are highest in most districts at a threshold of 24 °C and with the 90th percentile, followed by the 95th percentile. For the vegetative phase, no clear

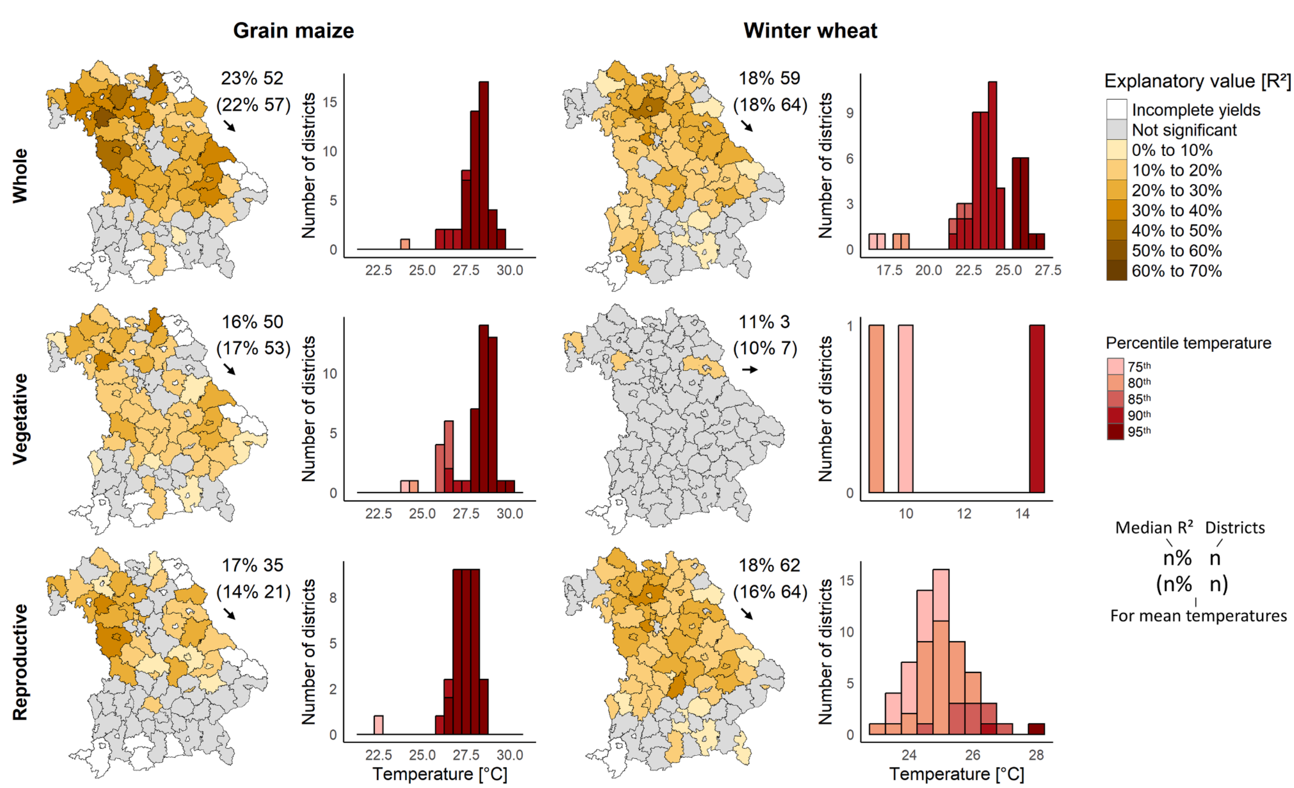

Fig. 2. The effect of heat calculated with daily maximum temperatures on yield variability. The effect is differentiated for grain maize and winter wheat in their whole, vegetative, and reproductive development phase. In the maps, the explanatory value within each district is illustrated, as well as their median value and the number of districts with a significant effect. In brackets, the same values for heat calculated with daily mean temperatures are shown. The arrow shows whether this effect is positive or negative. In the histograms, the thresholds that led to the highest explanatory values in these districts are shown with their absolute and percentile values.

threshold can be determined because of the few districts with a significant effect of heat. For the reproductive phase, a clearer peak is found with an absolute threshold around 25 °C and the 75th or 80th percentile in most districts (Fig. 2). Both in percentiles and in absolute thresholds, these values are lower compared to the ones from grain maize. Also, during the vegetative phase of grain maize and the reproductive phase of winter wheat, which are both from May to July. For heat calculated with daily mean temperatures, the percentiles and their distribution among districts are close to the values for daily maximum temperatures, while the absolute thresholds are lower (Figs. S5 and S7, Tabs. S5 and S6). For grain maize, the absolute thresholds with the highest explanatory values in most districts are around 21 °C during the whole phase, 21.5 °C during the vegetative phase, and 20 °C during the reproductive phase. For winter wheat, they have a broader range during the whole phase, between 16 °C and 19.5 °C, while for the reproductive phase they fall around 18 °C (Fig. S5).

For the effect of heat on grain maize, the largest difference to applying a modern reference period was detected. The modern period led to higher explanatory values for all development phases, especially the whole phase. For example, the median explanatory value for daily maximum temperatures in the whole phase reached 28 %, while it is 23 % when using the historic period. The thresholds are again mainly calculated with the 95th percentile, but in this case, they correspond to absolute values close to 30 °C. These higher explanatory values for a modern reference period persist for the effect of compound events on grain maize, although not as pronounced as for heat alone. For the effect of drought on grain maize and of all events on winter wheat, the explanatory values and thresholds are in a similar range for both reference periods (Tabs. S12 and S13).

3.1.2. Drought impact and thresholds

Whether heat or drought events can explain yield variability better depends on the time of the year and whether droughts are defined for a 10-day or a 30-day period. The results on 30-day droughts are described first in the following section (Figs. 3 and S9, Tabs. S7 and S8). For grain maize during the whole phase, the median explanatory values and the number of districts are with around 20 % and 50 districts in the same range for both drought durations compared to heat. For the vegetative phase, a median explanatory value of 16 % (versus 14 %) from less than half as many districts is reached when droughts are calculated for a 30-day duration compared to a 10-day duration. For the reproductive phase, on the other hand, 30-day droughts explain 23 % (versus 17 %) in more districts. The spatial pattern of districts is similar between the whole and the reproductive phase. Apart from three exceptions for 30-day droughts in the vegetative phase of grain maize, the effect of drought is negative in all districts. For winter wheat it is the other way around, with a positive effect of drought on yields in almost all districts. The median explanatory values are with between 10 % and 14 % from 15 to 33 districts lower for all development phases, compared to grain maize. During the whole and the reproductive phase of winter wheat, the explanatory values of drought are also lower than those of heat. Only during the vegetative phase, more districts (22 and 16) have a significant effect compared to heat, while the explanatory values are in the same range, around 11 %. Between 30-day and 10-day droughts, the median explanatory values for winter wheat are almost equal, only the number of districts is higher during the whole and reproductive phase and lower during the vegetative phase for 30-day droughts. The patterns of districts with a significant effect differ for drought compared to heat, with districts being located rather in the East for the whole and vegetative phase and the South for the reproductive phase (Fig. 3).

The thresholds that lead to the highest explanatory values are calculated for both crops with different percentiles. However, the related absolute thresholds show peaks, which are for 30-day droughts and grain maize during the whole and reproductive phase around 40

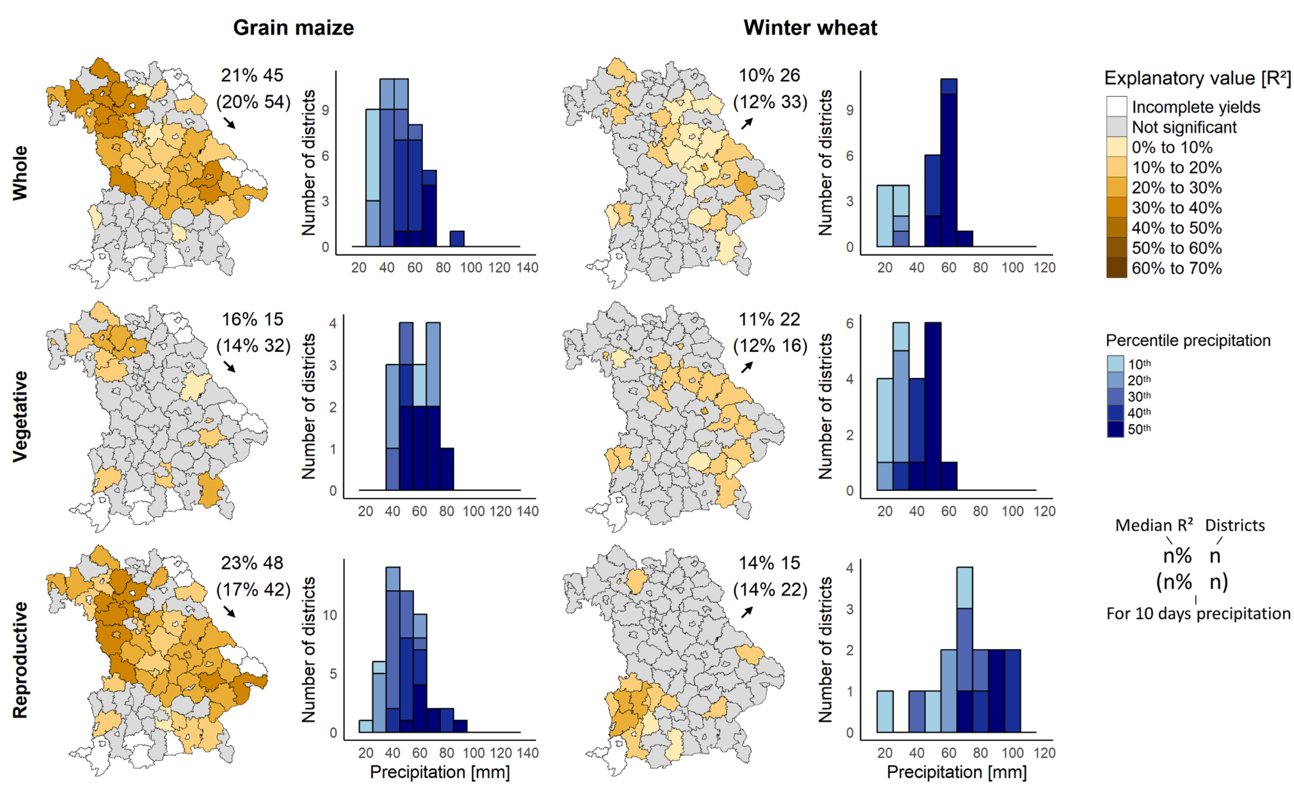

Fig. 3. The effect of drought calculated with 30-day precipitation on yield variability. The effect is differentiated for grain maize and winter wheat in their whole, vegetative, and reproductive development phase. In the maps, the explanatory value within each district is illustrated, as well as their median value and the number of districts with a significant effect. In brackets, the same values for drought calculated with 10-day precipitation are shown. The arrow shows whether this effect is positive or negative. In the histograms, the thresholds that led to the highest explanatory values in these districts are shown with their absolute and percentile values.

mm to 50 mm, during the vegetative phase around 50 mm to 70 mm. For 10-day droughts, the patterns between the development phases are comparable to the ones for 30-day droughts but with lower absolute thresholds of around 10 mm to 15 mm during the whole and vegetative phase and 30 mm during the reproductive phase. For winter wheat, it is important to keep in mind, that precipitations below the discovered thresholds have a positive effect on yields. The value for the whole phase is with 60 mm in between the thresholds of the vegetative phase with 30 mm to 50 mm and the reproductive phase with 70 mm (Fig. 3). For 10-day droughts, the thresholds are between 5 mm and 15 mm during the whole and vegetative phase and 30 mm during the reproductive phase. Lower thresholds, towards 0 mm precipitation, show a positive effect on winter wheat yields as well, although with lower explanatory values as the ones mentioned above (Figs. S8 and S10, Tabs. S7 and S8).

3.2. Compound events

3.2.1. Detection of compound events

In compound events, heat was calculated with daily maximum temperatures similar to individual extreme events. Concerning droughts, 30-day periods were used for grain maize and 10-day periods for winter wheat, as they generally led to higher explanatory values of compound events for the respective crop (Tab. S11). The results from heat and drought on suitable thresholds were used to set them for compound events. For winter wheat, the focus was set on the whole and reproductive phase, as the vegetative phase showed almost no effect from heat. Although drought alone had a positive effect on winter wheat yields, it was tested whether the negative effect of heat persists or is even amplified with drought. As heat showed clearer peaks at certain thresholds, they were set to the respective percentiles (95th for grain maize, 90th for winter wheat during the whole phase, 75th during the reproductive phase). As drought showed less clear thresholds, all five percentiles were used again, to be now combined with the heat thresholds. This way, again, five threshold-combinations were received to find the one explaining the impact of compound events best, avoiding the effect of having higher explanatory values because of more options to choose from.

3.2.2. Compound events impact and spatial distribution of thresholds

For grain maize, compound events lead during each development phase to higher median explanatory values from more districts compared to heat or drought (Fig. 4, Tabs. S9 and S10). With 69, 60, and 68 districts in the respective development phases, almost all of the 74 districts showed a significant effect. Areas in which yield variability can be explained best by compound events are in the North-West, West, and East of Bavaria, with explanatory values above 50 % in the whole phase, above 30 % in the vegetative phase, and above 40 % in the reproductive phase. For grain maize, this effect is negative across all development phases and districts. For winter wheat, it is also negative, with only one district as an exception. Compound events lead for winter wheat to higher median explanatory values from more districts compared to drought. However, with median explanatory values of 19 % and 18 % from around 40 districts, compound events led to the same explanatory values as heat but with around 20 districts less that had a significant effect. These districts are almost solely located in the northern half of Bavaria (Fig. 4).

Like for droughts, the thresholds that lead to the highest explanatory values of compound events are calculated with different percentiles for precipitation. The related absolute thresholds again show peaks, which are in the same range as for droughts (Fig. S11). For grain maize, a

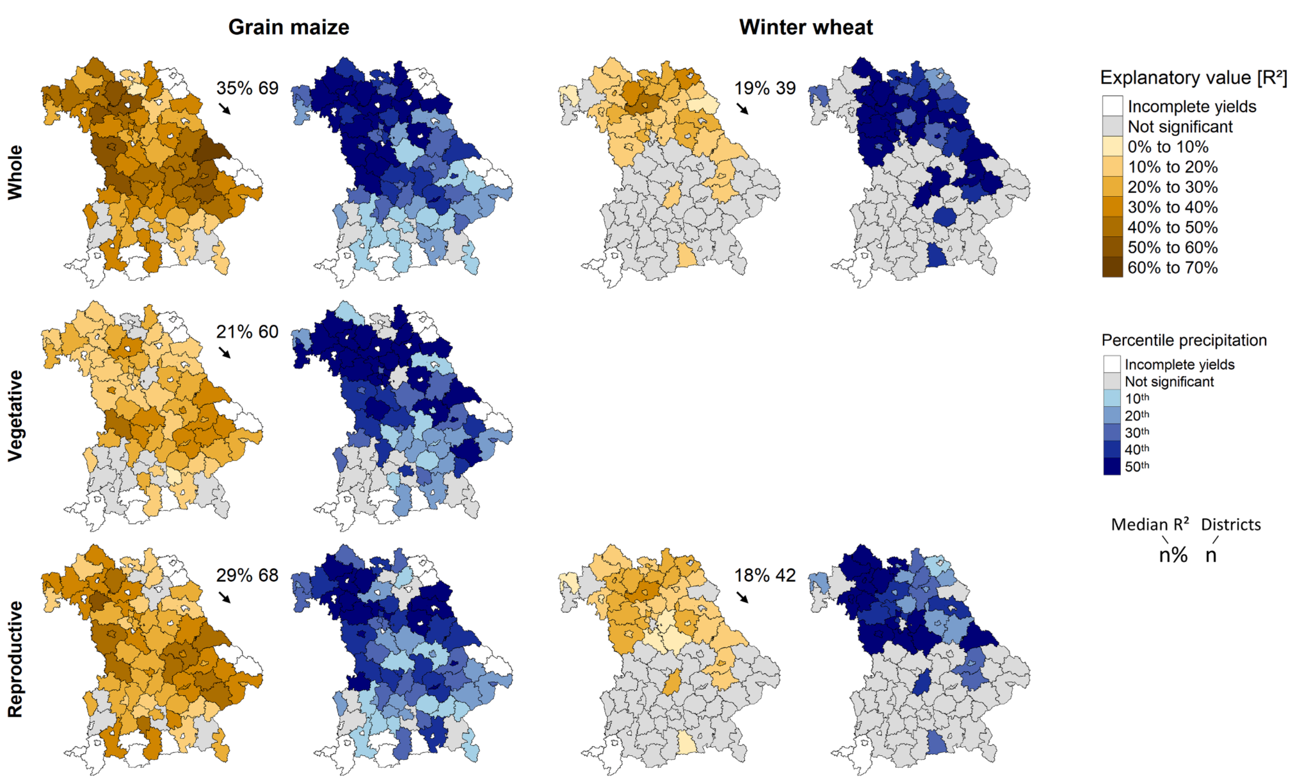

Fig. 4. The effect of compound events on yield variability. Heat is calculated with daily maximum temperatures and for grain maize with the 95th percentile, for winter wheat with the 90th percentile during the whole phase and the 75th percentile during the reproductive phase. Drought is calculated with 30-day precipitation for grain maize and 10-day precipitation for winter wheat. These definitions were discovered to fit best for the respective crops and development phases. The vegetative phase of winter wheat was omitted as it can barely be explained, especially by heat events. In the maps on the left of each crop, the explanatory value within each district is illustrated, as well as their median value and the number of districts with a significant effect. The arrow shows whether this effect is positive or negative. In the maps on the right of each crop, the percentile-based thresholds for drought that led to the highest explanatory values in these districts are shown with their percentile values.

North-South gradient is visible with lower percentiles in the South. The precipitation in the South of Bavaria is higher, so these lower percentiles lead to similar absolute thresholds as in the drier North. For winter wheat, this gradient cannot be detected, as only districts in the northern half of Bavaria show a significant effect of compound events (Fig. 4).

3.2.3. Time series in districts with the largest impact of compound events

To illustrate the temporal impact of compound events, the time series of two districts with full data between 1983 and 2021 and the highest explanatory values during the whole phase of grain maize are shown as examples (Fig. 5, Tab. S14). They are located in the North-West and East of Bavaria, which were identified as two of the areas in which yield variability can be explained best by compound events. In the district Kitzingen in the North-West, the explanatory value is 57 %, in the district Dingolfing-Landau in the East, the explanatory value is 56 %. As described under 2.1, the thresholds are defined with the 95th percentile of the daily maximum temperatures, which are as absolute thresholds 29.0 °C and 28.2 °C. For precipitation, the duration is 30 days and the percentiles explaining yield variability best are in Kitzingen the 40th and in Dingolfing-Landau the 30th, which are as absolute thresholds 47 mm and 53 mm. For both districts, the yield variability and the number of days with compound events during the whole phase calculated after these thresholds are illustrated. Peaks in compound events can be seen for both districts in the years 2003, 2015, and 2018, which are mirrored in the yield variability by strong losses. From the 184 days of this development phase, each of these years showed in Kitzingen at least 33 days with compound events and in Dingolfing-Landau at least 25 days. Also, years with fewer compound events fall together with yield losses. In Dingolfing-Landau, remarkably, the year 2013 showing 21 days with compound events. Before the year 2003, the days with compound events are in Kitzingen always not more than 18, in Dingolfing-Landau not more than 13, and no yield losses as strong as those in the years mentioned above occur.

4. Discussion

4.1. Relative and absolute thresholds to explain yield variability

Absolute thresholds with set temperature and precipitation values were found to be better suitable for explaining the impact of extreme and compound events on yield variability than their related percentile-based relative thresholds. While peaks of districts with a significant impact are found at certain absolute thresholds, the related percentiles are spread over different values in most cases. For heat and winter wheat, different relative thresholds of the 90th percentile during the whole phase and 75th to 80th percentile during the reproductive phase were received. Yet, they all represent similar absolute thresholds, as they are retrieved from development phases covering temperatures in winter and summer. The precipitation thresholds show for both crops a similar pattern, but on a spatial scale. The relative thresholds vary among almost all applied percentiles, from the 10th to the 50th. However, because of the North-South gradient in precipitation over Bavaria, the lower percentiles applied in the South lead to equal absolute thresholds compared to the higher percentiles in the North. This fits the statement from Siebert et al. (2017) that, from a plant physiological point of view, the absolute thresholds are more suitable to define stressors for the plants, as they are more relevant for them than the relative weather conditions in their area from which the percentile-based relative thresholds are derived. Sánchez et al. (2014) conducted a literature review on harmful temperature thresholds for maize and wheat. They emphasize that the stress response of a plant does not depend on how much the temperature changes relatively, but whether it passes a certain, absolute threshold (Sánchez et al., 2014). Zhang et al. (2017) confirmed this for maize and wheat in China by identifying a higher correlation between yield losses and absolute heat indices compared to relative ones.

For grain maize, the discovered absolute threshold for daily maximum temperatures is around 28 °C (30 °C with a modern reference period). This is substantially lower than described in the literature so far, fitting the statement from Lesk et al. (2022) that the absolute thresholds are 5 °C to 10 °C lower for larger study areas than thresholds found on the plant-level. Sánchez et al. (2014) report for the whole phase of maize a growth stop above 42 °C. Meanwhile, 28 °C to 32 °C is even considered optimum growth conditions. The lowest threshold for maximum temperatures occurs before and during anthesis, in the reproductive phase. Temperatures above 32 °C might affect pollination (Sánchez et al., 2014). The temperature threshold in the present study is, for almost all districts, derived from the 95th percentile. Therefore, the threshold

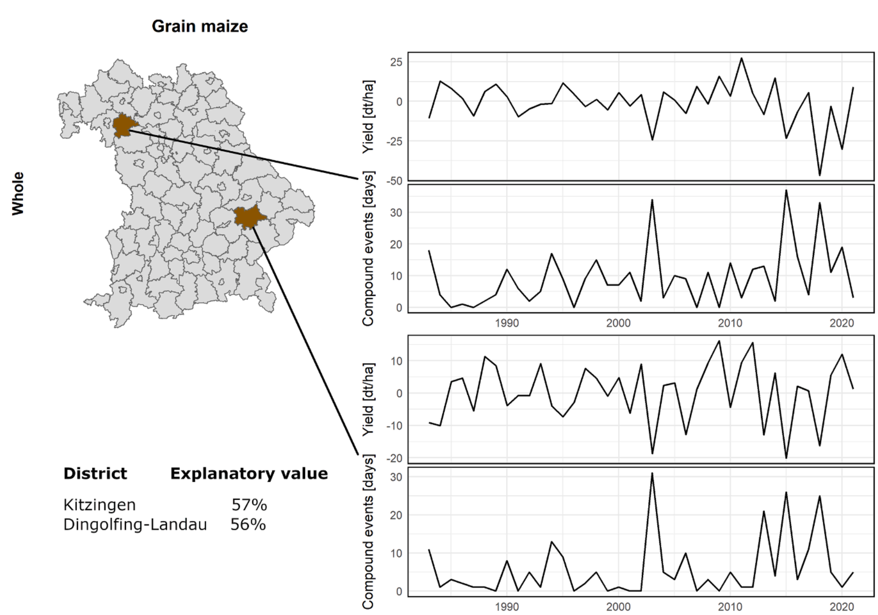

Fig. 5. Time series of yield variability and yearly days with compound events for the whole development phase of grain maize in the districts Kitzingen and Dingolfing-Landau. The two districts have complete data between 1983 and 2021 and high explanatory values of almost 60 %. The compound events are calculated with the 95th percentile of daily maximum temperatures and with 30-day precipitation.

value might become higher and closer to the values reported in the literature when this percentile is exceeded. This can also be seen when a modern reference period is used, explaining the effect of heat on grain maize better than using the historic period. Because of the already increased temperatures (StMUV, 2021), the 95th percentile corresponds to absolute thresholds for daily maximum temperatures of around 30 °C. On the one hand, this is another argument for applying absolute instead of percentile-based thresholds. On the other hand, winter wheat shows a similar pattern of lower temperature thresholds than reported in the literature, although for this crop, the thresholds are derived from different percentiles and match the ones derived from a modern reference period.

For winter wheat, the absolute thresholds for daily maximum temperatures are for the whole and the reproductive phase around 24 °C to 25 °C. Again, these values are lower than the thresholds summarized by Porter and Gawith (1999) in a literature review and updated by He et al. (2024). He et al. (2024) describe anthesis and grain-filling, falling in the reproductive phase, as sensitive to heat events. Their gathered thresholds during anthesis range between 25 °C and 35 °C, during grain-filling between 28 °C and 40 °C and He et al. (2024) calculated an intermediate threshold of 30 °C. One possible explanation for the lower thresholds at large-scale studies is methodological: The values are received from air temperatures, while plant-level studies often measure directly at the plant. The plant canopies can have lower temperatures but also several degrees higher temperatures than the surrounding area (Sánchez et al., 2014). Lembrechts et al. (2022) estimated the mean annual soil temperature globally to be on average 3.0 °C higher than the corresponding air temperature. Higher temperatures in plant canopies and the soil could explain why the corresponding air temperatures already have an effect at lower values. Another possible explanation is the interplay of heat effects with drought, as both together lead to yield losses already at lower maximum temperatures (Lesk et al., 2022). Water demand increases in the atmosphere and the soil with higher temperatures, potentially translating heat into water stress for the plant (Schauberger et al., 2017). This underlines the importance of studying the effect of heat and drought together.

The precipitation thresholds are for grain maize for a 30-day drought around 50 mm and for a 10-day drought around 15 mm. The absolute thresholds are for winter wheat in a similar range, but indicate a positive effect on yields with precipitation below them. One possible explanation for these contradicting effects of drought on maize and wheat lies in their precipitation requirements. They are during the whole development phase with 200–450 mm for maize substantially higher than for wheat with 60–90 mm (Neupane et al., 2022). Apart from precipitation being sufficient for winter wheat in the study region, it can be negatively affected by too high soil water content, for example, due to an increased risk of fungus infections (Powell and Reinhard, 2016).

Studies to compare these large-scale definitions for heat and drought with are sparse, as almost all studies use indices and relative thresholds. Indices used to define heat are mainly the Standardized Temperature Index (STI) (Brunner et al., 2021; Feng et al., 2019, 2021; Feng and Hao, 2020; Li et al., 2021a; Wu and Jiang, 2022; Zhan et al., 2020), the Temperature Condition Index (TCI) (Guo et al., 2023), and the Standardized Heat Index (SHI) (Shan, et al., 2024b). Especially for drought, the Standardized Precipitation Index (SPI) is often used (Brunner et al., 2021; Feng et al., 2019, 2021; Feng and Hao, 2020; He et al., 2022; Shan, et al., 2024b; Vogel et al., 2021; Wu and Jiang, 2022; Zhan et al., 2020; Zhang et al., 2022), as well as the Standardized Precipitation Evapotranspiration Index (SPEI) (Li et al., 2021a; Vogel et al., 2021; Zhang et al., 2022), the Palmer Drought Severity Index (PDSI) (Zhang et al., 2022), and the Soil Moisture Deficit Index (Guo et al., 2023). Percentile-based thresholds are also used in several studies to define heat (He et al., 2022; Vogel et al., 2021; Xu et al., 2024), drought (Zhang et al., 2019), or both extreme events (Feng et al., 2020; Lu et al., 2018; Ribeiro et al., 2020; Wu et al., 2021). They are often defined for each day separately instead of crop development phases and are not converted into absolute values. For meteorological studies, these indices and relative thresholds are useful, as they can be calculated directly from the data and simplify the comparison between different study regions. However, when including the reactions of plants, absolute thresholds are more suitable to capture conditions harmful to their physiology (Siebert et al., 2017). Studies that employed absolute thresholds always set them according to values discovered in plant-based studies. With daily maximum temperatures, Li et al. (2023) used 38 °C for maize in China, He et al. (2024) used 30 °C for wheat globally, and Mäkinen et al. (2018) used 31 °C and 35 °C for wheat in Europe. As these values are larger than the ones discovered in the present studies, further research could focus more on setting thresholds for large-scale assessments.

Addressing the first research aim, the following methodological recommendations for further studies can be formulated: Absolute thresholds should be used when defining heat and drought events that affect crop yield variability. Thresholds for daily maximum temperatures are lower than expected from plant-level studies and are for grain maize at least 28 °C, for winter wheat 24 °C to 25 °C. Daily mean temperatures can be used as well, with similar results on yield variability. The mechanisms leading to yield losses already at lower temperature thresholds should be further investigated. Especially, in the face of climate change, which leads to an increase in particularly heat events (Hao et al., 2022).

4.2. Impact of extreme and compound events on grain maize and winter wheat

A larger impact of compound events compared to individual extreme events was found for grain maize compared to winter wheat. The impact of compound events on grain maize is during the whole phase, with a median explanatory value of 35 % from 69 districts, higher than the 23 % from 52 districts for heat only and the 21 % from 45 districts for drought only. This is in the range of 5 % to 20 % better explanation of crop yield effects by statistical models when heat and drought are both included (Lesk et al., 2022). A possible explanation for this stronger impact of compound events is, at the cellular level, that the opening of stomata to increase transpiration is not possible under drought (Shan, et al., 2024a). More latent heat is stored in the leaves, inhibiting photosynthesis and respiration and therefore reducing yields (Daryanto et al., 2017). At the whole-plant level, heat and drought both can lead to reproductive failures and smaller seed sizes (Daryanto et al., 2017).

Yet, this stronger impact of compound events was not discovered for winter wheat. During the whole and the reproductive phase, the median explanatory value was with 19 % and 18 % from around 40 districts in the same range as for heat, with also 18 %, but from around 60 districts. Different results are reported from Becker et al. (2025); Ribeiro et al. (2020), and Shan, et al. (2024a) for Germany, Spain, and France. They discovered a larger impact of compound events on winter wheat yields compared to individual heat and drought. Ribeiro et al. (2020) calculated the likelihood of crop loss under compound events to be 19 % to 29 % higher than for heat only and 8 % to 11 % higher than for drought only. This suggests a larger contribution of drought in the effect of compound events, which occur mainly in the drier South of Spain (Ribeiro et al., 2020). As only a small, even positive, impact of drought on winter wheat was discovered in the present study, the precipitation in Bavaria might be sufficient to prevent an amplified effect of compound events. Webber et al. (2018) explain that in Europe, for Spain and Romania, the inclusion of drought increased how much winter wheat yields can be explained. However, in Germany, the United Kingdom, and Denmark, this inclusion did not increase the explanatory value compared to using heat only (Webber et al., 2018). This underlines that statements concerning the impact of compound events do not only depend on the target crop but also on the study region (Webber et al., 2018). Furthermore, the applied indices are important to identify the effect of drought and compound events. Becker et al. (2025) found a larger impact on winter wheat for Germany and also for Bavaria by capturing compound events at different levels of interactions via the indices “actual plant evapotranspiration”, “vapor pressure deficit”, and the combination of temperature and moisture indices that are relevant for the crop-atmosphere interaction.

Comparing the impact of heat and drought during the development phases of both crops, the impact of heat is slightly larger compared to drought during the whole phase of grain maize. For winter wheat, it is almost twice as large in terms of median explanatory value and number of districts. Grain maize is during the vegetative phase stronger affected by heat, during the reproductive phase by drought. Winter wheat shows almost no impact of heat during the vegetative phase and only a slight positive impact of drought during both phases. A larger impact of temperature or precipitation was discovered as being dependent on the time of the year and the region by Ceglar et al. (2016) for France as well. For winter wheat in France, the impact of weather conditions varies more across regions and development phases compared to grain maize, fitting the results of the present study (Ceglar et al., 2016). During the flowering period, falling in the reproductive phase, winter wheat is more sensitive to heat, leading to yield losses because of flower abortion (Ceglar et al., 2016). One reason for grain maize being especially affected by drought during the reproductive phase is that drought rather leads to male instead of female inflorescence, reducing the possible fertilization (Daryanto et al., 2017).

On a spatial scale, areas with a large impact of compound events on grain maize yield are discovered in the North-West, West, and East of Bavaria. Li et al. (2024) studied the spatial patterns of compound events' impacts on maize yield and found the importance of the following factors, in declining order: moisture regime, agricultural management, and soil properties. Also, for the present study, one possible reason for this spatial pattern is that these areas fall in the regions of the rivers Main and Danube (Donau), which have the lowest precipitation in Bavaria (StMUV, 2021). This is also reflected in the impact of drought, which is largest in these areas as well, during the whole and reproductive phase of grain maize. Becker et al. (2025) identified also the Danube river valley as showing larger effects of moisture on yield variability, with soil moisture deficit as the most important stressor. In drier regions, the effect of compound events can be amplified because of land-atmosphere coupling (Li et al., 2024). More of the incoming radiation that would lead to evapotranspiration (latent heating) instead contributes to surface temperatures (sensible heating) (Li et al., 2024). This dries the soil even more, leading to a positive feedback, explaining part of the amplified effect of compound events (Li et al., 2024). The other way around, precipitation and soil moisture can mitigate the impact of heat (Powell and Reinhard, 2016). Yet, an effect of only higher temperature thresholds being harmful for maize and wheat in areas of higher precipitation was not discovered in the present study. The absolute thresholds defining heat and drought are relatively evenly distributed across Bavaria.

Concerning soil, an influence on the spatial distribution of thresholds was also not discovered, but on the impact of compound events on grain maize yields. The areas with the largest impact in the North-West, West, and East of Bavaria are characterized by sandy geology and soils (LfU, 1996). Sandy soils show less capacity in holding water and buffering temperatures (Li et al., 2021b). Li et al. (2024) discovered for maize in China that areas with more than 30 % clay and more than 1.25 % top soil organic carbon showed 4 % and 5 % less yield losses caused by compound events. Also, Deng et al. (2023) describe that the impact of heat can mainly be buffered by soil organic carbon, followed by total nitrogen. As soil management, fields with less than 2.0 % soil organic carbon could receive organic inputs in form of crop residues, cover crops, and manure (Deng et al., 2023). Root growth, nutrient uptake of crops, and soil moisture retention would benefit from soil organic carbon, increasing the resilience against heat and drought (Deng et al., 2023). Yet, increasing N_2O emissions need to be considered an unwanted side-effect (Deng et al., 2023). Another management option is the application of mulch to limit soil evaporation and maintain moisture as a buffer against heat and drought (Zahra et al., 2021).

Besides soil, landscape homogeneity is a potential reason for the larger impact of compound events in the North-West, West, and East of Bavaria, as maize cultivation is concentrated in these areas (IACS, 2021). Incorporation of non-agricultural land in such regions is discussed to buffer the impact of compound events via the retention of water or the cooling of the microclimate (Lesk et al., 2022). Hao et al. (2022) mention, for example, forestation as one measure for buffering, while Geilfus et al. (2024) highlight water supply for crops from trees via hydraulic lift. Further adaptation strategies for heat and drought are nutrient management, irrigation, variety choice, and sowing dates (Rezaei et al., 2023). Breeding and variety choice in the past mainly focused on high yields instead of resistance against heat and drought (Zahra et al., 2021). In the future, varieties that can fine-tune their transpiration or have higher stomatal densities and conductance could be preferred for their resistance against heat and drought (Zahra et al., 2021).

On a temporal scale, most districts showed a high number of compound event days and a substantial decrease in crop yield, especially for the years 2003, 2015, and 2018. These years are characterized by the occurrence of heat and drought in Europe within other studies as well. Yield losses of 21 % for maize and 11 % for wheat were observed in Europe during 2003 (Lesk et al., 2022). Yield losses were also observed during 2018, for which, in spring to autumn, Germany experienced the most severe hot and dry conditions since the beginning of the measurement in 1881 (Zscheischler and Fischer, 2020). Although the development of precipitation is uncertain for the future, temperatures are projected to increase further, making years with many compound events more likely. Zscheischler & Fischer (2020) estimate for Germany that with 2 °C global warming, every spring to autumn as dry as in 2018, will also be as hot. For most regions of the world, compound events are projected to occur more often (Lesk et al., 2022), making yield losses like those in 2003, 2015, and 2018 more likely.

4.3. Limitations

One limitation of the applied methods is that the absolute temperature and precipitation thresholds cover only certain values, as they were defined in dependence on the five percentiles, respectively. This approach was chosen, as these percentiles are comparable to other studies. Additionally, over all districts, the related absolute thresholds cover a wide variance of values. Only the temperature thresholds for grain maize showed a significant effect in almost all districts for the 95th percentile. This indicates that the related absolute thresholds might be higher and a further study could focus on applying only absolute thresholds. The range of captured absolute values is limited not only by the chosen percentiles but also by the reference period, as shown when applying a modern period. Concerning heat, the exact percentile values were evaluated, not how much the temperature values exceeded them. Concerning drought, the sum of precipitation was used, not its temporal distribution within the drought period. Yet, both points are partly covered by using different percentiles and different drought lengths. Potential limitations of the applied linear regression are the assumption of linear relationships and a lower suitability for capturing tail dependencies (Beirlant and Bladt, 2025). Future studies with a larger sample size could validate the results with machine learning and copula-based approaches.

For the time spans of the development phases, fixed months were chosen, although their exact dates and lengths might differ between the years. However, the fixed time spans prevent years from having more compound events simply because of more available days to calculate them from. Additionally, applying whole months makes the methods more comparable to other studies that often use monthly precipitation data. Concerning the definition of compound events, they were calculated when heat and drought occur on the same day. A buffer would be possible as well, if heat and drought that are, e.g., one or two days apart from each other, still have an amplifying effect. Heat was defined for single days with temperatures above the given thresholds. Defining heat only if a certain number of consecutive days have temperatures above the threshold would be possible as well, as done by He et al. (2022). However, as the applied methods already led to several definitions for heat, drought, and compound events to be compared with each other, the most straightforward approach of defining heat and compound events for single days was chosen.

When comparing how well the yield variability can be explained between the different districts, the following points should be considered: Firstly, the study periods differ, depending on the available yield data, with the starting year 1983 and final years between 2015 and 2021. Secondly, the areas in which grain maize or winter wheat are grown differ between the districts. Districts with larger areas have a smaller amplitude in yield and weather data, as they are calculated from more data points. For the yield data, the exact areas from which they are gathered are not reported by the Statistical Office of Bavaria (2025a). Therefore, an orientation for the suitable areas for growing the two crops can be found in Figure S4. Additionally, Tables S2 and S3 show the available study periods for both crops in each district. When yield data on a field scale are available for a sufficiently large study area, spatially more explicit connections to the weather data can be made.

5. Conclusion

In this study, the impact of heat, drought, and compound events on crop yield variability is examined through linear regression. It is the first study comparing the suitability of different relative and related absolute thresholds for defining heat and drought. With these, the impact of extreme and compound events is compared between grain maize and winter wheat during their development phases. Absolute thresholds are discovered to be better suitable for explaining the impact on crop yield variability than their related percentile-based relative thresholds. The discovered absolute thresholds for daily maximum temperatures are with at least 28 °C for grain maize and 24 °C to 25 °C for winter wheat substantially lower than those found in plant-level analyzes. Compound events have a larger impact on the crop yield variability of grain maize compared to heat and drought occurring individually. Yet, this effect was not revealed for winter wheat in the study region, showing a larger impact of heat occurring individually. During the reproductive phase, grain maize was discovered to be sensitive to drought, winter wheat to heat.

The found absolute thresholds for winter wheat can be used in further studies on extreme and compound events. The thresholds for grain maize can be further refined by applying different absolute values exceeding the range of the applied percentiles. Especially, as until now, in most studies, relative thresholds have been applied. That the absolute thresholds are 5 °C to 10 °C lower than expected from plant-level studies is particularly relevant under global warming. Mechanisms leading to this effect should be examined, like the potential interplay of heat with drought. This underlines the importance of studying compound events, which is also shown by their larger impact on grain maize yields compared to individual extreme events. As this effect was not present for winter wheat, regional differences leading to a positive effect of drought should be considered in further studies. As political and practical implications, methods to buffer the impact of compound events should be considered. Especially for areas in which they are strongly connected to crop yield variability. This could prevent yield losses in years with many compound events. Potential options are to buffer the micro-climate by increasing the landscape heterogeneity with forests or agroforestry. Also, crop varieties that are more resilient to heat and drought could be utilized. Under the increasing frequency of compound events due to climate change, these results and measures can help to preserve food security.

CRediT authorship contribution statement

Jakob Bogenreuther: Writing – original draft, Visualization, Validation, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Christina Bogner:** Writing – review & editing, Supervision, Methodology. **Stefan Siebert:** Writing – review & editing, Supervision, Methodology. **Thomas Koellner:** Writing – review & editing, Supervision, Methodology, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Supplementary materials

Supplementary material associated with this article can be found, in the online version, at doi:10.1016/j.agrformet.2025.110836.

Data availability

The data on crop yields are openly available and are shared along with the data calculated by the authors in the supplementary material. Weather data were received from Zhao et al. (2015).

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