# Modeling the effect of a heat wave on maize production in the USA and its implications on food security in the developing world

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## ABSTRACT

This study uses geo-spatial crop modeling to quantify the biophysical impact of weather extremes. More specifically, the study analyzes the weather extreme which affected maize production in the USA in 2012; it also estimates the effect of a similar weather extreme in 2050, using future climate scenarios. The secondary impact of the weather extreme on food security in the developing world is also assessed using trend analysis.

Many studies have reported on the significant reduction in maize production in the USA due to the extreme weather event (combined heat wave and drought) that occurred in 2012. However, most of these studies focused on yield and did not assess the potential effect of weather extremes on food prices and security. The overall goal of this study was to use geo-spatial crop modeling and trend analysis to quantify the impact of weather extremes on both yield and, followed food security in the developing world.

We used historical weather data for severe extreme events that have occurred in the USA. The data were obtained from the National Climatic Data Center (NCDC) of the National Oceanic and Atmospheric Administration (NOAA). In addition we used five climate scenarios: the baseline climate which is typical of the late 20th century (2000s) and four future climate scenarios which involve a combination of two emission scenarios (A1B and B1) and two global circulation models (CSIRO-Mk3.0 and MIROC 3.2). DSSAT 4.5 was combined with GRASS GIS for geo-spatial crop modeling. Simulated maize grain yield across all affected regions in the USA indicates that average grain yield across the USA Corn Belt would decrease by 29% when the weather extremes occur using the baseline climate. If the weather extreme were to occur under the A1B emission scenario in the 2050s respectively, average grain yields would decrease by 38% and 57%, under the CSIRO-Mk3.0 and MIROC 3.2 global climate models, respectively.

The weather extremes that occurred in the USA in 2012 resulted in a sharp increase in the world maize price. In addition, it likely played a role in the reduction in world maize consumption and trade in 2012/13, compared to 2011/12. The most vulnerable countries to the weather extremes are poor countries with high maize import dependency ratios including those countries in the Caribbean, northern Africa and western Asia. Other vulnerable countries include low-income countries with low import dependency ratios but which cannot afford highly-priced maize. The study also highlighted the pathways through which a weather extreme would affect food security, were it to occur in 2050 under climate change.

Some of the policies which could help vulnerable countries counter the negative effects of weather extremes consist of social protection and safety net programs. Medium- to long-term adaptation strategies include increasing world food reserves to a level where they can be used to cover the production losses brought by weather extremes.

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## Introduction

The extreme weather event that occurred in the USA in 2012 had a significant impact on maize production. This was confirmed by the United States Department of Agriculture (USDA), which announced a reduction of USA maize production by 13% in 2012 compared to the reported 2011 production (USDA, 2013a). Many reports have tried to understand this reduction in maize production in the USA due to this weather extreme using a range of analysis techniques. However, earlier in the spring of 2012, the USDA and other studies predicted that maize production would increase by 20% in 2012 (FAO, 2012a). The heat wave, which started in May and June 2012, severely affected the USA Corn Belt in July and resulted in a reduction of maize yield. In addition, the drought that followed the heat wave in October 2012 impacted residual soil moisture for the following crop, affected maize yields in 2012 and could also impact USA maize production in 2013.

Extreme events such as heat waves, droughts, tornadoes, tsunami, and hurricanes have affected the USA for a long time. Moreover, the effects of such disasters have been well documented. Between 1980 and 2003, the USA experienced 58 weather-related disasters in which overall losses reached $1 billion dollars at the time of the event (Anderson and Bell, 2011; Lott and Ross, 2005). The USA and National Climatic Data Center (NCDC) have collected a variety of information detailing these events, categorized by type of event.

The USA heat wave in 2012 could have a large impact on food security in other parts of the world as the USA accounts for 40% of global maize production. The USA is the leading maize exporter in the world and between 2005 and 2010 accounted for 50% of global maize exports (FAOSTAT, 2013). Moreover, concerns over the effect of extreme events on global food security are high with the projections implying that climate change may increase the frequency, duration, and intensity of heat waves (Meehl and Tebaldi, 2004).

Understanding how heat waves affect crop production is key to preparing communities for heat waves and estimating the potential impact of heat waves due to climate change. Heat waves are usually defined as prolonged periods of extreme heat, although no consistent definition exists regarding the temperature threshold, temperature metric, and number of days used to define heat waves. For example, most studies on heat waves have used thresholds of mean temperature (Hajat et al., 2006; Lobell et al., 2013; Elliott et al., 2013), apparent temperature (Smoyer, 1998), or combinations of thresholds of apparent and minimum temperatures (Robinson, 2001; Weisskopf et al., 2002). Use of inconsistent heat wave definitions leads to different time periods being classified as heat waves, hindering comparison and synthesis of results across studies. Further, heat waves differ in their intensity (degree of heat) and duration, although most studies use measures of intensity and duration to define a heat wave.

A heat wave is more important among other extreme events because it is usually followed by drought. For example, the USA Corn Belt suffered from a severe drought that began after high temperatures hit between May and August 2012. Therefore, the 2012 USA maize crop was adversely affected by a severe drought across much of the Corn Belt, resulting in reduced total production and lowered average yield. Despite the drought, the overall quality of the final 2012 maize production was good (USDA, 2013a).

Ciais et al. (2005) evaluated the heat wave impact on crop production in Europe in 2003 using remote sensing techniques. Many experiments at the chamber- and field-level have been carried out to assess crop productivity and mitigation. Nuttall et al. (2013) studied wheat growth under heat wave conditions (heat shock) and increasing $CO_2$ levels in the Australian dryland environment. Process-based crop modeling is superior to other methods because it simulates the biophysical responses of crops using local crop management practices (i.e., irrigation and fertilizers). However, there are a few studies that have used process-based crop simulation models for impact assessments of the 2012 heat wave in the USA. Lobell et al. (2013) used a statistical model based on accumulated Extreme Degree Days (EDD) and APSIM-Maize. Elliott et al. (2013) used the CSM-CERES-Maize model of DSSAT to assess the 2012 heat wave of the USA at a county level.

The goal of this study is to determine the biophysical impact of weather extremes on maize production in the USA and assesses the secondary effects of such weather extreme on world maize prices, production, consumption and trade.

## Materials and methods

### Spatial biophysical framework

#### Climate extreme weather data selection

According to the NCDC, severe heat waves that have led to billion-dollar disasters occurred in the USA ten times between 1980 and 2012 (Lott and Ross, 2005). Based on the study conducted by Lott and Ross (2005) we selected 8 years, (1980, 1986, 1988, 1993, 1998, 1999, 2001, and 2002) and then added two additional years (2006 and 2012) with more recent extreme heat waves. We obtained the weather data from the NCDC for these 10 years across the USA.

#### Identification and characterization of heat waves

June and July are critical months for maize production in the USA. This is the period when there is a change from the vegetative to reproductive stage and grain filling is initiated. Data on monthly precipitation, and maximum and minimum temperatures between June and August for 10 years during which heat waves occurred were collected. Among the ten years selected, three years (2001, 2002, 2006, and 2012) were outside of the baseline window which reflects the average monthly climate data that has been recorded between 1950 and 2000. Since recorded monthly rainfall and temperatures between June and August for 1980, 1986, 1988, 1993, 1998, and 1999 were not too different to those of 2001, 2002, 2006 and 2012 (data not shown), the data were averaged across the 10 years. The average values of rainfall and temperature for the years involving heat waves were then compared with those of the baseline climate (1950−2000).

#### Map generation for baseline and future weather extreme

The period for the baseline climate was from 1950 to 2000. The baseline climate grids were obtained from the WorldClim Global Climate Data Center (WorldClim Global Climate Data Center, 2013) and additional details from Hijmans et al. (2005). For each month between June and August, we first interpolated and replaced the values to the baseline climate with the arithmetic average maximum and minimum temperature and precipitation for 10 years during which heat waves occurred. Hence, we generated one climate scenario that combines the climate variables reflecting heat waves between June and August and baseline climate variables for the other months: 'Baseline EW'. The climate variables were mapped at 5 arc-minutes spatial resolution (10 km at equator). We did not change other variables such as solar radiation and the number of rainy days since data collection of irradiation and the number of rainy days was difficult and there were few methods of interpolation.

Climate change was also considered in this study. Nelson et al. (2010) estimated the impact of various Global Climate Models on future precipitation and temperature; the two key variables affecting crop yields. Based on their estimation, the combination of the CSIRO-Mk3.0 climate model for 2050 and the B1 emission

scenario, from the Special Report on Emissions Scenario (SRES) (Nakicenovic et al., 2000), leads to the smallest changes in mean precipitation and temperature compared to the baseline climate. Similarly, the combination of the MIROC 3.2 climate model with the A1B emission scenario around 2050 leads to the largest changes in mean precipitation and temperature compared to the baseline climate. Hence, the range of crop yields under climate change should be encompassed by the yields generated under the CSIRO-B1 and MIROC-A1 climate scenarios.

The CSIRO-Mk3.0 and MIROC 3.2 climate models were used in this study and the climate grids were generated by the Consultative Group on International Agricultural Research (CGIAR) Research Program on Climate Change, Agriculture and Food Security (CCAFS) climate data archive (CCAFS, 2013). More details on these models are provided by Gordon et al. (2010) for CSIRO-Mk3.0 and Shiogama et al., 2010 for MIROC 3.2. These models were combined with the A1B and B1 emission scenarios. Between June and August, we again replaced the values from future climates with the mean maximum and minimum temperatures and precipitation from 10 years of heat wave occurrence. Hence, four future climate scenarios that incorporated the occurrence of heat waves were developed at the same spatial resolution of the baseline: 'CSI B1 EW', 'MIR B1 EW', 'CSI A1 EW' and 'MIR A1 EW'. 'CSI B1 EW' relates to the combination of CSIRO-Mk3.0 climate model, the B1 emission scenario and the extreme weather event; namely the combination of the heat wave, while 'MIR A1 EW' relates to the combination of the MIROC 3.2 climate model, the A1B emission scenario and the extreme weather event.

### Crop model

A process-based crop model (DSSAT CSM-CERES-Maize v4.5) (Hoogenboom et al., 2010; Jones et al., 2003) was used to estimate the impact of the extreme event on USA maize production. CSM-CERES-Maize is a popular crop model that is able to simulate crop growth with minimum weather datasets, for example maximum and minimum daily temperature, daily solar radiation, daily total precipitation, and the number of rainy days. Additional variables on soil and crop management practices, including crop variety used, are needed in DSSAT. A hybrid maize variety called Garst 8808, whose genetic parameters have already been estimated for DSSAT and used in another study (Nelson et al., 2010), was also used in this study. Additional information on soil profile and other crop management practices used in the biophysical simulations are described by Nelson et al. (2010) and Gbegbelegbe et al. (submitted for publication).

### Run High Performance Computer (HPC) cluster

Maize production across the USA was simulated at the 5 arc-minutes resolution scale. The simulations were performed in the High Performance Computing (HPC) clusters. Large volumes of spatial data is needed to run CSM-CERES-Maize in the HPC clusters and detailed explanations of these processes can be found in Nelson et al. (2010) and Gbegbelegbe et al. (submitted for publication).

### Association between heat wave and maize production

Simulated maize yields across the USA Corn Belt states were extracted which were affected by heat for the following climate scenarios: baseline climate (Baseline), 'Baseline EW', 'CSI B1 EW', 'MIR B1 EW', 'CSI A1 EW', and 'MIR A1 EW'. The results were then sorted across the USA Corn Belt states. The USA Corn Belt states which were affected by the extreme event comprise 14 states from North Dakota to Texas. The simulated biophysical results were compared to the impact of the extreme event with the observed USDA 2012 yield report which was released on February 21, 2013 (USDA, 2013a). The reported production and yield of 2012 are aggregated across rainfed and irrigated areas. Regardless of rainfed and irrigated cultivation, the values in the USDA report were the sum of yields in each state. Hence, recorded rates on irrigated and rainfed areas in the USA (USDA, 2007) were used to estimate recorded irrigated and rainfed production and yield separately.

## Results

### Biophysical results

#### Characteristics of heat waves

Maximum temperatures from the baseline climate were compared with those related to the 'Baseline EW' climate scenario. The deviations related to the maximum temperature were about 1.0 °C across all three months (June–August) (Table 1). However, when the comparison involves the highest maximum temperatures between the baseline and 'Baseline EW' climate scenarios, the

**Table 1**
Deviations of monthly maximum and minimum temperature and precipitation from June to August in 'Baseline EW'. Deviations are subtracted from the baseline climate.

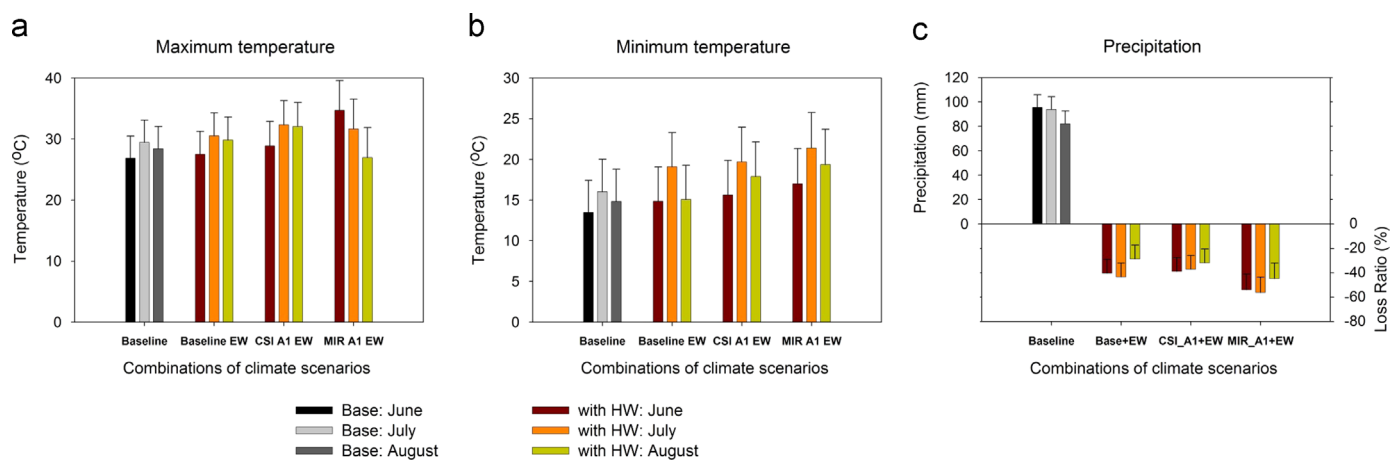| States | Deviations | | | | | | | | | | | |
| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
| | Maximum temperature (°C) | | | | | | Minimum temperature (°C) | | | Precipitation (mm) | | |
| | Average | | | Highest | | | Average | | | Monthly total | | |
| | June | July | August | June | July | August | June | July | August | June | July | August |
| Iowa (IA) | 0.3 | 1.0 | 0.8 | 9.2 | 9.5 | 8.6 | 1.4 | 2.9 | −0.6 | −41 | −83 | −43 |
| Illinois (IL) | −0.5 | 0.7 | 0.4 | 9.2 | 9.3 | 7.8 | 0.1 | 2.8 | −0.3 | −46 | −78 | −7 |
| Nebraska (NE) | 1.0 | 1.6 | 0.8 | 12.0 | 8.9 | 8.7 | 2.5 | 2.6 | −0.5 | −49 | −62 | −41 |
| Minnesota (MN) | 0.6 | 1.4 | 1.1 | 8.5 | 8.4 | 7.7 | 2.5 | 4.1 | 0.6 | 3 | −22 | −53 |
| Indiana (IN) | 0.2 | 1.0 | 0.8 | 11.6 | 9.9 | 7.2 | 0.2 | 3.1 | −0.2 | −69 | −62 | 9 |
| South Dakota (SD) | 0.3 | 0.5 | 0.5 | 10.5 | 8.9 | 9.6 | 2.2 | 3.4 | −0.1 | −36 | −35 | −25 |
| Kansas (KS) | 1.0 | 1.1 | 1.4 | 12.2 | 8.9 | 8.9 | 1.6 | 2.6 | −0.7 | −47 | −70 | −16 |
| Ohio (OH) | 0.7 | 1.4 | 1.3 | 10.9 | 9.3 | 6.9 | 1.1 | 3.3 | 0.6 | −47 | −42 | −21 |
| Wisconsin (WI) | 0.6 | 1.5 | 1.3 | 9.3 | 10.3 | 7.7 | 2.6 | 4.1 | 1.1 | −40 | −30 | −47 |
| Missouri (MO) | 0.9 | 1.2 | 1.6 | 11.0 | 9.3 | 8.7 | 0.9 | 3.1 | 0.2 | −59 | −68 | −24 |
| Michigan (MI) | 1.6 | 1.7 | 1.7 | 10.7 | 9.6 | 8.3 | 2.1 | 3.2 | 1.2 | −16 | −9 | −13 |
| Texas (TX) | 0.5 | 1.5 | 2.0 | 7.8 | 5.8 | 6.1 | 1.4 | 1.6 | 2.0 | −7 | 2 | −1 |
| North Dakota (ND) | 0.3 | 0.5 | 0.3 | 9.0 | 8.8 | 8.4 | 1.5 | 3.4 | −0.3 | −17 | −31 | −24 |
| Kentucky (KY) | 1.3 | 1.8 | 1.8 | 11.4 | 9.5 | 5.4 | −0.4 | 2.8 | 0.3 | −68 | 21 | −23 |
| Average | 0.6 | 1.2 | 1.1 | 10.2 | 9.0 | 7.9 | 1.4 | 3.1 | 0.2 | −38 | −41 | −23 |
| Average June to August | 1.0 | | | 9.0 | | | 1.6 | | | −34 | | |

**Fig. 1.** Climate scenarios with extreme heat wave from June to August in the Corn Belt (maximum temperature (a), minimum temperature (b), precipitation and its loss ratio based on baseline (c)). The baseline illustrates the normal climate and "Baseline EW" means the normal climate applied with extreme heat wave for 10 years and 'CSI A1 EW' and 'MIR A1 EW' express the future climate scenarios with extreme heat events under CSIRO-Mk3.0 and MIROC 3.2 of 2050 (2041–2060), respectively. The emission group of these future scenarios is A1B. HW=heat wave.

deviations across June to August reached over 9.0 °C in some cases (Table 1). Moreover, the deviations were highest for the months of June and July. In the case of minimum temperatures, the deviations across all three months were also about 1.6 °C. On a month-to-month basis, the deviations were highest for July. The deviations for monthly total precipitation were more than 40 mm for the months of June and July: there was less precipitation in June and July under the 'Baseline EW' climate scenario compared to the baseline climate (Table 1). Usually, heat waves are accompanied by drought. Lobell et al. Lobell et al. (2013) found that the water supply/demand ratio was reduced in August 2012 for the region in the USA affected by the heat wave. Precipitation had been decreasing since May and the drought peaked in September 2012 (Elliott et al., 2013). Similarly, in our study, precipitation for all three months under the 'Baseline EW' scenario across the Corn Belt (Table 2) was reduced by half.

A comparison of temperature and precipitation values was also made between the baseline and future climates (Fig. 1). The average maximum temperatures of June to August in the 'CSI A1 EW' climate scenario were similar to those of June–August in the 'Baseline EW'. On the other hand, the average maximum temperature was substantially higher under the 'MIR A1 EW' climate scenario compared to the baseline climate for June. The trend of average maximum temperature of 'MIR A1 EW' was quite different compared with that of two scenarios (Fig. 1a).

For minimum temperature, average monthly values were higher under the 'MIR A1 EW' climate scenario compared to the baseline climate between June and August (Fig. 1b). For precipitation, monthly averages were substantially lower (40%) under the three scenarios compared to the baseline climate (Fig. 1c), in particular the loss ratio of precipitation in July reached 60% under the 'MIR A1 EW' compared to the baseline climate. Hence, the risk of water stress should be higher under the future climate scenarios compared to the baseline scenario for rainfed maize.

*Association between heat waves and maize production*

Table 3 shows the recorded grain yields for 26 years, especially around the Corn Belt. Between 1980 and 2000, maize production was much smaller in 1988 and 1993 than in 1980, 1986, 1998, and 1999 even though there was no large change in harvested area. Production in the Corn Belt was much smaller in 1983 compared to other years even though there were no weather extreme recorded in 1983: the country was rather going through an economic recession. After 2000 (Table 3), maize production has

**Table 2**
Major maize producing states (Corn Belt) in the USA between 2005 and 2010.

| States | Average yield (kg/ha) | Average production (1000 t) | State share (%) |
|---|---|---|---|
| Iowa (IA) | 10,754 | 56,565 | 18.5 |
| Illinois (IL) | 10,377 | 50,597 | 16.5 |
| Nebraska (NE) | 10,178 | 35,385 | 11.5 |
| Minnesota (MN) | 10,429 | 30,301 | 9.9 |
| Indiana (IN) | 9980 | 22,970 | 7.5 |
| South Dakota (SD) | 7929 | 13,550 | 4.4 |
| Kansas (KS) | 8410 | 12,678 | 4.1 |
| Ohio (OH) | 9666 | 12,605 | 4.1 |
| Wisconsin (WI) | 9185 | 11,081 | 3.6 |
| Missouri (MO) | 8484 | 9955 | 3.2 |
| Michigan (MI) | 8892 | 7569 | 2.5 |
| Texas (TX) | 8191 | 6318 | 2.1 |
| North Dakota (ND) | 7647 | 5607 | 1.8 |
| Kentucky (KY) | 8703 | 4139 | 1.4 |
| Others[a] | 8747 | 27,228 | 8.9 |
| United States | 9625 | 306,546 | 100 |

[a] 34 other states outside the Corn Belt states (Alaska and Hawaii were excluded).

been increased by improving crop managements (i.e., irrigation, fertilizer etc.); there was also the reduction of maize production in the years when heat waves occurred even though the harvested area did not change largely. Maize production in 2012 was much smaller than in 2001, 2002 and 2006 even if there were no large change in planted and harvested area. The simulated average grain yield across the USA was 12,009 kg/ha under the baseline climate (Table 4). This value of yield was not much different from the recorded average maize yield for the USA, which stood at around 9239 kg/ha of the recorded average grain yield in 2011 and 9625 kg/ha for the five year average (2005–2010) (Table 4). In addition, the recorded grain yield in 2012, when the heat wave occurred, and the simulated 'Baseline EW' grain yield were not too different. Overall, it can be anticipated that the recorded yields from USDA report in 2013 (USDA, 2013a) validate the geo-spatial crop model on USA maize production: the simulated grain yields of the baseline and 'Baseline EW' in the HPC cluster are consistent with recorded yields.

The extreme weather event under the baseline climate would decrease maize yield by 29% (8545 kg/ha) compared to the baseline climate (Table 4). If the climate extreme occurs under future

**Table 3**
The recorded production and (area) from 1980 to 2012.

| Year | Iowa | Illinois | Nebraska | Minnesota | Indiana | S. Dakota | Kansas | Ohio | Wisconsin | Missouri | Michigan | Texas | N. Dakota | Kentucky |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1980* | 37.2 (5.4) | 27.1 (4.6) | 15.3 (2.9) | 15.5 (2.5) | 15.3 (2.5) | 3.1 (0.9) | 3.0 (0.5) | 11.2 (1.6) | 8.8 (1.4) | 2.8 (0.8) | 6.3 (1.1) | 3.0 (0.5) | 0.4 (0.1) | 2.6 (0.6) |
| 1981 | 44.7 (5.6) | 36.9 (4.6) | 20.1 (2.7) | 18.9 (2.7) | 16.6 (2.4) | 4.6 (1.0) | 3.8 (0.5) | 9.1 (1.5) | 9.6 (1.4) | 5.4 (0.8) | 6.9 (1.2) | 3.2 (0.4) | 1.1 (0.2) | 3.8 (0.6) |
| 1982 | 40.4 (5.3) | 38.7 (4.6) | 19.6 (2.8) | 18.7 (2.6) | 20.7 (2.6) | 4.9 (1.1) | 3.6 (0.5) | 12.1 (1.6) | 9.2 (1.4) | 5.2 (0.8) | 7.8 (1.1) | 3.0 (0.5) | 0.9 (0.2) | 4.0 (0.6) |
| 1983 | 18.9 (3.5) | 15.9 (3.2) | 11.9 (2.0) | 9.3 (1.8) | 8.7 (1.9) | 2.7 (0.8) | 2.2 (0.4) | 5.7 (1.1) | 5.7 (0.9) | 1.9 (0.6) | 4.2 (0.7) | 2.7 (0.4) | 0.7 (0.2) | 1.2 (0.4) |
| 1984 | 3.7 (5.2) | 31.7 (4.4) | 20.5 (2.8) | 17.5 (2.6) | 17.9 (2.4) | 4.7 (1.1) | 3.0 (0.4) | 11.7 (1.6) | 8.8 (1.3) | 3.9 (0.8) | 5.6 (1.1) | 3.7 (0.6) | 1.1 (0.3) | 3.7 (0.6) |
| 1985 | 43.4 (5.5) | 39.0 (4.6) | 24.2 (3.0) | 18.4 (2.5) | 19.2 (2.5) | 6.4 (1.2) | 3.6 (0.4) | 13.0 (1.6) | 9.1 (1.4) | 6.9 (1.0) | 7.3 (1.1) | 4.0 (0.6) | 1.0 (0.2) | 4.0 (0.6) |
| 1986* | 41.3 (5.0) | 35.7 (4.3) | 22.8 (3.0) | 18.0 (2.6) | 17.7 (2.4) | 5.9 (1.3) | 4.6 (0.6) | 12.1 (1.6) | 9.3 (1.6) | 7.1 (1.0) | 6.5 (1.1) | 3.8 (0.6) | 1.3 (0.4) | 3.6 (0.7) |
| 1987 | 33.2 (4.2) | 30.5 (3.7) | 20.6 (2.6) | 16.1 (2.2) | 16.0 (1.9) | 5.8 (1.3) | 3.6 (0.5) | 9.2 (1.3) | 8.4 (1.4) | 6.2 (0.9) | 4.7 (0.9) | 3.4 (0.5) | 1.2 (0.3) | 3.0 (0.5) |
| 1988* | 22.8 (4.6) | 17.8 (4.0) | 20.8 (2.8) | 8.8 (2.3) | 10.5 (2.1) | 3.4 (1.3) | 3.7 (0.5) | 6.5 (1.3) | 3.3 (1.4) | 3.9 (0.9) | 2.8 (0.8) | 3.3 (0.6) | 0.6 (0.3) | −2.0 (0.5) |
| 1989 | 36.7 (5.1) | 33.6 (4.4) | 21.5 (3.0) | 17.8 (2.5) | 17.6 (2.2) | 4.8 (1.4) | 3.9 (0.6) | 8.7 (1.3) | 7.9 (1.5) | 5.6 (1.0) | 5.7 (0.9) | 3.8 (0.7) | 0.9 (0.4) | 3.5 (0.5) |
| 1990 | 39.7 (5.2) | 33.5 (4.3) | 23.7 (3.1) | 19.4 (2.7) | 1.8 (2.3) | 5.9 (1.4) | 4.8 (0.6) | 10.6 (1.5) | 9.0 (1.5) | 5.2 (0.8) | 6.0 (1.0) | 3.3 (0.7) | 0.9 (0.3) | 3.0 (0.5) |
| 1991 | 36.3 (5.1) | 29.9 (4.5) | 25.2 (3.3) | 18.3 (2.7) | 13.0 (2.3) | 6.1 (1.5) | 5.2 (0.7) | 8.3 (1.5) | 9.7 (1.5) | 5.4 (0.9) | 6.4 (1.1) | 4.2 (0.7) | 1.3 (0.4) | 2.8 (0.5) |
| 1992 | 48.4 (5.3) | 41.8 (4.5) | 27.1 (3.4) | 18.8 (2.9) | 22.3 (2.5) | 7.0 (1.5) | 6.6 (0.7) | 12.9 (1.5) | 7.8 (1.6) | 8.2 (1.0) | 6.1 (1.1) | 5.1 (0.7) | 0.9 (0.4) | 4.4 (0.6) |
| 1993* | 22.4 (4.9) | 33.0 (4.2) | 19.9 (3.2) | 8.2 (2.5) | 18.1 (2.2) | 4.1 (1.4) | 5.5 (0.8) | 9.2 (1.4) | 5.5 (1.4) | 4.2 (0.9) | 6.0 (1.0) | 5.4 (0.8) | 0.4 (0.3) | 3.2 (0.6) |
| 1994 | 49.0 (5.3) | 45.4 (5) | 29.3 (3.5) | 23.3 (2.8) | 21.8 (2.5) | 9.3 (1.5) | 7.7 (0.9) | 12.4 (1.5) | 11.1 (1.5) | 7.0 (1.0) | 6.6 (1.0) | 6.1 (0.9) | 1.4 (0.3) | 4.0 (0.5) |
| 1995 | 35.6 (4.7) | 28.7 (4.1) | 21.7 (3.2) | 18.6 (2.7) | 15.2 (2.2) | 4.9 (1.1) | 6.2 (0.9) | 9.5 (1.3) | 8.8 (1.5) | 3.8 (0.7) | 6.3 (1.0) | 5.5 (0.8) | 1.0 (0.3) | 3.1 (0.5) |
| 1996 | 43.6 (5.1) | 37.3 (4.5) | 30.1 (3.4) | 22.1 (3.0) | 17.0 (2.3) | 9.4 (1.6) | 9.1 (1.0) | 7.8 (1.2) | 8.5 (1.6) | 9.0 (1.1) | 5.5 (1.1) | 5.1 (0.8) | 1.7 (0.4) | 3.8 (0.5) |
| 1997 | 41.7 (4.9) | 36.2 (4.5) | 28.8 (3.6) | 21.6 (2.8) | 17.8 (2.4) | 8.3 (1.5) | 9.4 (1.1) | 12.1 (1.5) | 10.2 (1.6) | 7.6 (1.1) | 6.5 (1.0) | 6.1 (0.8) | 1.5 (0.3) | 3.0 (0.5) |
| 1998* | 44.9 (5.1) | 37.4 (4.3) | 31.5 (3.6) | 26.2 (3.0) | 19.3 (2.3) | 10.9 (1.6) | 10.6 (1.2) | 12.0 (1.4) | 10.3 (1.5) | 7.2 (1.1) | 5.8 (0.9) | 4.7 (1.0) | 2.2 (0.4) | 3.4 (0.5) |
| 1999* | 44.7 (4.9) | 37.9 (4.4) | 29.3 (3.5) | 25.1 (2.9) | 19.0 (2.3) | 9.3 (1.5) | 10.7 (1.3) | 10.2 (1.4) | 10.4 (1.5) | 6.3 (1.1) | 6.4 (0.9) | 5.8 (0.8) | 1.9 (0.3) | 3.1 (0.5) |
| 2000 | 43.9 (5.0) | 42.4 (4.5) | 25.8 (3.4) | 24.5 (2.9) | 20.6 (2.3) | 10.8 (1.7) | 10.5 (1.4) | 12.3 (1.4) | 9.2 (1.4) | 10.1 (1.2) | 6.1 (0.9) | 6.0 (0.8) | 2.6 (0.4) | 4.1 (0.5) |
| 2001* | 42.3 (4.7) | 41.9 (4.5) | 28.9 (3.3) | 20.5 (2.8) | 22.5 (2.3) | 9.4 (1.5) | 9.8 (1.4) | 11.1 (1.4) | 8.4 (1.4) | 8.8 (1.1) | 5.1 (0.9) | 4.3 (0.6) | 2.1 (0.4) | 4.0 (0.5) |
| 2002* | 49.9 (5.0) | 38.0 (4.5) | 23.9 (3.4) | 26.7 (2.9) | 16.0 (2.2) | 7.7 (1.8) | 7.4 (1.3) | 6.4 (1.3) | 9.9 (1.5) | 7.2 (1.1) | 5.9 (0.9) | 5.2 (0.8) | 2.9 (0.5) | 2.7 (0.5) |
| 2003 | 47.5 (5.0) | 46.0 (4.5) | 28.6 (3.3) | 24.7 (2.9) | 20.0 (2.3) | 10.9 (1.8) | 7.6 (1.2) | 12.2 (1.3) | 9.3 (1.5) | 7.7 (1.2) | 6.6 (0.9) | 4.9 (0.7) | 3.3 (0.6) | 3.8 (0.5) |
| 2004 | 57.0 (5.1) | 53.0 (4.8) | 33.5 (3.3) | 28.5 (3.0) | 23.6 (2.3) | 13.7 (1.9) | 11.0 (1.3) | 12.5 (1.4) | 9.0 (1.5) | 11.9 (1.2) | 6.5 (0.9) | 5.9 (0.7) | 3.1 (0.7) | 4.4 (0.5) |
| 2005 | 54.9 (5.2) | 43.4 (4.9) | 32.3 (3.4) | 30.3 (3.0) | 22.6 (2.4) | 11.9 (1.8) | 11.8 (1.5) | 11.8 (1.4) | 10.9 (1.5) | 8.4 (1.3) | 7.3 (0.9) | 5.4 (0.8) | 3.9 (0.6) | 4.0 (0.5) |
| 2006* | 52.1 (5.1) | 46.2 (4.6) | 29.9 (3.3) | 28.0 (3.0) | 21.5 (2.2) | 7.9 (1.8) | 8.8 (1.4) | 12.0 (1.3) | 10.2 (1.5) | 9.2 (1.1) | 7.3 (0.9) | 4.5 (0.7) | 3.9 (0.7) | 3.9 (0.5) |
| 2007 | 60.4 (5.7) | 58.0 (5.3) | 37.4 (3.8) | 29.1 (3.4) | 24.9 (2.6) | 13.8 (2.0) | 12.9 (1.6) | 13.8 (1.6) | 11.2 (1.6) | 11.6 (1.4) | 7.3 (1.1) | 7.4 (0.9) | 6.9 (1.0) | 4.4 (0.6) |
| 2008 | 55.6 (5.4) | 54.1 (4.9) | 35.4 (3.6) | 30.0 (3.1) | 22.2 (2.3) | 14.9 (1.9) | 12.4 (1.6) | 10.7 (1.3) | 10.0 (1.5) | 9.7 (1.1) | 7.5 (1.0) | 6.4 (0.9) | 7.2 (1.0) | 3.9 (0.5) |
| 2009 | 61.5 (5.5) | 52.2 (4.9) | 40.0 (3.7) | 31.6 (3.1) | 23.7 (2.3) | 17.9 (2.0) | 15.2 (1.7) | 13.9 (1.4) | 11.4 (1.6) | 11.3 (1.2) | 7.9 (1.0) | 6.5 (1.0) | 5.1 (0.8) | 4.8 (0.5) |
| 2010 | 54.7 (5.4) | 49.4 (5.1) | 37.3 (3.7) | 32.8 (3.1) | 22.8 (2.4) | 14.5 (1.8) | 14.8 (2.0) | 13.5 (1.4) | 12.8 (1.6) | 9.4 (1.3) | 8.0 (1.0) | 7.7 (0.9) | 6.3 (0.8) | 3.9 (0.5) |
| 2011 | 59.9 (5.7) | 49.4 (5.1) | 39.0 (4.0) | 30.5 (3.3) | 21.3 (2.4) | 16.6 (2.1) | 11.4 (2.0) | 12.9 (1.4) | 13.2 (1.7) | 8.9 (1.3) | 8.5 (1.0) | 3.5 (0.8) | 5.5 (0.9) | 4.6 (0.6) |
| 2012* | 47.7 (5.7) | 32.7 (5.2) | 32.8 (4.0) | 34.9 (3.5) | 15.2 (2.5) | 13.6 (2.5) | 9.6 (1.9) | 11.4 (1.6) | 10.1 (1.8) | 6.3 (1.5) | 8.1 (1.1) | 5.1 (0.7) | 10.7 (1.5) | 2.6 (0.7) |

The columns with asterisk (*, i.e. 1980, 1986, 1988, 1998, 1999, 2001, 2002, 2006, and 2012) are years that extreme weather event occurred. Unit of production is million tons and unit of harvested area is million hectares. Source: USDA National Agricultural Statistics Service.

**Table 4**
Recorded and simulated grain yield and loss ratio for maize in the USA.

| | Recorded | | | | Simulated | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | With Extreme weather event | | | | |
| | 2009 | 2010 | 2011 | 2012 | Baseline | Baseline EW (1950–2000) | B1 (2050) | | A1B (2050) | |
| | | | | | | | CSIRO | MIROC | CSIRO | MIROC |
| Grain yield (kg/ha) | 10,369 | 9590 | 9239 | 7745 | 12,009 | 8545 | 7659 | 7643 | 7491 | 5081 |
| Loss ratio (%) | | | | −20 | | −29 | −36 | −36 | −38 | −58 |

*Source*: USDA National Agricultural Statistics Service (USDA, 2013a).

climate, average grain yields under the CSIRO-Mk3.0 and MIROC 3.2 climate models would decrease by 36% under the B1 emission scenario compared to the baseline climate model. Under the A1B emission scenario, average grain yields under the CSIRO-Mk3.0 and MIROC 3.2 models would decrease by 38% and 58%, respectively, compared to the baseline climate (Table 3). Moreover, average grain yields under the 'CSI A1 EW' and 'CSI B1 EW' future climate scenarios are similar with yield reductions of 36% and 38%, respectively; however, there was a substantial difference between average grain yields under the 'MIR A1 EW' (58%) and 'MIR B1 EW' (36%) (Table 4).

Fig. 2 illustrates the simulated grain yield of irrigation with and without an extreme heat wave across all affected regions in the USA. The spatial irrigated maize yields in the Corn Belt states were between 5029 kg/ha and 12,573 kg/ha under the baseline climate (Fig. 2a), and between 5026 kg/ha and 12,566 kg/ha under the 'Baseline EW' scenario (Fig. 2b). When the climate extreme occurs under climate change, grain yield for irrigated maize ranged between 5089 kg/ha and 12,722 kg/ha under the 'CSI A1 EW', and between 5000 kg/ha and 12,499 kg/ha under the 'MIR A1 EW' scenario (Fig. 2c and d). In the case of rainfed maize, the simulated grain yields were between 3776 kg/ha and 9439 kg/ha for the baseline, and between 3171 kg/ha and 7928 kg/ha under the 'Baseline EW', respectively (figures not shown). Also, under the 'CSI A1 EW' and 'MIR A1 EW', the simulated grain yields were between 3132 kg/ha and 7463 kg/ha, and between 3006 kg/ha and 6013 kg/ha, respectively (figures not shown). Therefore, rainfed maize appears to be more sensitive to high temperature and drought. Overall, the spatial crop modeling framework performed well, as the simulated average maize yield under the baseline climate was similar to the reported average grain yield by the USDA (Table 4).
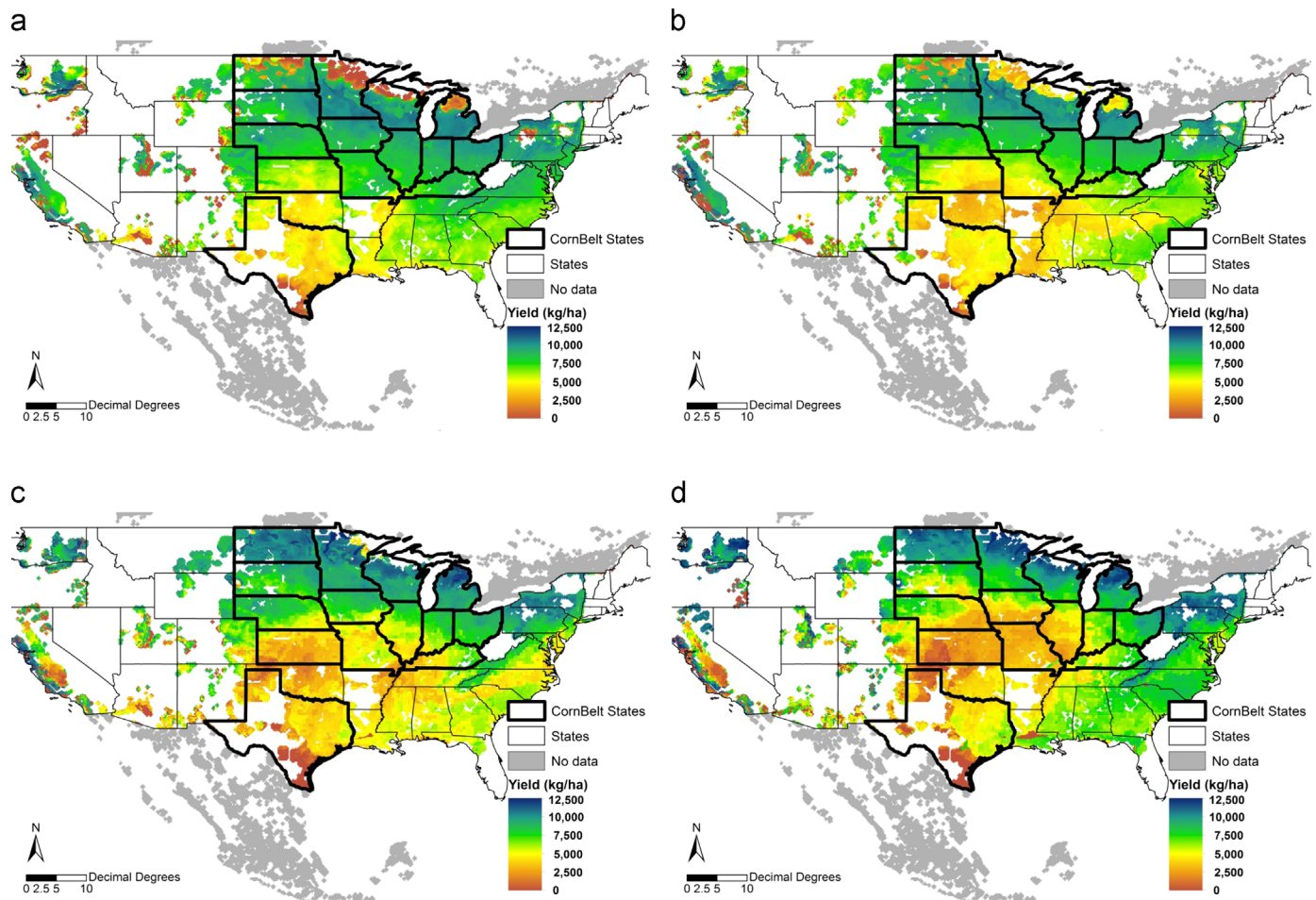
**Fig. 2.** The maps express the spatial changes of grain yields under each condition and irrigated cropping system. Top-left is for the baseline climate (a), top-right for 'Baseline EW' (b), bottom-left for 'CSI A1 EW' under extreme heat (c), and bottom-right for 'MIR A1 EW' under extreme heat (d).

*Socio-economic results: trend analysis to assess impact of weather extreme in 2012*

*Linkages between world maize prices and the weather extreme in the USA*

At the beginning of 2012, historically low maize inventories were recorded in the USA, the largest maize producer and exporter in the world. However, a projected increase in global maize production, driven mainly by increased maize plantings in the USA and a record maize harvest in Brazil, kept world maize prices relatively stable during the first half of 2012 (Fig. 3). Other factors behind the projected increase in global maize production included stable maize production in China, the largest maize producer in the world after the USA, and projected increased maize plantings in the EU (FAO, 2012b).

In early 2012, the USDA projected that USA maize production would increase substantially in 2012/13 compared to 2011/12 (WASDE, 2012). More specifically, planted maize area would increase by 4%; maize yields would increase by 13%; the combination of these two factors would lead to maize production increasing by 20% or 53 million tons during the 2012/13 season (USDA, 2012a). Such projections usually support governments' efforts in assessing the food security status in their countries and identify import needs. They also help investors along the food value chain make better investment decisions, including the negotiation of fairer prices.

By July 2012, extreme and persistent drought had been recorded in June 2012 across the central and eastern Corn Belt. In addition, extreme heat from late June to early July was recorded

across the central plains of the USA (USDA, 2012b). The combination of extreme heat and dryness lingered through July (USDA, 2012c). In August 2012, the USDA re-adjusted their projections, which involved a decrease of 16% in maize yields in 2012/13 compared to 2011/12. Hence, despite an increase of 5% in planted maize area, total maize production was projected to be 12% lower in 2012/13 compared to 2011/12 (USDA, 2012d).

Between June and August 2012, as knowledge on the effect of the weather extreme on the USA maize crop spread, the two indicators of the world maize price, namely the price of the USA no. 2 yellow maize and that of the Argentina yellow maize (Up River), increased by 25% each (Fig. 3). In August 2012, the USA no. 2 yellow maize, reached an all-time high of USD $331 per ton; it was 18% higher than its peak of USD $281 per ton which was recorded during the food price crisis in 2008. With a value of USD $297 per ton, the price of the Argentina yellow maize was 15% higher than its peak of USD $258 per ton during the food price crisis in 2008.

The rising maize prices were also fueled by reduced maize production in the EU due to a summer drought and low maize reserves worldwide. By November 2012, world maize reserves for the 2011/12 season were expected to be at their lowest since 2006/2007 (FAO, 2012c).

*Effects of rising maize prices on maize consumption, trade and stocks in the USA*

The sharp increase in world maize prices does not seem to have had substantial negative effects on maize consumption and retail
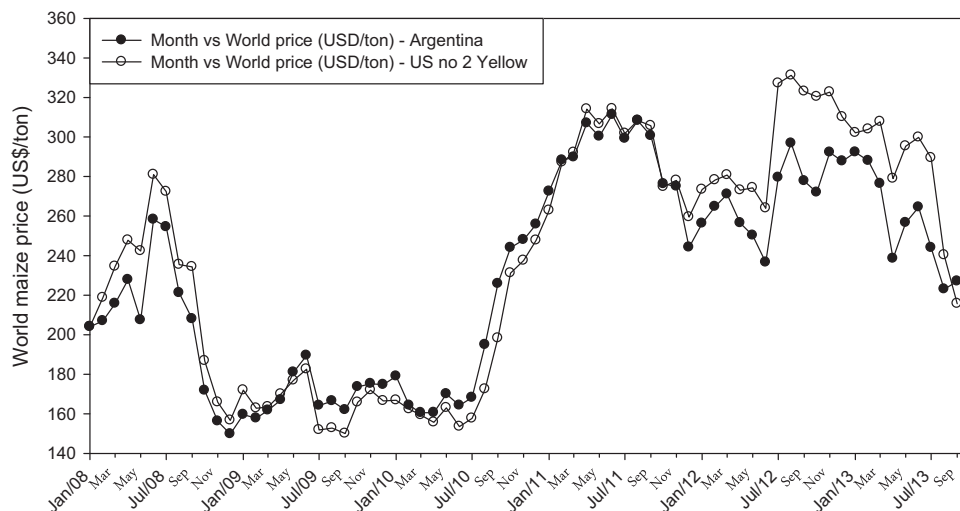
**Fig. 3.** Trends in world maize prices.

food prices within the USA. USA maize production is estimated to have decreased by 13% or 40 million tons in 2012/13 vs. 2011/12 (WASDE, 2014). On the other hand, domestic maize consumption has barely changed: it is estimated to have decreased by 5% or 15 million tons (WASDE, 2014).

A strong USA dollar in 2012–2013 (USDA, 2012) made exports less attractive compared to the domestic markets; in addition, USA policies that have been boosting the biofuel industry in recent years (Piesse and Thirtle, 2009; Yano et al., 2010) implied a strong domestic maize demand. Hence, domestic maize consumption reached 263.6 million tons (Fig. 4). On the other hand, USA maize exports decreased by 53% to 18.6 million tons (Fig. 4). Given that the total amount of maize utilized by the USA in 2013 amounted to 282.1 million tons (domestic consumption and exports) against an estimated total production of 273.8 million tons, the country had to supplement its production by importing 4 million tons of maize and reducing its maize stocks by 4.3 million tons (Fig. 4).

The weather extreme of 2012 is similar to the one which occurred in 1993, in terms of its effects on USA maize production, consumption, trade and stocks. The 1993 weather extreme led to the highest year-to-year relative decrease in maize production since 1980. More specifically, USA maize production fell by 33% in 1993, compared to 1992; by contrast, USA maize consumption that same year fell only by 7.6% over the same period. USA maize production amounted to 160.9 million tons in 1993; the same amount of maize was domestically consumed within the USA, that same year (Fig. 4). In addition, the country decreased its maize exports by 20% to a low of 33.7 million tons (Fig. 4). In order to meet all its utilization requirements in 1993, the country had to reduce its stocks by 32.1 million tons and import 533 thousand tons of maize (Fig. 4). The key difference between the 2012 and 1993 event relates to the heavier reliance of the USA on maize stocks to meet its maize utilization in 1993. This is not surprising as USA maize ending stocks in 1992 stood at 53.7 million tons and were twice as high as those of 2011 (Fig. 4).

By contrast, the weather extreme of 1988 occurred when the USA had large maize stocks which stood at 108 million tons and hence were 4.3 times higher than ending maize stocks in 2011 (Fig. 4). The weather extreme of 1988 reduced maize production by 30% compared to 1987. In this case, the country slightly reduced their maize consumption but increased their maize exports and even reduced maize imports. That year, the USA heavily drew down its stocks to supplement its maize production so as to meet its total maize utilization (Fig. 4).

*Effect of the weather extreme on world maize production, consumption and trade*

The substantial reduction in USA maize exports implied a reduction in the supply of maize in international markets (FAO, 2012c). Recent estimates imply that world maize export decreased by 24% (23 million tons) between 2011/12 and 2012/13 (USDA, 2013b). Overall, world maize production decreased by 24 million tons whereas maize consumption decreased by 11.5 million tons. Hence, the world had to rely on world maize reserves to meet its consumption requirements: world maize stocks decreased by 7% between the beginning and the end of the 2012/13 season (USDA, 2013b).

World maize prices remained high after their peak in August 2012. Eleven months after the price spike, the USA no. 2 yellow maize was only 11% lower compared to August 2012; the Argentina yellow maize was only 9% lower (Fig. 3). This suggests that poor countries that depend on imports to meet their maize consumption requirements had to contend with high maize prices for much of 2012/13. Some of these countries include vulnerable countries in the Caribbean, northern Africa and western Asia, where the ratio of imports to maize consumption has remained above 50% for the last years (Table 5). Other countries have low import dependency ratios; however, they are vulnerable because they would be too poor to afford highly-priced maize. This would be true for some countries in Sub-Saharan Africa (SSA), which import white maize; the latter is usually consumed as food and is sold at a premium over yellow maize. A detailed analysis involving a global multi-market and multi-commodity model would be necessary to estimate the impact of the weather extreme on food security across vulnerable and import-dependent countries.

*Socio-economic results: assessing impact of the weather extreme in 2050*

Some of the key drivers that would determine the effect of the weather extreme, were it to occur in 2050, include the cumulative effect of climate change on maize production; population and income growth worldwide; and the ability of maize farming systems to adapt to climate change through the adoption of improved maize technologies. The weather extreme could still have devastating effects if it were to occur in 2050. Food security worldwide could be enhanced between the 2000s and 2050s, due to favorable economic growth. However, the gains in enhancing food security might be lost to the adverse weather extremes
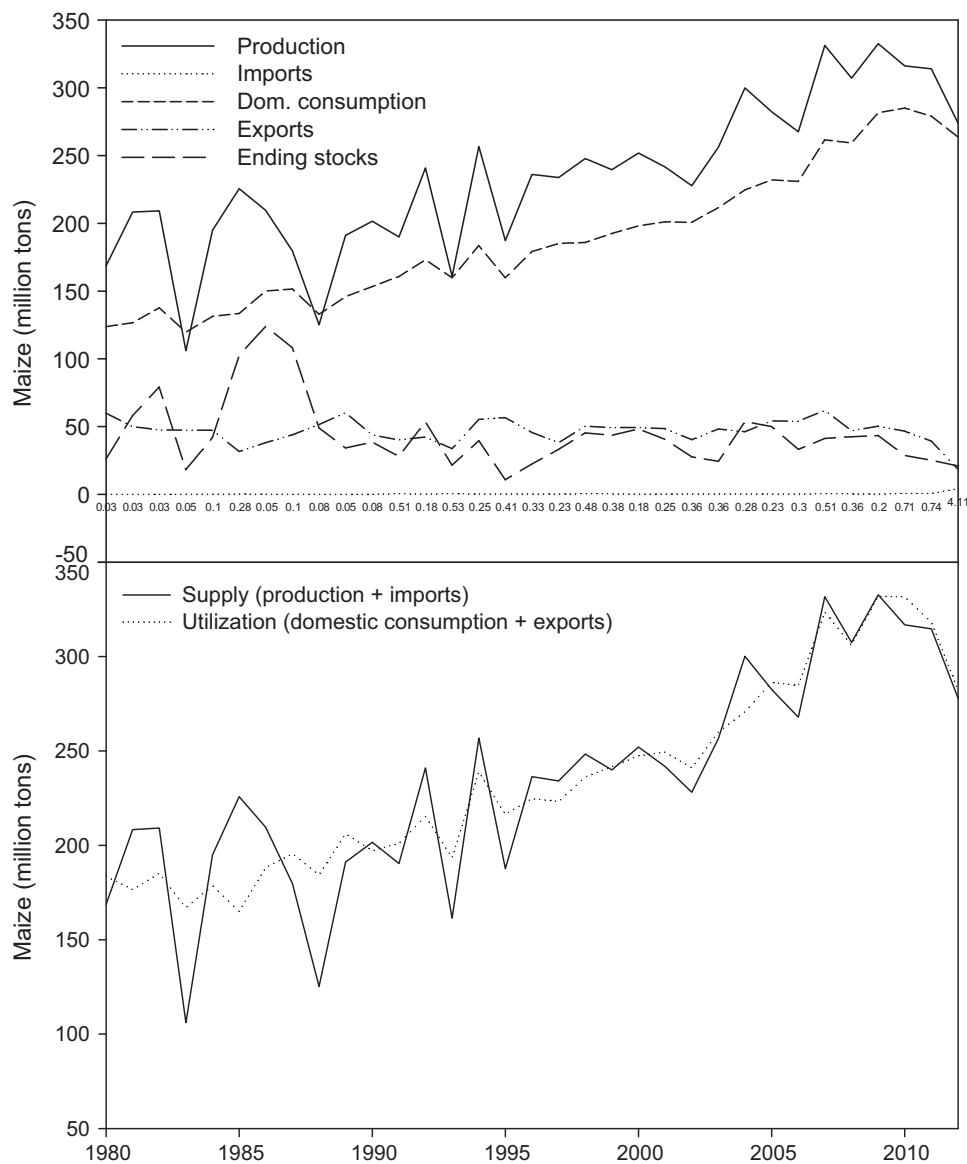
**Fig. 4.** Impact of weather extremes on US maize production, consumption and trade. Source: USDA World Agricultural Supply and Demand Estimates – from 1981 to 2014.

brought by climate change. Hence, one more weather extreme, that would substantially reduce maize production in the USA, would worsen food security in countries already weakened by climate change.

However, some of the developing countries that would be vulnerable to the weather extreme in 2012 might not experience any loss if the weather extreme occurred in the 2050s under climate change. In such countries, the improvement in national food security over the years could outweigh the negative effect of climate change. In addition, world maize trade might change by 2050 with less dependence on the USA as an exporter. Under circumstances where the USA ends up accounting for 20% or less of world maize exports by 2050, a weather extreme that would affect maize production in the USA might have more subdued effects on world maize prices and hence on food security across vulnerable countries. The adoption of improved maize technologies coupled with adequate policies that facilitate technology adoption could also change the structure of world maize trade and hence dampen the negative effects of the weather extreme. For example, high-yielding maize germplasm with resistance to the abiotic and biotic stresses brought by climate change

(Shiferaw et al., 2011) might help sustain maize production in some regions and increase production in others.

The impact of future weather extremes would also depend on the terms of trade that would exist in 2050. Some countries, namely the ones in Latin America and the Caribbean, could join forces to adjust their production and consumption patterns so as to reduce their maize import dependency by 2050. Under such scenario, a weather extreme that would substantially reduce USA maize production could have relatively insignificant effects on global food security.

## Discussion

*Characteristics of extreme weather events in the Corn Belt of the USA*

Crop yield is a result of the interactions in the soil-plant-atmosphere continuum of crop models. Weather data is the driving factor in crop modeling and it is important to use accurate weather data inputs in models. Although extreme events are common features of weather, they usually have negative consequences ranging from tolerable to disastrous conditions depending

**Table 5**
Trend in import to consumption ratio for developing regions.

| Region | 2005 | 2006 | 2007 | 2008 | 2009 |
|---|---|---|---|---|---|
| **Sub-Saharan Africa (SSA)** | | | | | |
| Eastern Africa | 5.3 | 10.3 | 5.4 | 7.5 | 15.3 |
| Central Africa | 12.8 | 11.1 | 8.4 | 9.0 | 11.5 |
| Southern Africa | 4.7 | 14.0 | 15.7 | 7.0 | 5.8 |
| Western Africa | 3.4 | 3.4 | 2.7 | 2.5 | 2.6 |
| **CWANA** | | | | | |
| Central Asia | 1.2 | 1.8 | 4.2 | 6.1 | 4.9 |
| Northern Africa | 61.7 | 57.4 | 61.8 | 55.3 | 58.0 |
| Western Asia | 54.2 | 57.2 | 63.9 | 58.2 | 61.3 |
| **East and South East Asia** | | | | | |
| Eastern Asia | 18.7 | 18.7 | 17.4 | 16.8 | 16.1 |
| South-eastern Asia | 11.2 | 19.2 | 13.6 | 11.5 | 12.0 |
| **South Asia** | 10.8 | 10.5 | 13.8 | 12.1 | 17.3 |
| **LAC region** | | | | | |
| Caribbean | 77.0 | 81.5 | 78.2 | 78.9 | 77.5 |
| Central America | 26.5 | 30.1 | 31.2 | 30.9 | 28.6 |
| South America | 11.2 | 13.7 | 13.7 | 11.3 | 13.6 |

CWANA=Central and West Asia and North Africa; LAC=Latin America and Caribbean.

on the magnitude and duration of the extreme events. Since 1980, in the USA alone, heat wave events have occurred more than ten times. In 2012, maize-growing farmers in the USA experienced the highest temperatures on record since 2000. In addition, the heat wave was followed by severe drought. According to the latest USA Drought Monitor report, more than two-thirds of the contiguous United States was under drought conditions, the highest level since record-keeping began in January 2000; indeed soil moisture was reduced by half compared to normal years (Lobell et al., 2013).

Our results illustrate the considerable utility of the process-based spatial bio-economic framework, as a tool for assessing the impacts of extreme heat waves on maize production. Our approach for heat wave generation also underlines the usefulness of monthly weather data, even though the methodology is a simple arithmetic method. However, we need further studies on solar radiation and the number of rainy days that we did not change in the study and more high resolution climate maps focused on country level since the spatial resolution is a key decision in agricultural systems modeling (Zhao et al., 2013). Additionally, we should clearly address four basic properties: validation, uncertainty, credibility, and clarify to generate climate maps with extreme events such as spatial (i.e., km or degree on the gridded maps) and temporal resolutions (i.e., daily or monthly weather data) (Knutti et al., 2008; Elliott et al., 2013).

*Biophysical impact of extreme weather events in the Corn Belt of the USA*

Depending on the cultivar and the cultivated area of maize, rainfall requirements can vary much. However, maize generally requires at least 90 to 300 mm of average precipitation between June and August in rainfed areas (Shaw, 1988; Dowswell et al., 1996; Hartkamp et al., 2000). The range of normal temperature for good growth and development of maize is between 26 °C and 32 °C (Hartkamp et al., 2000). Also, if soil moisture is adequate, maize can grow well even under high temperatures, varying between 32 °C and 38 °C. However, precipitation when the heat wave occurred was just half of that reported for the baseline climate in Fig. 2. The high temperatures and reduced precipitation for three months decreased actual 2012 grain yield to an average 7745 kg/ha—20% less than the average yield over 2009–11 (10,369 kg/ha, 9590 kg/ha and 9239 kg/ha in 2009, 2010 and

2011, respectively, giving an average of 9733 kg/ha), a period when there was no weather extreme (Table 4). The simulated grain yield of 'Baseline EW' was 8545 kg/ha and the simulated grain yield of the baseline climate was 12,009 kg/ha, a reduction of 29%. The 9% difference between recorded and simulated yield losses results from the baseline overestimation typical of most models, given that the baseline represents optimal conditions, and is actually less than the differences projected by several other leading models (Table 4). Thus, the simulation faithfully represents the effects of a weather extreme such as high temperatures from June to August—when ears are developing, a crucial period for maize growth—and can be used to predict grain yield losses from a heat wave. Our study involved the use of daily weather data generated based on average monthly data. Indeed, not using recorded daily weather data might lead to an underestimation of the biophysical impact of weather extremes. However, our results are consistent with those of Elliott et al. (2013) who used recorded daily weather data and found that the 2012 weather extreme reduced USA maize yields by 25% relative to trend.

The input data used to reflect weather extremes were the same regardless of the climate models used. In reality, future weather extremes might involve greater heat and/or larger rainfall reduction. Hence, the results on future weather extremes can be considered as lower bounds on the impact of such extremes on maize yields in the USA.

Recently, studies on heat stress and drought tolerance have been being robustly investigated. We also need additional research on the effect of weather extremes on food security in the developing world if the weather extremes occur in the developing world in the near future. Another area of future research consists of simulating the biophysical effect of weather extremes using future farm technologies adapted to future climates.

*Socio-economic analysis of the weather extreme*

Since the USA is the major maize producer and exporter world-wide, shocks that affect its maize supply are likely to impact international maize markets and by extension, maize systems and food security in other regions of the world. The weather extreme which affected USA maize production in 2012 likely influenced the 25% increase in world maize prices between June and August 2012. However, other factors might have also been at play, including speculation.

The weather extreme also led to a reduction in global maize trade and consumption in 2012/13 compared to 2011/12. Countries most likely to have experienced adverse effects from the weather extreme, including reduced food consumption and hence worsened food insecurity, include poor countries with high maize import dependency ratios. Other vulnerable countries have lower import dependency ratios but would be too poor to afford highly-priced maize.

The trend analysis used in this study highlights the linkages between the weather extreme and maize consumption and trade worldwide. However, it is not enough to pinpoint the exact effect of the weather extreme. Some careful analysis involving geo-spatially disaggregated economic modeling would be needed to isolate the potential impact of the weather extreme on food security across the developing world.

The study also highlighted some of the factors that could mitigate or fuel the negative effect of the weather extreme, were it to occur 40 years from now. Some of these factors include socio-economic growth over the years and the adoption of improved maize technologies. Adaptation to weather extremes would include policies aimed at supporting countries to cope with the aftermath of the weather extremes and policies that would enhance the adaptive capacity of countries. Social protection and

safety net programs to protect the vulnerable would fall under coping-related policies. They include cash transfers to vulnerable households where markets work; where markets do not work, food aid might be the best option. Other programs targeting the vulnerable include those on school feeding and food-for-work. Medium- to long-term interventions would include the replenishment of food stocks in the world's breadbaskets: these food stocks need to be high enough to counter the negative effect of weather extremes on food production. If the USA ending maize stocks of 2011 were similar to those of 1992, the USA would have been able to use these stocks to cover the production loss brought by the 2012 weather extreme.

## Concluding remarks

The objectives of this study were to estimate the biophysical impact of the 2012 weather extreme in the USA on maize production in the country and assess its related effects on food security across the developing world. If the climate extreme occurs under the baseline climate, our estimates suggest a 29% reduction in maize yields across the USA. The socio-economic analysis suggests that the extreme climate of 2012 that occurred in the USA is likely to increase food insecurity among poor communities where maize provides a substantial portion of daily caloric intake and where households cannot easily adjust their food consumption patterns in the face of increased maize scarcity. Our results indicate that food insecurity would be more severe in SSA. Nelson et al. (2010) assessed the economic impact under four climate scenarios while we used only two scenarios for this assessment.

However, although this challenge is a good example due to the reasonable results achieved under the HPC cluster, there still remains many challenges to improve the gridded weather data and crop models on the HPC cluster. Chung et al. (2011) suggested the method that can predict the flowering date of a cherry tree by inputting gridded (i.e., spatial) real-time weather data with the normal years data (i.e., historical weather data). Extreme weather events, such as high temperatures or severe drought will occur many times in the future and it is difficult to forecast in real-time. However, we anticipate that the real-time forecasting technology will be improved and it would be easier to directly run the crop model on the HPC cluster. Also, the real-time result from HPC cluster can be useful in adaptive planning, strategies, and economic decisions in the mid- to long-term perspective.

The socio-economic analysis demonstrated that the weather extreme in the USA likely affected maize prices, consumption and trade worldwide. It also highlighted the potential pathways through which the weather extreme could affect food security across the developing world. However, additional research involving a process-based economic model that can capture the terms of trade of the key staple crops across the globe would be needed to isolate the socio-economic impact of the weather extreme.

## Acknowledgments

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