npj | natural hazards

Article

https://doi.org/10.1038/s44304-024-00026-7

Compound and cascading droughts and heatwaves decrease maize yields by nearly half in Sinaloa, Mexico

Check for updates

Samuel J. Sutanto ✉, Susana B. Zarzoza Mora, Iwan Supit & Mengru Wang

The impact of droughts and heatwaves on agriculture losses has been exacerbated by the occurrence of compound and cascading events. Here we present a study that evaluates the impact of these events both as singly and as compound and cascading on maize yield in Sinaloa Mexico from 1990 to 2022, using the WOFOST crop model. Drought and heatwave events were identified using the Standardized Precipitation Index and threshold method, respectively. Results show that yield reduction (25%) is found during extreme drought events, emphasizing the vulnerability of maize farming to unfavorable drought conditions. While heatwaves alone did not show a significant impact on maize yields, the compound and cascading droughts and heatwaves amplified the loss of maize yields by up to 44% compared to normal conditions. This study highlights the need for adaptive strategies in agriculture to sustain food security during extreme events, especially in the context of multi hazard framework.

Climate change-induced extreme weather events, such as heatwaves and droughts have emerged as significant contributors to global hunger and rising food prices[1,2]. These events are renowned as the two most important stresses that significantly impact crop growth and yield[3,4]. Even the mildest heatwave and drought stress during the vegetative stage can markedly reduce crop yield, resulting in low crop productivity and reduced income for farmers[5]. Previous research has demonstrated that maize and wheat yields can decrease up to 40% in cases of water scarcity and drought[6]. The reduction in yield will be intensified when heatwaves and droughts occur concurrently at the same time (compound) compared to the occurrence of individual extremes[7–9]. Many studies have evaluated the impact of compound drought and heat on crop yields using statistical methods, including machine learning[7,9–12]. Yet, these studies do not account for the occurrences of both drought and heatwave events as singly and as compound and cascading events during crop growing periods. This study aims to assess the impact of compound drought and heatwave events on crop yield simulated using process-based models, which is novel and still under researched[13,14]. In this study, we adopted the definition of compound hazard as drought and heatwave events occurring simultaneously i.e., at the same time and in the same region (CDH), while a cascading hazard refers to drought and heatwave events occurring consecutively one after another (CaDH)[15,16].

This study investigates the impacts of droughts and heatwaves on crop yields, examining both single effects and compound and cascading effects of these hazards. For this study, we purposely selected the state of Sinaloa in Mexico, given its status as one of the country's major maize-producing regions and its substantial historical exposure to droughts and heatwaves[17] (Supplementary Fig. 1). Maize is a staple food in Mexico and is more resistant to drought and heat than rice. Moreover, we aim to utilize in situ soil data, crop information, and agricultural practices to comprehend the real-world impact of extreme events on maize production. These in situ observation data combined with the ERA5 meteorological data from 1990 to 2022 were employed to estimate the maize yields using the WOFOST crop growth simulation model[18]. The ERA5 data[19] was also used to identify the historical drought and heatwave hazards using the Standardized Precipitation Index with 3-month accumulation period to represent agricultural drought (SPI-3)[20,21] and threshold approaches, respectively (see Method section). A heatwave was identified if the daily maximum temperatures exceeded threshold levels (90th percentile) for a minimum of three consecutive days[22]. Finally, we compared maize yield estimations under normal, drought, heatwave, compound, and cascading conditions. Pearson correlation was applied to assess the strength of relationships between hazards and yields[23]. Although this study is a case study, the results and approaches employed here hold relevance for other regions and have global applicability.

The simulation of maize yields under various conditions reveals a significant reduction in average yields under drought conditions. Heatwaves, on the other hand, only marginally reduce maize yield compared to normal conditions. The substantial reductions in maize yields were simulated when compound and cascading events occurred during the crop growing period. During the study period, the three highest yield reductions were simulated, which were during the worst drought event in 2010[24,25], the cascading event in 1998, and the compound event in 1999. Because of this reason, the Mexican government declared water as an issue of national interest due to its scarcity[25].

Earth Systems and Global Change Group, Environmental Sciences Department, Wageningen University and Research, Wageningen, the Netherlands.
✉e-mail: samuel.sutanto@wur.nl

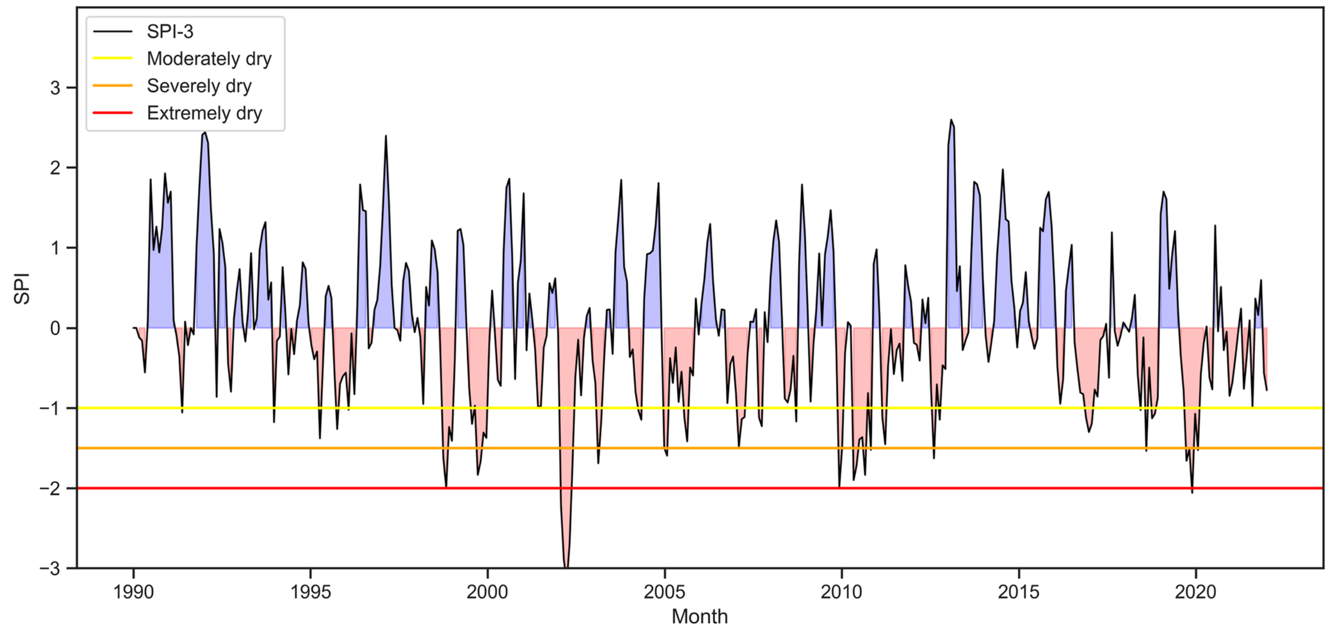

Fig. 1 | Agricultural droughts derived from the Standardized Precipitation Index with 3-month accumulation period (SPI-3) in Sinaloa Mexico from 1990 to 2022. Shaded blue area indicates wet condition and red shaded area indicates dry condition.

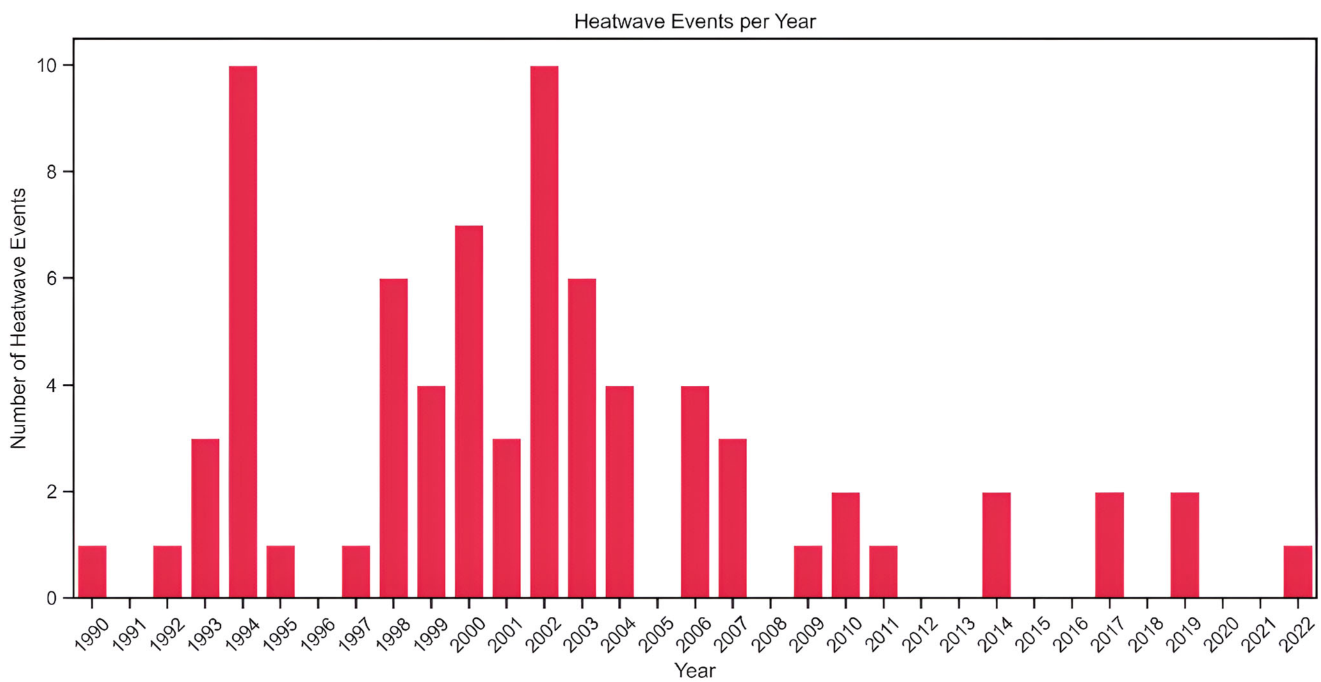

Fig. 2 | The total number of heatwave events per year. The heatwaves were identified during the study period from 1990 to 2022.

Results

The occurrence of droughts and heatwaves

Based on the ERA5 reanalysis data, 27 distinct drought events were identified, with various durations from one month to multiple months (Fig. 1). A few severe drought events were observed in 1999, 2000, 2002, 2011, and 2020. These drought events, however, are not all relevant to the study. For example, the five-month extreme drought in 2002 was excluded since it occurred during the summer, which is outside the crop planting season in Mexico, spanning from November to May for each annual crop cycle. On the other hand, the drought experienced in Sinaloa from December 2010 to April 2011 was acknowledged as the most severe drought in the past 70 years and fell within the crop growing period[26]. In total, 15 drought events were identified that occurred during the crop cycle. Among these events, 10 were classified as moderate droughts (1994, 1995, 1996, 1999, 2006, 2008, 2009, 2011, 2017, and 2019), four as severe droughts (2000, 2010, 2013, and 2020), and one as extreme drought (1999), all of which were considered in the study.

There were in total 75 heatwave events that occurred in Sinaloa from 1990 to 2022 (Fig. 2). Interestingly, almost every year Sinaloa experienced at least 1–2 heatwave events, with the highest number recorded in 1994 and 2002 (10 events). In 1994, a long heatwave was observed in May, spanning seven days and peaking at a temperature of 38.7 °C. Conversely, August 2002 marked the lengthiest heatwave event, lasting 10 days with temperatures reaching up to 39.6 °C. From a total of 75 heatwave events, only nine heatwaves occurred during the crop cycle and were, therefore, considered in

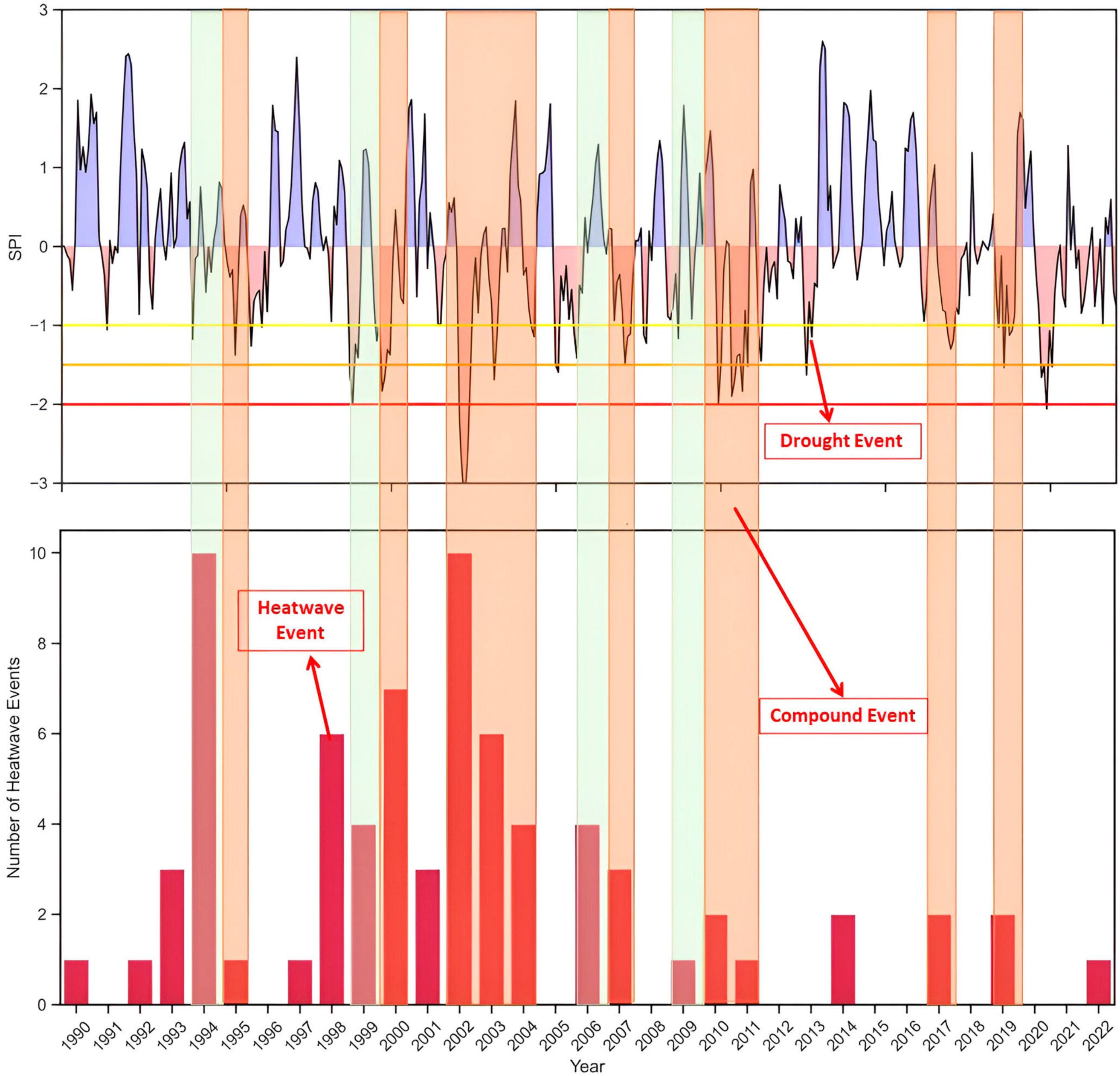

Fig. 3 | The occurrence of compound and cascading (CnC) drought and heatwave events. Light orange shaded lines indicate the compound events while the light green shaded lines indicate the cascading events. A compound hazard refers to drought and heatwave events occurring at the same time and in the same region, while a cascading hazard refers to drought and heatwave events occurring one after another[15,16].

our study. The years 1993 and 1994 were exceptional heatwave years, witnessing four heatwave events during the 1993 growing period. We would like to note that the 1993 growing season includes episodes from November-December 1993 to January–May 1994, all attributed to 1993. In April 1994, one event occurred, and the remaining three took place in May 1994, where distinct episodes were identified, each considered an individual event due to the non-continuous intervals. Only one heatwave event during the crop cycles of the years 1998, 1999, 2001, 2002, and 2013 was documented.

The occurrence of compound and cascading (CnC) events

To illustrate the occurrence of compound and cascading (CnC) drought and heatwave events, we superimposed the SPI-3 index with the number of heatwave events (Fig. 3). In total, 14 CnC events, comprising 10 events categorized as CDH events (light orange lines) and four events categorized as CaDH events (light green lines) are identified from Fig. 3. One CDH event occurred in June 1995, May 2000, October 2004, July 2010, October 2011, October 2017, and June 2019. Additionally, two CDH events were observed in July and August 2003 and in August and October 2007. The year 2022 experienced a prolonged CDH event that occurred from June to October 2022 (five Months). The occurrences of drought and heatwave in the years 1994, 1999, 2006, and 2009 are categorized as CaDH events since both drought and heatwave events did not happen in the same month but consecutively (see Method). While 14 CnC events were observed in the climate data, only one CDH and two CaDH events occurred during the maize growing period in Sinaloa, spanning from November to May. The limited occurrence of CnC events is attributed to the fact that CnC drought and heatwave events are less frequent than single events, Moreover, these events are characterized by dry and hot conditions that mainly occur during summer, which does not align with the crop cycle.

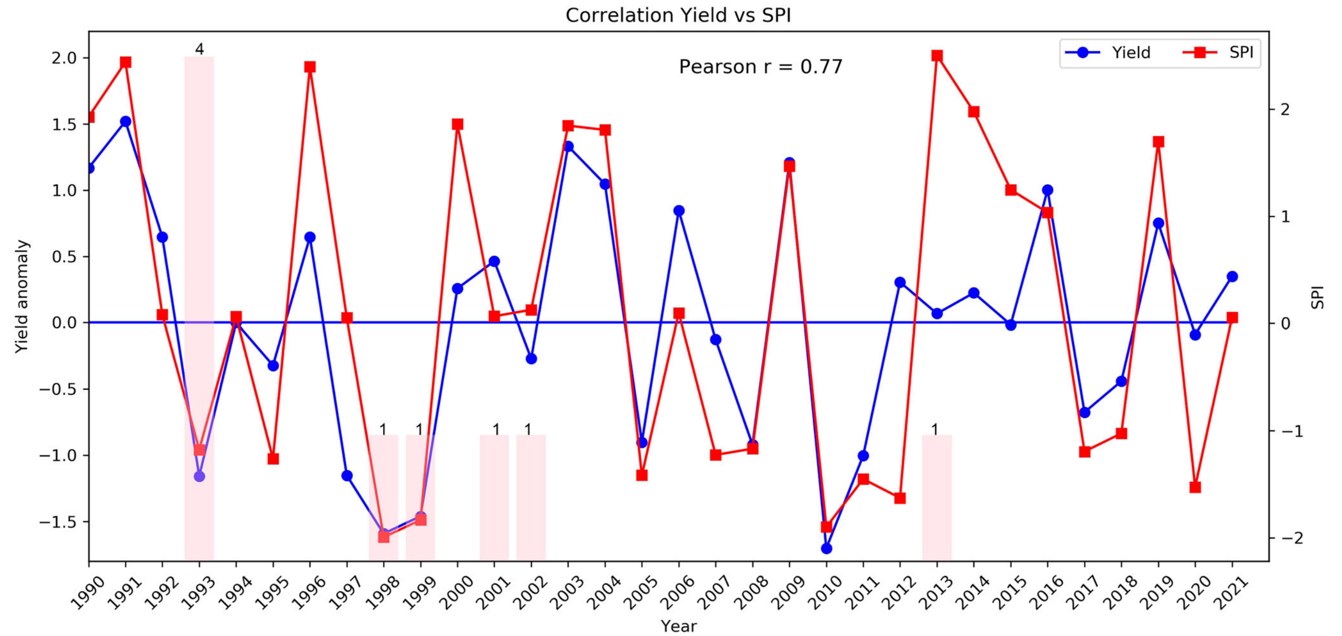

Fig. 4 | The relationship between the Standardized Precipitation Index with 3-month accumulation period (SPI-3) and maize yield anomaly. The number of heatwave events are plotted as bar plot with pink color. A blue horizontal line indicates a threshold between wet and dry years (SPI-3 = 0).

Given that CnC events may lead to higher impacts than single hazard, many literature in Mexico has focused solely on the occurrence of these hazards in isolation. For instance, certain reports and studies have exclusively documented droughts that caused significant agricultural losses in Mexico in 1993–1995, 2010, and 2011, despite the presence of CnC events in these years[27–31]. Unlike drought, there are limited studies reporting the impact of heatwaves or heat stress on crop production specifically in Mexico[32]. To our knowledge, there is no study specifically documenting the impact of CnC droughts and heatwaves on agriculture in Mexico. On the other hand, only a few studies have indicated the occurrence of CnC events in Mexico, mainly derived from global/regional studies[33,34]. For instance, a study conducted by Zhang et al.[33] highlights an increase in the magnitude of CnC drought and heatwave in northern Mexico under extreme global warming (SSP5-8.5). The limited number of studies discussing the occurrence of CnC events in Mexico may result in low awareness within the Mexican Government regarding the high impacts triggered by CnC events, despite their awareness of the impact of single events. Nevertheless, the high impact of droughts in Mexico resulted in the Mexican National Drought Program[35,36].

Relation between extreme events and maize yields

In this section, the occurrence of drought, heatwave, and compound events was considered only for the events that occurred during the crop cycle (Supplementary Table 1). In total, we observed 10 drought events, three heatwave events, one compound event (CDH), and two cascading events (CaDH). We then correlated the lowest SPI-3 values in each year with annual crop yield and the number of heatwave events, aiming to understand how maize yield responds to different climate conditions (Fig. 4). The impact of drought, compound, and cascading events on maize yield in Sinaloa is demonstrated in Fig. 4. Yields are notably lower during drought occurrences and are the lowest during CDH and CaDH events. Conversely, heatwave events do not exert a strong influence on the yield. For example, severe drought in 2005 and extreme drought in 2010 reduced the yield to below 3.5 T/ha, while the lowest yields up to below 2.7 T/ha were simulated in 1998–1999, marked as compound years. Despite the presence of heatwave events in the years 2001, 2002, and 2013, no observable impact on the yield was noted, with the average yield remaining above 3.9 T/ha.

We also employed a Pearson correlation coefficient to quantify the relationship between droughts and crop yields, as well as between heatwaves and crop yields. The result shows a strong positive correlation between maize yields and the SPI-3, with a correlation coefficient of 0.77 (Supplementary Fig. 2). In this context, we considered a Pearson correlation greater than 0.5 as strong[37]. The lowest yields, ranging from 2.4 to 2.8 T/ha, were simulated during the extreme drought in 2010 and the CnC events in 1998 and 1999, corresponding to SPI-3 values of approximately −2 (extreme drought). Conversely, the correlation between heatwave events and maize yields is moderate to weak ($r = -0.34$, Supplementary Fig. 3)[37]. Similar to the correlation between drought and yield, the lowest yields were simulated during CnC events and not during heatwave events as single hazard. Heatwaves occurring only once during the crop cycle (e.g., 2001, 2002, and 2013 events) did not significantly reduce yields (Fig. 4). These years were characterized as normal and wet years in Sinaloa, with SPI-3 above 0 for years 2001 and 2002, and SPI-3 >2 for the year 2013.

The annual maize yields simulated using the WOFOST model based on observed ERA5 meteorological data from 1990 to 2021 are presented in Fig. 5. High maize yields are predominantly associated with crop cycle planting under normal weather conditions (light blue). Interestingly, during heatwave events (light red), the simulated yields are comparable to, or in some cases, exceed those simulated under normal conditions. This is due to the occurrence of heatwaves during normal and wet conditions (see Fig. 4). The presence of droughts (brown), whether occurring in isolation or as part of a CnC event (red for compound and orange for cascading events), is consistently associated with lower yields, as evidenced in years 1993, 1998, 1999, and 2010. The cascading event in 1998 produced the lowest yield, followed by the extreme drought in 2010 (SPI-3 ≈ −2), compound event in 1999, and compound event in 1993. A prolonged single drought event in 2010 during the critical six-month growth cycle, with two months experiencing moderate drought and three months facing severe drought, led to a particularly low yield.

The average maize yield under normal and wetter conditions is generally higher (4.8 T/ha) than during extreme events (Fig. 5). As expected, droughts led to a 25% reduction in maize yield (to 3.6 T/ha). Heatwave events result in a slightly lower reduction compared to normal and wet conditions, with an average yield of 4.3 T/ha (10%). More severe impacts are observed during compound events, where yields drop significantly to 2.7 T/ha (44%). Cascading events also result in considerable yield reductions, with an average of 2.8 T/ha. The highest yield reduction

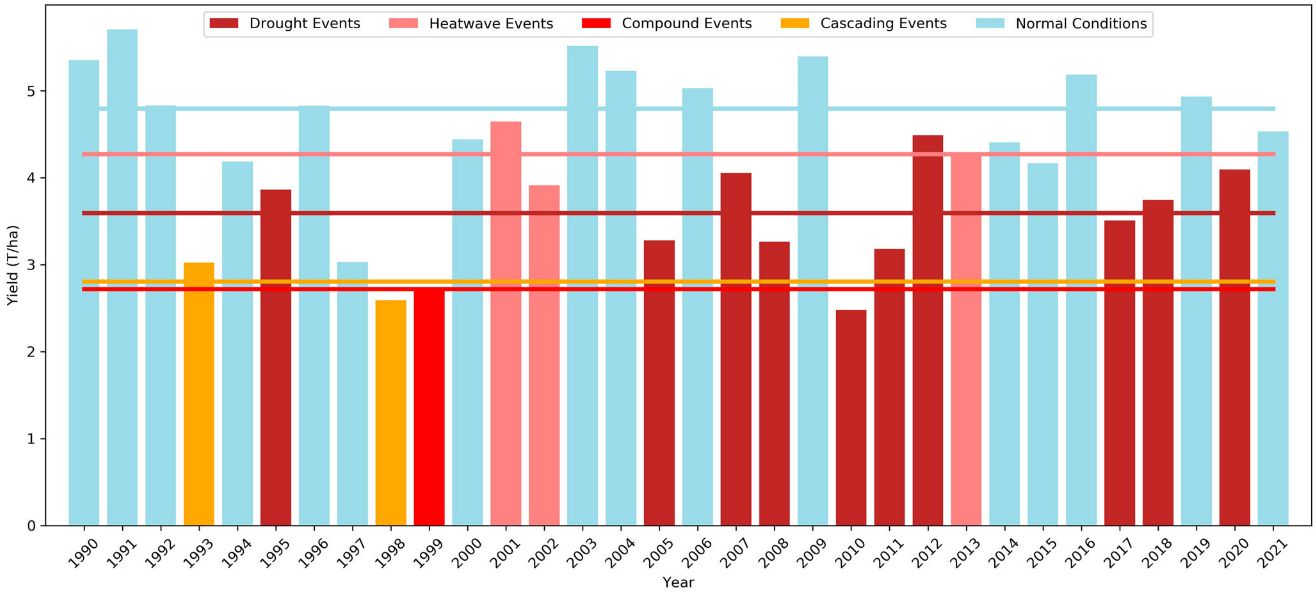

Fig. 5 | The simulated crop yields under different climatic conditions: droughts, heatwaves, compound, cascading, and normal conditions. Colored lines indicate the average yields calculated during different scenarios: normal conditions (light blue), heatwave conditions (light red), drought conditions (brown), cascading conditions (orange), and compound condition (red).

during prolonged drought and CnC events implies that these extreme events exert a strong impact on maize, even though maize is relatively more tolerant to heat and water scarcity. It is expected that the impact would be even more pronounced if other crop types, such as rice and vegetables were planted.

In comparison with reported maize yield for the state of Sinaloa, the critical drought events in 1998–2000[27] did not strongly impact maize yield (Supplementary Fig. 4). This is evident in the reported yield data, which showed steady average yields of 7.7 and 1.4 T/ha from 1993 to 1997 for irrigated and rainfed farms, respectively, while the WOFOST model simulated a significantly lower yield of 2.6 T/ha. In contrast, a significant drop in maize yield was reported and modeled during severe to extreme drought events in 2010-2012. The reported yields for irrigated white and yellow maize showed a decrease from 10.5 T/ha to 3.7 T/ha and from 9.9 T/ha to 0.31 T/ha, respectively.

Overall, maize production in Sinaloa has increased due to the expansion of agricultural areas. Starting from 2001, Sinaloa reported white maize yields, replacing traditional maize cultivation, and from 2004, yellow maize has been harvested in addition to white maize. The increase in reported yield may also be attributed to the rise in CO_2 level, which increases water use efficiency, resulting in high yields during normal conditions[38]. Additionally, the increase in winter temperatures toward more favorable conditions and agricultural intensification may further contribute to yield increases[39]. However, the model does not indicate an increase in maize yield, as constant CO_2 levels were applied.

Discussion

Mexico has a long history of prolonged droughts, as evidenced by droughts in 1998, 1999, and from 2010 to 2012, which have recurrently and adversely impacted agriculture[30,40]. These drought years were also identified in our study, with the SPI-3 index < −1.5 (below severe drought). The years 1998 and 1999 were particularly identified as critical for drought, marked by the occurrence of heatwaves and forest fires across the country[27]. These events led to a drastic reduction in staple grain production up to 50%. Additionally, water reserves in dams plummeted, reaching as low as 10% of their capacity. Furthermore, the drought in 2011 was considered the worst in six decades, affecting 2.7 million hectares of agricultural land, particularly in Sinaloa, Zacatecas, and Guanajuato[41]. As a result, an institutional and legal framework was established to address the consequences of drought, empowering the Mexican National Water Commission (CONAGUA) to issue general agreements in emergency situations[35,41].

This study utilized the WOFOST model to simulate maize yields under the same conditions each year, such as planting date, thermal time since emergence (Tsum), fertilizer application, and soil properties (see Method). Thus, the changes in maize yields are primarily influenced by the weather data and not by different farming practices during normal and extreme conditions. Our findings reveal the significant impact of drought and CnC events on crop production, while heatwaves do not exhibit a substantial effect on yields. High yields were still simulated during single heatwave events in the years 2001, 2002, and 2013. This resilience might be attributed to the fact that maize requires optimal daytime temperature ranges higher than those needed by other crops, such as wheat and rice[42,43]. For instance, maize only loses 5% of its assimilation capacity at a high temperature of 36 °C[5], meaning that yield decline is mainly driven by water shortages during drought and temperature stress plays a minor role. However, the yield could potentially begin to sharply decline with prolonged exposure to extreme temperatures[5,44]. In our study, the lowest yield during one single heatwave event in 2002 was simulated because the heatwave event lasted for 10 days, longer than the heatwave events in 2001 and 2013. In general, maize yields are anticipated to be lower than normal during both short and long extreme drought events. The long drought event in 2010, lasting for five months during the crop cycle, further reduced the yield, comparable to the impact observed during CnC events.

The occurrence of extreme events during different crop developmental stages considerably influences maize yield. For example, severe drought observed in 2020 (SPI-3 = −1.5) did not substantially reduce maize yield. The high yield of 4T/ha was simulated because a drought occurred during the vegetative stage (Supplementary Table 2). The yield in 2011 was higher than in 2010 because drought occurred only during the vegetative stage. The lowest yields of 3.3 T/ha and 2.5 T/ha were simulated in the years when drought occurred during both stages (2005 and 2010, respectively). Although droughts in 1995 and 2005 occurred during both stages, yield in 2005 was lower due to the severe drought event (SPI-3 = −1.4) during the reproductive stage compared to 1995 (SPI-3 = −1). The vegetative stage is not the most sensitive phase of maize crop development concerning heat and drought, unlike the reproductive stage[5]. Furthermore, some studies have emphasized the vulnerability of the reproductive stage to unexpected high temperature fluctuations, leading to severe yield loss[42,45,46]. High temperatures, especially during the critical pollination stage, can result in reduced kernel formation and lower yields in maize cultivation in Mexico[47].

Given the higher occurrence of droughts and heatwaves in the past and their projected increase in the future[48–50], a proactive approach to coping with drought has been initiated through the implementation of the national program against drought, known as PRONACOSE[51]. This program emphasizes preventive and mitigation measures for drought tailored to each of the 26 river basin authorities in the country, with CONAGUA leading program coordination. These measures prioritize: (1) the development of drought monitoring system and early warning, (2) the establishment of a legal administrative protocol for declaring drought emergencies and ensuring water supply for affected communities, and (3) the coordination of resource allocation and various federal programs to effectively and efficiently mitigate the impacts of drought[51,52]. While the proposed program could reduce the impacts of drought and heatwave in Mexico, it does not dismiss the risk of these extreme events.

In addition to instigating adaptation and mitigation strategies for extreme events, reducing the impacts of drought on agriculture in Mexico could involve implementing changes in agricultural practices. Crop agriculture is one of the major sectors vulnerable to droughts and heatwaves[52]. This study has developed a modeling assessment approach that could contribute greatly to exploring the effects of applied adaptation strategies, such as changing planting dates, modifying fertilizer application and irrigation practices, and considering the cultivation of different crop types during extreme events. The outcomes of this research could aid in identifying optimal agricultural management practices. Specifically, investigating whether the reduction in yield could be minimized through the implementation of adaptation measures during extreme events could enhance our understanding of crop yield predictions under various weather extremes events. This could be done through sensitivity analysis by simulating maize yields under extreme events occurring during different crop stages, nor by simulating the yield after adaptation measures were applied. Such analyses could provide valuable insights although they are beyond the scope of the study and are thus suggested as potential future research as a follow-up.

To conclude, this study has revealed a substantial impact of extreme events, including compound and cascading events, on maize yield in Sinaloa, Mexico. Despite maize being one of the staple crops that have inherent tolerance to high temperature and water scarcity, simulations revealed reductions in yields during droughts (25%), heatwaves (10%), and the CnC events (44%). The loss in agricultural production is expected to be more pronounced when other crops are cultivated. These findings underscore the need for adaptive strategies in agriculture to mitigate yield losses during such events, especially during the CnC events.

Methods

Data

Crop and soil characteristic data were collected from a 20 ha farm field situated in the southwest of Culiacan, Sinaloa, Mexico (24° 40' 33.45" latitude and 107° 29' 40.81" longitude). We gathered information regarding crop and soil characteristics from the local expert working in a regional agricultural institute through a survey-based data collection. The crop and agricultural practice data represent the average from the past eight growing seasons. These data include the crop calendar, encompassing planting, emergence, flowering, and maturity days, thermal time since emergence (TSUM), and the application of fertilizers. The value of TSUM was determined based on the date of planting and the time it takes to reach different stages of crop growth (emergence, flowering, and maturity) in Sinaloa. We ran multiple historical simulations using different TSUM values and selected the one that best aligned with actual field data, which is 1000 for TSUM1 and 1800 for TSUM2. The detailed TSUM simulations are presented in Supplementary Table 3.

The meteorological data from 1990 to 2022 obtained from the ERA5 re-analysis product[19] were used for identifying drought and heatwave events and for the WOFOST model input. ERA5 has a spatial resolution of 0.5° x 0.5° on hourly estimations. This dataset is sometimes used as a proxy for observed data due to the assimilation of a vast amount of observation data, approximately 94.6 billion observations. The daily meteorological variables considered in the study are maximum and minimum 2-m air temperatures (Tmax and Tmin), precipitation, wind speed at 10 meters, vapor pressure, and solar radiation. From all the meteorological data, only the precipitation data was aggregated to monthly for drought analysis using the Standardized Precipitation Index (SPI) (McKee et al., 1993). Supplementary Table 4 provides detailed data used in the study for extreme event analysis and crop modeling.

Drought

The SPI with a 3-month accumulation period was employed to identify agricultural drought (SPI-3)[20,21]. The SPI measures precipitation anomalies at specific locations by comparing monthly observed precipitation amounts with the long-term historical rainfall record for the studied period, here is from 1990 to 2022. The SPI was calculated by fitting a gamma probabilistic distribution on long-term monthly precipitation data, which is then transformed into a normal distribution. Thus, the median SPI for the site and selected period is zero. Moderate drought occurs when the SPI value drops to between −1 and −1.49 ($-1 \leq \text{SPI} < -1.5$), severe drought occurs when the SPI value drops to between −1.5 and −1.99 ($-1.5 \leq \text{SPI} < -2$), and extreme drought occurs when the SPU value is lower than −2 ($\text{SPI} \geq$- 2). The SPI value between −0.99 and 0.99 is categorized as near normal and above 1 is wet[21]. Given that WOFOST provides annual yield simulations, only one SPI value representing the six-month crop cycle (from November to May) was considered to assess the relationship between crop yields and the occurrence of droughts. We selected the lowest SPI value if there was at least one drought event that occurred during those six months crop cycle. If no drought occurred, then the highest SPI value was chosen to underscore the wet conditions. We classified drought that occurred during the crop cycle from November-December 2010 to January–May 2011 as drought in the year 2010.

Heatwaves

A heatwave generally is characterized by temperatures higher than the long-term average for a particular time of year and persists for several days or longer. This study defines a heatwave as an event when the daily maximum temperature (Tmax) exceeds a certain threshold and lasts over three consecutive days[22]. The threshold was derived from the 90th percentile of the Tmax, which is the daily temperature that equaled or exceeded 90 percent of the time during the study period of 1990–2022 (365 thresholds). We applied a 31-day centered moving average window technique to the daily thresholds, eventually leading to a daily smooth threshold level (365 thresholds for no leap and 366 thresholds for leap years). Same as drought event, we only counted the number of heatwave events that occurred during the crop cycle to compare with yield.

Compound and cascading events

A compound event is identified when drought and heatwave occur at the same time and location (CDH) while a cascading event is observed if drought and heatwave occur consecutively, one after another (CaDH)[16]. Attention should be given that drought and heatwave have different temporal resolutions, which are monthly and daily, respectively. Therefore, it was crucial to identify the months in which droughts occurred throughout the study period, as well as the specific days in which heatwaves occurred in the same month with drought to identify the compounding month. Cascading month was defined when heatwaves occurred in the month before or after the drought month. This made the analysis of temporal overlapping between drought and heatwave possible, thus facilitating the identification of compound and cascading events (CnC) on a monthly scale.

The WOFOST model

The WOrld FOod STudies (WOFOST) model is a crop growth simulation model, that has been developed to simulate the growth and yield of a variety of crops, including maize. It is based on a set of equations describing the physiological processes of crop growth and development, including photosynthesis, respiration, transpiration, and biomass partitioning[18]. WOFOST can provide accurate and detailed information on the effects of different environmental and management factors on crop growth and yield, and can help farmers and researchers make data-driven decisions on crop management practices[18,53]. Crop growth can be classified into three levels: potential growth, limited growth, and reduced growth. Each level of growth corresponds to a specific level of crop production, including potential, attainable, and reduced production. In this study, the potential production approach was applied, which refers to the maximum amount of crop yield that can be obtained under specific weather conditions and with high input of fertilizers, irrigation, and pest control. Therefore, the yields simulated in this study might overestimate the actual yields.

The WOFOST model can simulate the impact of water and heat stresses on yield, with crop assimilation being influenced by temperature. This temperature dependency is expressed in tables derived from calibrated field trials and literature. For Maize, the optimum temperature range is typically between 20–30 degrees Celsius. Assimilation rates decrease linearly with only a 5% reduction between 30 and 36 degrees Celsius. However, from 36 to 42 degrees Celsius, assimilation rates can decrease by up to 56% of the optimum assimilation. For water-limited conditions, assimilation is further reduced by water stress, quantified as the ratio of actual daily transpiration over potential daily transpiration[54]. Detailed information about the WOFOST model can be obtained from De Wit et al.[18] and the parameters used to run the WOFOST are provided in Supplementary Table 4.

Data availability

The historical ERA5 data is accessible through the Copernicus Data Store (CDS) (https://cds.climate.copernicus.eu/cdsapp#!/dataset/reanalysis-era5-single-levels?tab=overview). Other data and generated and/or analyzed during this study will be available online in the 4TU Center for Research Data at https://doi.org/10.4121/8f9ff222-fa1f-46a2-8027-9ca50a1be02b (Sutanto and Zarzoza Mora, 2024). WOFOST model is an open source and can be obtained from https://pcse.readthedocs.io/en/stable/.

Code availability

WOFOST model is an open source and can be obtained from https://pcse.readthedocs.io/en/stable/.

Received: 1 March 2024; Accepted: 7 August 2024;
Published online: 10 October 2024

References

1. Hasegawa, T. et al. Extreme climate events increase risk of global food insecurity and adaptation needs. *Nat. Food* **2**, 587–595 (2021).
2. Mehrabi, Z. et al. Research priority for global food security under extreme events. *One Earth* **5**, 756–766 (2022).
3. Fahad, S. et al. Crop production under drought and heat stress: plant responses and management options. *Front. Plant Sci.* **8**, 1147 (2017).
4. Lamaoui, M., Jemo, M., Datla, R. & Bekkaoui, F. Heat and drought stresses in crops and approaches for their mitigation. *Front. Chem.* **6**, 26 (2018).
5. Waqas, M. et al. Thermal stresses in maize: Effects and management strategies. *Plants* **10**, 293 (2021).
6. Daryanto, S., Wang, L. & Jacinthe, P. Global synthesis of drought effects on maize and wheat production. *Plos One* **11**, e0156362 (2016).
7. Hamed, R., Van Loon, A. F., Aerts, J. & Coumou, D. Impacts on compound hot-dry extremes on us soybean yields. *Earth Syst. Dynam.* **12**, 1371–1391 (2021).
8. He, Y., Fang, J., Xu, W. & Shi, P. Substantial increase of compound droughts and heatwaves in wheat growing seasons worldwide. *Int. J. Climatol.* **42**, 5038–5054 (2022).
9. Li, E., Zhao, J., Pullens, J. W. M. & Yang, X. The compound effects of drought and high temperature stresses will be the main constraints on maize yield in Northeast China. *Sci. Total Environ.* **812**, 152461 (2022).
10. Feng, S., Hao, Z., Zhang, X. & Hao, F. Probabilistic evaluation of the impact of compound dry-hot events on global maize yields. *Sci. Total Environ.* **689**, 1228–1234 (2019).
11. Ribeiro, A. F. S., Russo, A., Gouvenia, C. M., Páscoa, P. & Zscheischler, J. Risk of crop failure due to compound dry and hot extremes estimated with nested copulas. *Biogeosciences* **17**, 4815–4830 (2020).
12. Haqiqi, I., Grogan, D. S., Hertel, T. W. & Schlenker, W. Quantifying the impacts of compound extremes on agriculture. *Hydrol. Earth Syst. Sci.* **25**, 551–564 (2021).
13. Xie, W. et al. Decreases in global beer supply due to extreme drought and heat. *Nat. Plants* **4**, 964–973 (2018).
14. Lesk, C. et al. Stronger temperature-moisture couplings exacerbate the impact of climate warming on global crop yields. *Nat. Food* **2**, 683–691 (2021).
15. Leonard, M. et al. A compound event framework for understanding extreme impacts. *WIREs Clim. Change* **5**, 113–128 (2014).
16. Sutanto, S. J., Vitolo, C., Di Napoli, C., D'Andrea, M. & Van Lanen, H. A. J. Heatwaves, droughts, and fires: exploring compound and cascading dry hazards at the pan-European scale. *Environ. Int.* **134**, 105276 (2019).
17. Murray-Tortarolo, G. N. & Jaramillo, V. J. The impact of extreme weather events on livestock populations: the case of the 2011 drought in Mexico. *Climatic Change* **153**, 79–89 (2019).
18. De Wit, A. et al. 25 years of the wofost cropping systems model. *Agric. Syst.* **168**, 154–167 (2019).
19. Hersbach, H. et al. Global reanalysis: goodbye era-interim, hello era5. ecmwf newsletter 159, European Centre for medium-range weather forecasts. https://www.ecmwf.int/en/elibrary/81046-global-reanalysis-goodbye-era-interim-hello-era5 (2019).
20. McKee, T. B., Doesken, N. J. & Kleist, J. The relationship of drought frequency and duration to time scale. *In Proc. of 8th Conf. on Applied Climatology (Amer. Meteor. Soc., Anaheim, California* 179–184 (1993).
21. WMO. Standardized precipitation index user guide. in world meteorological organization report (eds Svoboda, M., Hayes, M. & Wood, E.) (wmo, Geneva, Switzerland. https://library.wmo.int/idurl/4/39629 (2012).
22. Russo, S. et al. Magnitude of extreme heat waves in present climate and their projection in a warming world. *J. Geophys. Res. Atmos.* **119**, 12,500–12,512 (2014).
23. Pearson, K. Notes on regression and inheritance in the case of two parents. *Proc. R. Soc. Lond.* **58**, 240–242 (1895).
24. Seager, R. et al. Model projections of an imminent transition to a more arid climate in southwestern North America. *Science* **316**, 1181–1184 (2007).
25. Gutierrez, J. Water scarcity and supply challenges in Mexico City's informal settlements. penn institute for urban research. https://penniur.upenn.edu/uploads/media/02_Gutierrez.pdf (2019).
26. World Bank, C., CIAT. Climate-smart agriculture in Sinaloa, Mexico. CSA country profiles for Latin America series. 2nd. ed. washington d.c. the World Bank Group. https://assets.publishing.service.gov.uk/media/57a089dee5274a27b20002d9/CSA-in-Sinaloa-Mexico.pdf (2015).
27. CENAPRED. Serie "impacto socioeconomico de los desastres naturales". *Centro Nacional de Prevencion de Desastres*. SEGOB, Mexico (2014).
28. Escalante-Sandoval, C. Expected impacts on agriculture due to climate change in Northern Mexico. in *Water Resource of Mexico* (eds Raynal-Villasenor, J.) 6 (World Water Resources, 2020).
29. Ortega-Gaucin, D., Ceballos-Tavares, J. A., Sánchez, A. O. & Castellano-Bahena, H. V. Agricultural drought risk assessment: a spatial analysis of hazard, exposure, and vulnerability in Zacatecas, Mexico. *Water* **13**, 1431 (2021).

30. Orimoloye, I. R. Agricultural drought and its potential impacts: enabling decision-support for food security in vulnerable regions. *Front. Sustain. Food Syst.* **6**, 838824 (2022).
31. Hernández-Péerez, J. L. & Jerez-Ramírez, D. O. The impacts of drought disasters on Mexican agriculture: an interpretation from the perspective of the political economy of disasters. in *Climate Change, Agriculture and Society* (eds Alam, A., Rukhsana). (Springer, 2023).
32. Aguilar-Gomez, S., Gutierrez, E., Heres, D., Jaume, D. & Tobal, M. Thermal stress and financial distress: extreme temperatures and firms' loan defaults in Mexico. *J. Dev. Econ.* **168**, 103246 (2003).
33. Zhang, Q. et al. High sensitivity of compound drought and heatwave events to global warming in the future. *Earth Future* **10**, e2022EF002833 (2022).
34. Afroz, M., Chen, G. & Anandhi, A. Drought- and heatwave-associated compound extremes: a review of hotspots, variables, parameters, drivers, impacts, and analysis frameworks. *Front. Earth Sci.* **10**, 914437 (2023).
35. Federman, D. K., Cortés, F. I. A. & Pérez, M. L. Crop production under drought and heat stress: plant responses and management options. *Front. Plant Sci.* **8**, 1147 (2017).
36. Aguilar-Barajas, I., Sisto, N. P., Magaña Rueda, V., Ramírez, A. I. & Mahlknecht, J. Drought policy in Mexico: a long, slow march toward an integrated and preventive management model. *Water Policy* **18**, 107–121 (2016).
37. Turney, S. Pearson correlation coefficient (r), guide and examples. scribbr. https://www.scribbr.com/statistics/pearson-correlation-coefficient/ (2023).
38. Abebe, A. et al. Growth, yield and quality of maize with elevated atmospheric carbon dioxide and temperature in north-west India. *Agricul. Ecosyst. Environ.* **218**, 66–72 (2016).
39. Sharma, R. K. et al. Impact of recent climate change on corn, rice, and wheat in southeastern USA. *Sci. Rep.* **12**, 16928 (2022).
40. Estrada, F., Mendoza-Ponce, A., Calderón-Bustamante, O. & Botzen, W. Impacts and economic costs of climate change on Mexican agriculture. *Reg. Environ. Change* **22**, 126 (2022).
41. FAO. Proactive approaches to drought preparedness: Where are we now and where do we go from here? food and agriculture organization of the United Nations, white paper, Rome. http://www.fao.org/3/ca5794en/ca5794en.pdf (2019).
42. El-Sappah, A. H. et al. Heat stress-mediated constraints in maize (Zea mays) production: challenges and solutions. *Front. Plant Sci.* **13**, 879366 (2022).
43. Villa-Falfán, C., Valdées-Rodríguez, O., Vázquez-Aguirre, J. L. & Salas-Martinez, F. Climate indices and their impact on maize yield in Veracruz, Mexico. *Atmosphere* **14**, 778 (2023).
44. Carter, E. K., Melkonian, J., Riha, S. J. & Shaw, S. B. Separating heat stress from moisture stress: analyzing yield response to high temperature in irrigated maize. *Environ. Res. Lett.* **11**, 094012 (2016).
45. Bhandari, K. et al. Temperature sensitivity of food legumes: a physiological insight. *Acta Physiol. Plant* **39**, 68 (2017).
46. Choukri, H. et al. Effect of high temperature stress during the reproductive stage on grain yield and nutritional quality of lentil (lens culinaris medikus). *Front. Nutr.* **9**, 857469 (2022).
47. Ureta, C. et al. Maize yield in Mexico under climate change. *Agric. Syst.* **177**, 102697 (2020).
48. Wehner, M., Easterling, D. R., Lawrimore, J. H., Heim Jr, R. R. & Vose, R. S. Projections of future drought in the continental United States and Mexico. *J. Hydrometeorol.* **12**, 1359–1377 (2011).
49. Martínez-Austria, P. F., Bandala, E. R. & Patiño Gómez, C. Temperature and heat wave trends in northwest Mexico. *Phys. Chem. Earth* **91**, 20–26 (2016).
50. Navarro-Estupiñan, J. et al. Observed trends and future projections of extreme heat events in Sonora, Mexico. *Int. J. Climatol.* **38**, 5168–5181 (2018).
51. Ortega-Gaucin, D., López-Pérez, M. & Cortés, F. I. A. Drought risk management in Mexico: progress and challenges. *Int. J. Saf. Secur. Eng.* **6**, 161–170 (2016).
52. Dobler-Morales, C. & Bocco, G. Social and environmental dimensions of drought in Mexico: an integrative review. *Int. J. Disaster Risk Reduct.* **55**, 102067 (2021).
53. Hadiya, N., Kumar, N. & Mote, B. M. Use of Wofost model in agriculture—a review. *Agricult. Rev.* **39**, 234–240 (2018).
54. Gilardelli, C., Confalonieri, R., Cappelli, G. A. & Bellocchi, G. Sensitivity of wofost-based modelling solutions to crop parameters under climate change. *Ecol. Model.* **368**, 1–14 (2018).

Acknowledgements
The research is supported by the CDHEU project, which is funded by the Wageningen Data Driven Discoveries in Changing Climate (D3-C2). The meteorological data was downloaded from the Copernicus Data Store (CDS, see data availability section).

Author contributions
All authors conceived and implemented the research. Data analyses, model output analyses, and all figures have been performed by S.B.Z.M.; S.J.S. and I.S. wrote the initial version of the paper. S.J.S., I.S., and M.W. contributed to interpreting the results, discussion, and improving the paper.

Competing interests
The authors declare no competing interests.

Additional information
Supplementary information The online version contains supplementary material available at https://doi.org/10.1038/s44304-024-00026-7.

Correspondence and requests for materials should be addressed to Samuel J. Sutanto.

Reprints and permissions information is available at http://www.nature.com/reprints

Publisher's note Springer Nature remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.

Open Access This article is licensed under a Creative Commons Attribution 4.0 International License, which permits use, sharing, adaptation, distribution and reproduction in any medium or format, as long as you give appropriate credit to the original author(s) and the source, provide a link to the Creative Commons licence, and indicate if changes were made. The images or other third party material in this article are included in the article's Creative Commons licence, unless indicated otherwise in a credit line to the material. If material is not included in the article's Creative Commons licence and your intended use is not permitted by statutory regulation or exceeds the permitted use, you will need to obtain permission directly from the copyright holder. To view a copy of this licence, visit http://creativecommons.org/licenses/by/4.0/.

© The Author(s) 2024