WORKSHOP 01

미국 Corn Belt 폭염이 개발도상국의 식량안보에 미치는 영향 평가

정유란*

APEC 기후센터

Modeling the Effect of a Climate Extreme on Maize Production in the USA and Its Related Effects on Food Security in the Developing World

Uran Chung*

Climate Change Research Department, APEC Climate Center

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, 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

* Correspondence to : uchung@apcc21.org

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.

Key-words: Geo-spatial crop modeling, DSSAT 4.5, HPC cluster, Global maize price, Food security

I. 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 *et al.,* 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 results in 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.

II. Materials and Methods

2.1. *Spatial biophysical framework*

(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 (http://www.ccafs-climate.org). 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.

2.1.4. *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.*(2014).

2.1.5. *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.*(2014).

2.1.6. *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.

III. Results

3.1. *Biophysical results*

3.1.1. *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 to August) (Table 1). However, when the comparison involves the highest maximum temperatures between the baseline and 'Baseline EW' climate scenarios, the 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.*(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 was reduced by half (Table 2).

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 to 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).

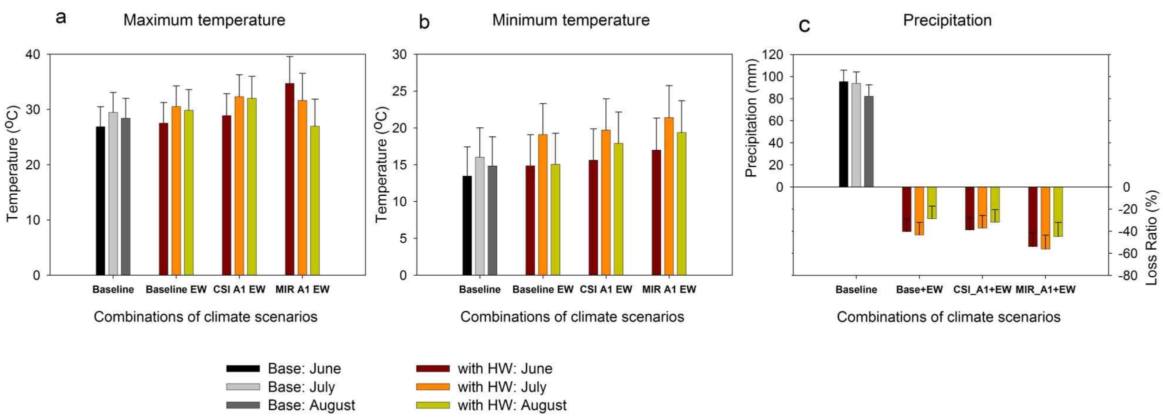


Fig. 1. Climate scenarios with extreme heat wave from June to August in the Corn Belt (maximum temperature (a), minimum temperature (b), precipitation and its loss ratio based on baseline (c)). The baseline illustrates the normal climate and "Baseline EW" means the normal climate applied with extreme 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.

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.

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

	Deviations											
	Maximum temperature(°C)						Minimum temperature (°C)			Precipitation (mm)		
	Average			Highest			Average			Monthly total		
STATES	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	

3.1.2. ***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 been increased by improving crop managements (i.e., irrigation, fertilizer and 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 9,239 kg/ha of the recorded average grain yield in 2011 and 9,625 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% (8,545 kg/ha) compared to the baseline climate (Table 4). If the climate extreme occurs under future 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 5,029 kg/ha and 12,573 kg/ha under the baseline climate (Fig. 2a), and between 5,026 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 5,089 kg/ha and 12,722 kg/ha under the 'CSI A1 EW', and between 5,000 kg/ha and 12,499 kg/ha under the 'MIR A1 EW' scenario (Fig. 2c and 2d). In the case of rainfed maize, the simulated grain yields were between 3,776 kg/ha and 9,439 kg/ha for the baseline, and between 3,171 kg/ha and 7,928 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 3,132 kg/ha and 7,463 kg/ha, and between 3,006 kg/ha and 6,013 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 for 5 years by the USDA (Table 4).

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

States	Average yield (kg/ha)	Average production (1,000 tons)	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)	9,980	22,970	7.5
South Dakota (SD)	7,929	13,550	4.4
Kansas (KS)	8,410	12,678	4.1
Ohio (OH)	9,666	12,605	4.1
Wisconsin (WI)	9,185	11,081	3.6
Missouri (MO)	8,484	9,955	3.2
Michigan (MI)	8,892	7,569	2.5
Texas (TX)	8,191	6,318	2.1
North Dakota (ND)	7,647	5,607	1.8
Kentucky (KY)	8,703	4,139	1.4
Others*	8,747	27,228	8.9
United States	9,625	306,546	100

*34 other states outside the Corn Belt states (Alaska and Hawaii were excluded).

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	(0.6)
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 maize grain yield in US. The 'simulated' grain yield and loss ratio of grain yield under extreme heat wave. The loss ratio of 2012 in 'recorded' was calculated from the average grain yield of three years when the heat wave did not occur. The loss ratio of 'Baseline EW' and future scenarios were calculated with the baseline climate.

	Recorded				Simulated					
						with Extreme weather event				
							B1 (2050)		A1B (2050)	
	2009	2010	2011	2012	Baseline	Baseline EW (1950-2000)	CSIRO	MIROC	CSIRO	MIROC
Grain yield (kg/ha)	10,369	9,590	9,239	7,745	12,009	8,545	7,659	7,643	7,491	5,081
Loss ratio (%)				-20		-29	-36	-36	-38	-58

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

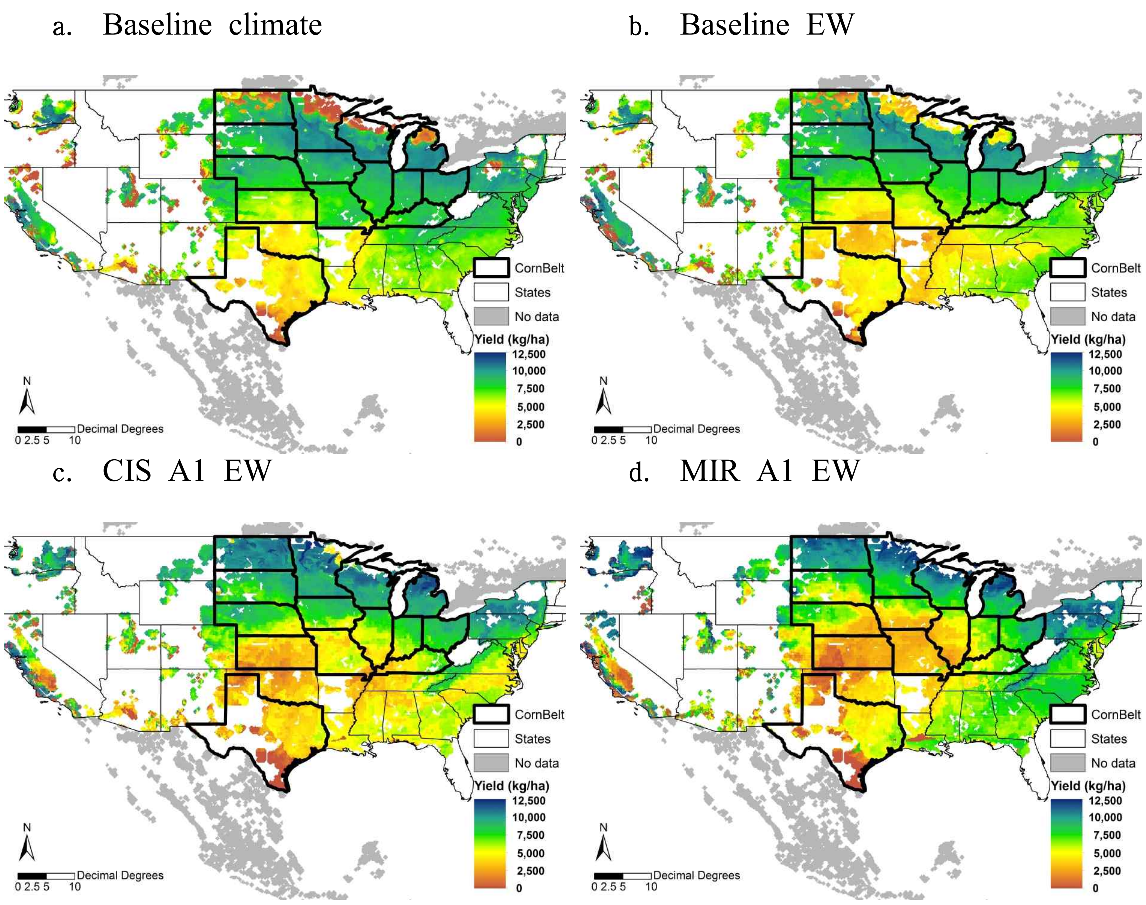


Fig. 2. The maps express the spatial changes of grain yields under each condition and irrigated cropping system. Top-left is for the baseline climate (a), top-right for 'Baseline EW' (b), bottom-left for 'CSI A1 EW' under extreme heat (c), and bottom-right for 'MIR A1 EW' under extreme heat (d).

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

3.2.1. *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).

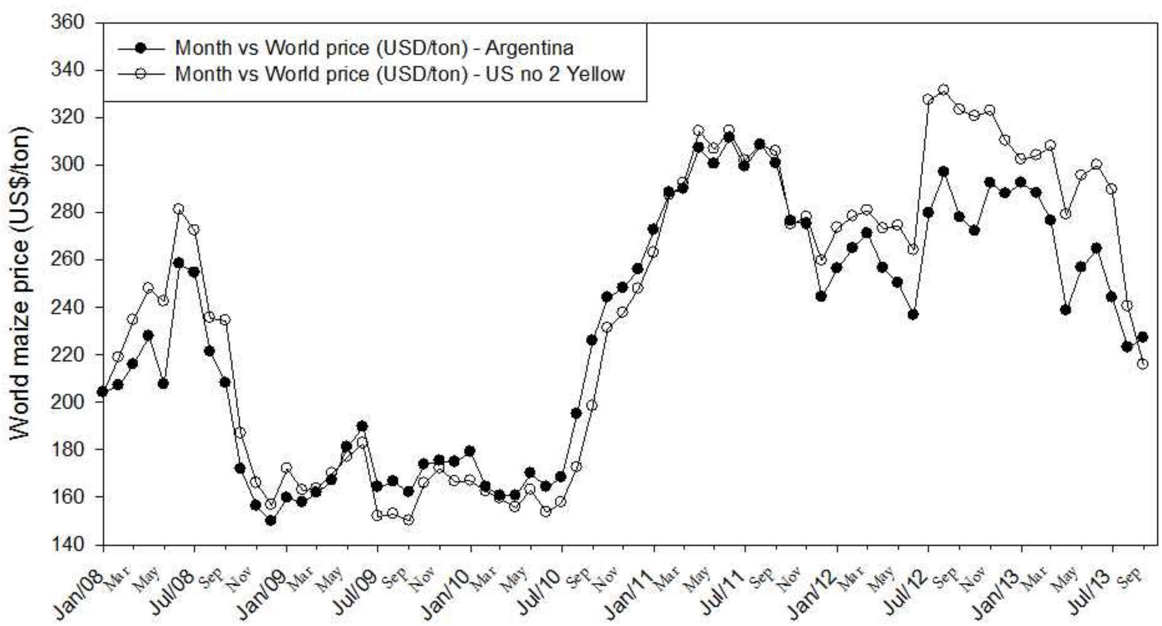


Fig. 3. Trends in world maize prices

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).

3.2.2. *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 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 US 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).

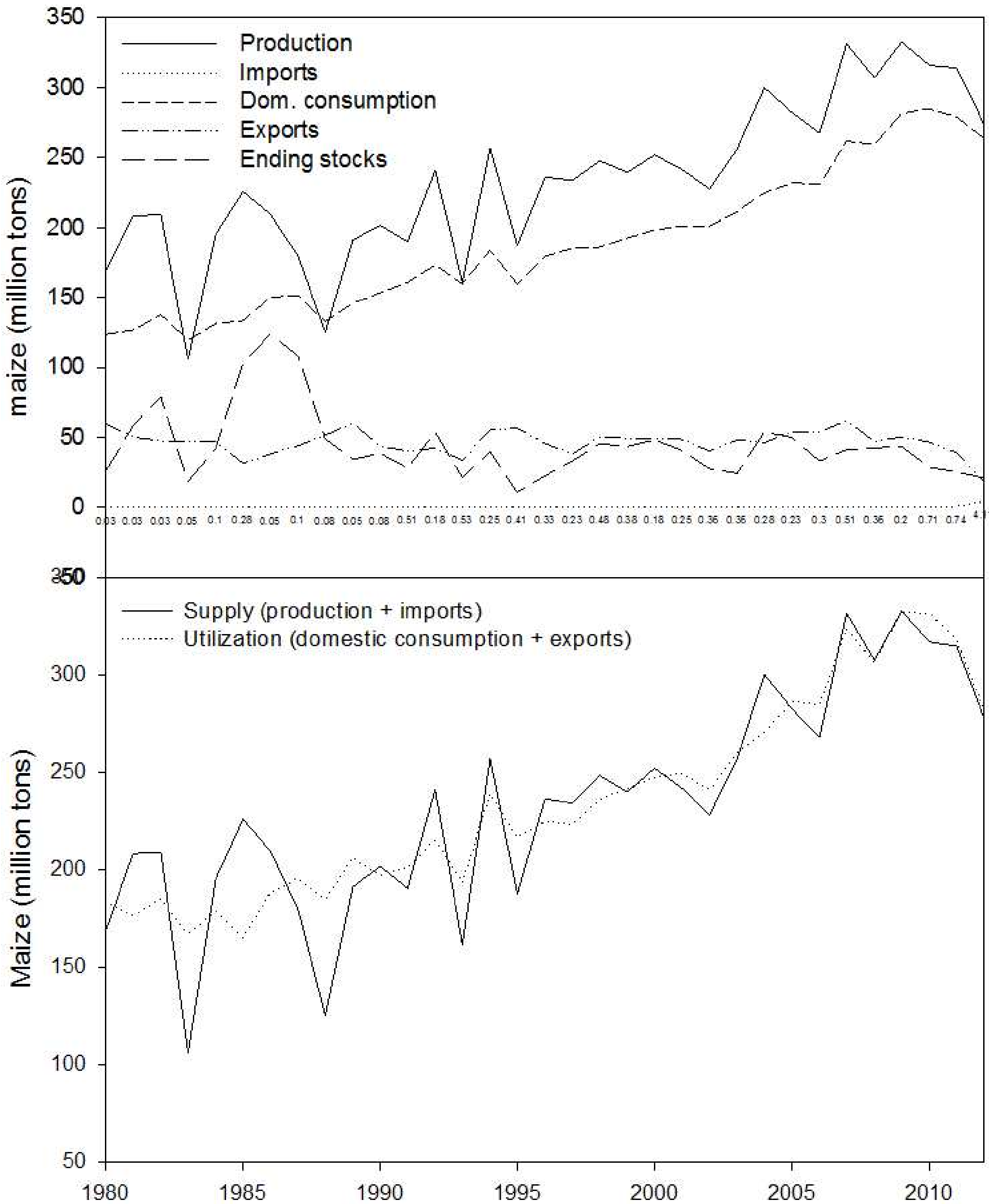
The weather extreme of 2012 is similar to the one which occurred in 1993, in terms of its effects on USA maize production, consumption, trade and stocks. The 1993 weather extreme led to the highest year-to-year relative decrease in maize production since 1980. More specifically, USA maize production 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).

3.2.3. *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.



1)

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.

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

3.3. 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 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.

IV. Discussion

4.1. *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 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 didn’t 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).

4.2. ***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 7,745 kg/ha－20% less than the average yield over 2009-11 (10,369 kg/ha, 9,590 kg/ha and 9,239 kg/ha in 2009, 2010 and 2011, respectively, giving an average of 9,733 kg/ha), a period when there was no weather extreme (Table 4). The simulated grain yield of 'Baseline EW' was 8,545 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 Elliot *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.

4.3. ***Socio-economic analysis of the weather extreme***

Since the USA is the major maize producer and exporter worldwide, 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.

V. 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.

적 요

2012년 상반기 미국의 옥수수 생산량은 재배면적의 증가 등으로 20% 이상 증가할 것으로 예측되었다. 하지만 2012년 봄 미국의 폭염과 가뭄이 발생하였고, 그 현상이 지속될 것으로 예측되면서 많은 경제학자들, 국제곡물수급 관련 전문가들은 미국의 옥수수 생산량이 감소할 것으로 예측했다. 실제로, 2013년 미국 농무부 (USDA)의 작물생산 총 보고서에서 2012년 미국 폭염과 가뭄으로 미국의 2012년 옥수수 생산량은 2011년에 비해 20% 감소했다고 발표했다. 많은 연구에서 곡물 생산량을 예측하지만 기상이변과 함께 작물의 생물학적 반응뿐 아니라 경제모형이 결합된 연구는 많지 않다. 본 연구에서는 기상이변과 작물모형, 경제모형을 결기상합하여 미국의 최대 옥수수 생산지역의 옥수수 생산량을 예측하고 생산량의 변화가 개발도상국의 식량안보에 어떤 영향을 줄 것인가를 예측하였다.

기상이변 시나리오를 재현하기 위해 미국 NOAA의 NCDC에서 미국의 폭염 발생 연도의 정보를 획득하고 해당 연도에 대하여 미국 전역의 기상관측소에서 6월부터 8월까지의 월별 일 기상자료 (최고 및 최저기온, 강수량)를 수집하였으며 기준연도 (1950-2000)에 산술평균 방법으로 폭염/가뭄 정보를 적용했다. 미래 시나리오 (2050)는 CGIAR의 CCAFS에서 CO_2 emission scenario에 따라 A1B와 B1, 전지구 모형에 따라 CSIRO-MK 3와 MIROC 3.2를 다운로드하였으며, 해상도는 5 arc-minutes (적도에서 10km)이다. 작물모형 (CERES-Maize)으로부터 출력된 옥수수의 생물리학적 결과는 경제모형의 단위 (FPU)로 다시 정리되어 사회경제, 정책과 농업생산을 예측하기 위해 글로벌 경제모형 (IMPACT2)에 입력되었다.

작물모형에서 기준연도에 비해 미국 폭염과 가뭄에 의한 옥수수 생산량은 29% 감소할 것으로 예측되었다. 미래 시나리오 B1의 CSIRO-MK 3과 MIROC 3.2에서는 36% 감소할 것으로 예측되었으며, A1B의 CSIRO-MK 3에서는 38%, MIROC 3.2에서는 58% 감소할 것으로 나타났다. 미국의 기상이변으로 인한 옥수수 생산량의 감소는 전세계 옥수수 시장에 부정적 영향을 끼칠 것으로 예상되면서 세계 옥수수 소비의 감소로 이어질 것으로 예측되었다. 사하라 사막 이남 아프리카 (SSA)의 나라들에서 가장 많은 기아인구가 발생하고 그 외 남아시아와 라틴 아메리카, Caribbean 지역의 나라들에서 기아와 함께 식량 불안이 증가할 것으로 나타났다. 옥수수를 매일 섭취하는 사람들은 옥수수 생산량 감소에서 비롯된 옥수수 소비 감소에 즉각적으로 반응하지 못함으로써 영양불균형에 처하는 등 식량수급의 불안정은 이러한 개발도상국 지역에서 계속 악화될 것으로 나타났다.

References

Anderson, G. B., and M. L. Bell, 2011: Heat waves in the United States: mortality risk during heat waves and effect modification by heat wave characteristics in 43 U.S. communities. *Environmental Health Perspect* **119**(2) 210–8.

CCAFS., 2013: GCM downscaled GCM Data Portal. Available at: http://www.ccafs-climate.org

Chung, U., L. Mack, J. I. Yun, and S.-H. Kim, 2011: Predicting the timing of cherry blossoms in Washington, DC and mid-Atlantic states in response to climate change. *PLoS ONE* **6**(11): e27439. doi:10.1371/journal.pone.0027439

Ciais, P., M. Reichstein, N. Viovy, A. Granier, J. Ogee, V. Allard, M. Aubinet, N. Buchmann, C. Bernhofer, A. Carrara, F. Chevallier, N. De Noblet, A. D. Friend, P. Friedlingstein, T. Grunwald, B. Heinesch, P. Keronen, A. Knohl, G. Krinner, D. Loustau, G. Manca, G. Matteucci, F. Miglietta, J. M. Ourcival, D. Papale, K. Pilegaard, S. Rambal, G. Seufert, J. F. Soussana, M. J. Sanz, E. D. Schulze, T. Vesala, and R. Valentini, 2005: Europe-wide reduction in primary productivity caused by the heat and drought in 2003: *Nature* **437**, 529–533.

Dowswell, C. R., R. L. Paliwal, and R. P. Cantrell, 1996: *'Maize in the Third World'.* Westview Press.

Elliott, J., M. Glotter, N. Best, K. Boote, J. Jones, C. Rosenzweig, L. A. Smith, and I. Foster, 2013: *Predicting agricultural impacts of large-scale drought: 2012 and the case for better modeling. - more details needed for this reference.* The Center for Robust Decision Making on Climate and Energy Policy No.13-01, http://dx.doi.org/10.6084/m9.figshare.501263.

FAO., 2012a: *Food Outlook.* Food and Agriculture Organization, Rome.

FAO., 2012b: *Food Outlook: Global Market Analysis - May 2012.* Food and Agriculture Organization, Rome.

FAO., 2012c: Food Outlook: *Global Market Analysis - November 2012.* Food and Agriculture Organization, Rome.

FAOSTAT., 2013: *Statistical Databases on Global Food Production and Trade.* Food and Agriculture Organization, Rome.

Gbegbelegbe, S., D. Cammarano, S. Asseng, R. Robertson, U. Chung, M. Adam, O. Abdalla, T. Payne, M. Reynolds, B. Shiferaw, and G. Nelson, 2014: *Baseline simulations for global wheat production: capturing genetic diversity of cultivars.* (submitted for publication)

Gordon, H., S. O'Farrell, M. Collier, M. Dix, L. Rotstayn, E. Kowalczyk, T. Hirst, and I. Watterson, 2010: *The CSIRO Mk3. 5 climate model.* Centre for Australian Weather and Climate Research, CSIRO and the Bureau of Meteorology.

Hajat, S., B. Armstrong, M. Baccini, A. Biggeri, L. Bisanti, A. Russo, A. Paldy, B. Menne, and T. Kosatsky, 2006: Impact of high temperatures on mortality: is there an added heat wave effect? *Epidemiology* (Cambridge, Mass.) **17**, 632 – 8.

Hartkamp, A. D., J. W. White, A. Rodriguez, M. Banziger, G. Srinivasan, G. Granados, and J. Crossa, 2000: *Maize production environments revisited: a GIS-based approach.* CIMMYT, Mexico, D.F. 33p.

Hijmans, R. J., S. E. Cameron, J. L. Parra, P. G. Jones, and A. Jarvis, 2005: Very high resolution interpolated climate surfaces for global land areas. *International Journal of Climatology* **25**, 1965 – 1978.

Hoogenboom G., J. W. Jones, P. W. Wilkens, C. H. Porter, L. A. Hunt, K. Boote, U. Singh, O. Uryasev, J. I. Lizaso, and A. J. Gijsman, 2010: *Decision Support System for Agrotechnology Transfer (DSSAT) Version 4.5.0.43 [CD-ROM]*. University of Hawaii, Honolulu, Hawaii.

Jones, J. W., G. Hoogenboom, C. H. Porter, K. J. Boote, W. D. Batchelor, L. A. Hunt, P. W. Wilkens, U. Singh, A. J. Gijsman, and J. T. Ritchie. 2003: DSSAT Cropping System Model. *European Journal of Agronomy* **18,** 235-265.

Knutti, R., M .R. Allen, P. Friedlingstein, J. M. Gregory, G. C. Hegerl, G. A. Meehl, M. Meinshausen, J. M. Murphy, G.-K. Plattner, S. C. B. Raper, T. F. Stocker, P. A. Stott, H. Teng, and T. M. L. Wigley, 2008: A review of uncertainties in global temperature projections over the twenty-first century. *Journal of Climate* **21**, 2651 – 2663.

Lobell, D. B., G. L. Hammer, G. McLean, C. Messina, M. J. Roberts, and W. Schlenker, 2013: The critical role of extreme heat for maize production in the United States. *Nature Climate Change* **3**, 1 – 5.

Lott, N., and T. Ross, 2005: *1.2 Tracking and evaluating U.S. billion dollar weather disasters*, 1980-2005 Neal Lott *, Tom Ross * NOAA's National Climatic Data Center, Asheville, North Carolina.

Meehl, G. A., and C. Tebaldi, 2004: More intense, more frequent, and longer lasting heat waves in the 21st Century. *Science* **305**, 994 – 997.

Nakicenovic, N., J. Alcamo, G. Davis, B. D. Vries, J. Fenhann, S. Gaffin, K. Gregory, and A. Grubler, 2000: *Special report on emissions scenarios : a special report of Working Group III of the Intergovernmental Panel on Climate Change.* Cambridge University Press, Cambridge.

Nelson, G. C., M. W. Rosegrant, A. Palazzo, I. Gray, C. Ingersoll, R. Robertson, S. Tokgoz, T. Zhu, n.d. Gerald C. Nelson, Mark W. Rosegrant, Amanda Palazzo, Ian Gray, Christina Ingersoll, Richard Robertson, Simla Tokgoz, Tingju Zhu, Timothy B. Sulser, Claudia Ringler, Siwa Msangi, and Liangzhi You., 2010: Food Security, Farming, and Climate Change to 2050:Scenarios, Results, Policy Options: DOI: 10.2499/9780896291867

Nuttall, J., S. Brady, J. Brand, G. O. Leary, and G. J. Fitzgerald, 2013: Heat waves and wheat growth under a future climate. *Australian Society of Agronomy.* Available at: http://www.regional.org.au/au/asa/2012/climate-change/8085_nuttalljg.htm accessed 29 September 2013

Piesse J., and C. Thirtle, 2009: Three bubbles and a panic: An explanatory review of recent food commodity price events. *Food Policy*, **34**(2), April 2009, Pages 119 – 129.

Robinson, P. J., 2001: On the definition of a heat wave. *Journal of Applied Meteorology* **40**, 762–775.
Shaw, R. H., 1988: *Climate requirement. In: Sprague,* G. H., Dudley, J.W. (ed.) 'Corn and corn improveent. CAB Direct.
Shiferaw, B., B. Prasanna, J. Hellin, and M. Banziger. 2011: Feeding a hungry world: past successes and future challenges to global food security in maize. *Food Security* **3**: 307-327.
Shiogama, H., S. Emori, K. Takahashi, T. Nagashima, T. Ogura, T. Nozawa, and T. Takemura, 2010: Emission scenario dependency of precipitation on global warming in the MIROC3.2 model. *Journal of Climate* **23**, 2404–2417.
Smoyer, K. E., 1998: A comparative analysis of heat waves and associated mortality in St. Louis, Missouri –1980 and 1995. *International Journal of Biometeorology* **42**, 44–50.
USDA., 2007: *United States Summary and State data.* United States Department of Agriculture.
USDA., 2012. U.S. Drought 2012. *Farm and Food Impacts.* United States Department of Agriculture, Washington DC.
USDA., 2012a: Projected world and USA Supply and Use of Agricultural Commodities - Database - May 2012, United States Department of Agriculture.
USDA., 2012b: *World Agricultural Supply and Demand Estimates - July 2012.* United States Department of Agriculture, Washington DC.
USDA., 2012c: *World Agricultural Supply and Semand Estimates - August 2012.* United States Department of Agriculture, Washington DC.
USDA., 2012d: *Projected world and USA Supply and Use of Agricultural Commodities - Database - August 2012,* United States Department of Agriculture.
USDA., 2013: *U.S. Drought 2012: Farm and Food impacts.* United States Department of Agriculture, Washington DC.
USDA., 2013a: *Crop Production 2012 Summary*. United States Department of Agriculture.
USDA., 2013b. *Projected world and USA Supply and Use of Agricultural Commodities - Database - September 2013.*
WASDE., 2012: May WASDE Report 2012/13 Outlook & Market Impacts
WASDE., 2014. March 2014 WASDE Report.
Weisskopf, M. G., H. A. Anderson, S. Foldy, L. P. Hanrahan, K. Blair, T. J. Török, and P. D. Rumm, 2002: Heat wave morbidity and mortality, Milwaukee, Wis, 1999 vs 1995: an improved response? *American Journal of Public Health* **92**, 830–3.
WorldClim Global Climate Data Center, 2013 Available at: http://www.worldclim.org accessed 29 September 2013.
Yano Y., D. Blandford and Y. Surry, 2010: *Do Current U.S. Ethanol Policies Make Sense?* Policy Issue.
Zhao, G., B. A. Bryan, D. King, Z. Luo, E. Wang, U. Bende-Michl, X. Song, Q. Yu, 2013: Large-scale, high-resolution agricultural systems modeling using a hybrid approach combining grid computing and parallel processing. *Environmental Modelling & Software* **41**, 231–238.