

Takle, Eugene S. et al.

Article

US food security and climate change: Agricultural futures

Economics: The Open-Access, Open-Assessment E-Journal

Provided in Cooperation with:

Kiel Institute for the World Economy – Leibniz Center for Research on Global Economic Challenges

Suggested Citation: Takle, Eugene S. et al. (2013) : US food security and climate change: Agricultural futures, Economics: The Open-Access, Open-Assessment E-Journal, ISSN 1864-6042, Kiel Institute for the World Economy (IfW), Kiel, Vol. 7, Iss. 2013-34, pp. 1-41,
<https://doi.org/10.5018/economics-ejournal.ja.2013-34>

This Version is available at:

<https://hdl.handle.net/10419/78706>

Standard-Nutzungsbedingungen:

Die Dokumente auf EconStor dürfen zu eigenen wissenschaftlichen Zwecken und zum Privatgebrauch gespeichert und kopiert werden.

Sie dürfen die Dokumente nicht für öffentliche oder kommerzielle Zwecke vervielfältigen, öffentlich ausstellen, öffentlich zugänglich machen, vertreiben oder anderweitig nutzen.

Sofern die Verfasser die Dokumente unter Open-Content-Lizenzen (insbesondere CC-Lizenzen) zur Verfügung gestellt haben sollten, gelten abweichend von diesen Nutzungsbedingungen die in der dort genannten Lizenz gewährten Nutzungsrechte.

Terms of use:

Documents in EconStor may be saved and copied for your personal and scholarly purposes.

You are not to copy documents for public or commercial purposes, to exhibit the documents publicly, to make them publicly available on the internet, or to distribute or otherwise use the documents in public.

If the documents have been made available under an Open Content Licence (especially Creative Commons Licences), you may exercise further usage rights as specified in the indicated licence.



<http://creativecommons.org/licenses/by/3.0/>

US Food Security and Climate Change: Agricultural Futures

*Eugene S. Takle, David Gustafson, Roger Beachy,
Gerald C. Nelson, Daniel Mason-D'Croz, and Amanda Palazzo*

Abstract

Agreement is developing among agricultural scientists on the emerging inability of agriculture to meet growing global food demands. Changes in trends of weather conditions projected by global climate models will challenge physiological limits of crops and exacerbate the global food challenge by 2050. These climate- and constraint-driven crop production challenges are interconnected within a complex global economy, where diverse factors add to price volatility and food scarcity. Our scenarios of the impact of climate change on food security through 2050 for internationally traded crops show that climate change does not threaten near-term US food security due to the availability of adaptation strategies. However, as climate continues to change beyond 2050 current adaptation measures will not be sufficient to meet growing food demand. Climate scenarios for higher-level carbon emissions exacerbate the food shortfall, although uncertainty in projections of future precipitation is a limitation to impact studies.

Published in Special Issue [Food Security and Climate Change](#)

JEL Q17 Q54

Keywords Climate change; food security; crop production; United States

Authors

Eugene S. Takle, ✉ Iowa State University, Ames, IA, USA, gstakle@iastate.edu

David Gustafson, ILSI Research Foundation, Washington, DC, USA

Roger Beachy, Danforth Plant Science Research Center, St. Louis, Missouri, USA

Gerald C. Nelson, International Food Policy Research Institute, Washington, DC, USA

Daniel Mason-D'Croz, International Food Policy Research Institute, Washington, DC, USA

Amanda Palazzo, International Institute of Applied Systems Analysis, IIASA, Laxenburg, Austria

Citation Eugene S. Takle, David Gustafson, Roger Beachy, Gerald C. Nelson, Daniel Mason-D'Croz, and Amanda Palazzo (2013). US Food Security and Climate Change: Agricultural Futures. *Economics: The Open-Access, Open-Assessment E-Journal*, Vol. 7, 2013-34. <http://dx.doi.org/10.5018/economics-ejournal.ja.2013-34>

Received February 19, 2013 Published as Economics Discussion Paper February 22, 2013

Revised July 19, 2013 Accepted August 7, 2013 Published August 13, 2013

© Author(s) 2013. Licensed under the [Creative Commons License - Attribution 3.0](#)

1 Introduction

World population will be approximately 7.6 billion by 2020, according to both the UN and the US Census Bureau. By mid-century, population will likely exceed 9 billion, leading to a predicted doubling of crop demand, when combined with expected changes in diets and the increasing use of crops to displace fossil fuels. However, total investments in agriculture have not risen as fast as demand, contributing to a drop in the rate of global crop yield gains (Pardey and Alston, 2010). For the second time in less than four years, many countries have again experienced rapid price increases for several basic food commodities. Numerous factors explain these price spikes (including petroleum price swings), but the increased frequency of extreme and unpredictable weather events has played a significant role, in a manner consistent with the changes predicted by global climate models (Hatfield et al., 2011). Specific examples of catastrophic crop losses and their weather-related causes during 2011 include: Australia (\$6 billion, flooding), Pakistan (\$5 billion, flooding), and Russia (\$5 billion, extreme heat). High daily minimum temperatures, such as those occurred in the Midwestern US during 2010, 2011, and 2012, have been cited as contributing to yield loss (Peters et al., 1971; Hamlin, 2012).

A growing number of agricultural scientists now agree that agriculture is beginning to encounter global limitations to its ability to meet growing demand, especially for staple crops that are not receiving the same private investment that commodity crops attract (such as corn and soybeans). Besides arable land, probably the most challenging of these physical constraints is the availability of freshwater, and this limitation is expected to intensify in key parts of the eastern hemisphere, particularly in India and sub-Saharan Africa.

These climate- and constraint-driven crop production challenges are playing out in an increasingly inter-connected and complex global economy, in which a number of diverse factors add to price volatility and food scarcity. Prices for food have become closely linked to those for petroleum and have increased during the past decade, after having generally fallen (in real terms) during the previous 50 years. In addition to such economic concerns, the environmental footprint of agriculture is also receiving increased scrutiny,

especially its reliance on inorganic fertilizers and impacts on water quality and biodiversity.

Against this backdrop of multiple challenges to global agriculture, the present report projects the impact of climate change on food security through the year 2050. Yield reductions below expectations for well-managed crops in any given year are largely due to less-than-favorable weather conditions during the growing season. Global climate change caused by increasing accumulations of heat-trapping gases is expected to create climate conditions outside the range of observations over the last hundred years. We use results of widely accepted global climate models to project changes in climate over the next 40 years to assess their impacts on yields, both directly through crop-climate interactions and indirectly through prices, income, and international trade. We focus on five crops that are widely traded through international markets and also consumed directly as human food or indirectly through cooking oil or feed for animals that produce meat, milk, and eggs. We do not address contributions to food security from locally grown fruits and vegetables and lower-volume components of international commodity markets. In our modeling framework, producers of these commodity crops protect their income by responding to price signals through changes crops planted and other management strategies.

The first part of this paper summarizes the underlying natural resources available in USA. The second part reviews the USA-specific outcomes of a set of scenarios for the future of global food security in the context of climate change based on IMPACT model runs from July 2011.

Next, integrated assessment models (IAMs) simulate the interactions between humans and their surroundings, including industrial activities, transportation, agriculture and other land uses and estimate the emissions of the various greenhouse gases. The emissions simulation results of the IAMs are made available to the GCM models as inputs that alter atmospheric chemistry. The end result is a set of estimates of precipitation and temperature values around the globe often at 2-degree intervals (about 200 km at the equator) for most models. Periodically, the Intergovernmental Panel on Climate Change (IPCC 2007) issues assessment reports on the state of our understanding of climate science and interactions with the oceans, land and human activities. Each IPCC report (the fourth assessment report issued in

2007 is sometimes referred to as AR4) is based on an updated set of GCM model results. The study reported herein is based on the AR4 GCMs.

Our study does not include effects of ozone, increased pest and disease pressure nor increases in extreme weather events. Although we do not include effects on livestock or fruits and vegetables, the recent summary report of Walthall et al., (2012) provides evidence of production challenges in these areas by mid-Century that are consistent with the results for commodity crops we describe herein.

2 Impacts of Climate Change

In the Fourth Assessment Report of the Intergovernmental Panel on Climate Change, Working Group 1 reports that “climate is often defined as 'average weather'. Climate is usually described in terms of the mean and variability of temperature, precipitation and wind over a period of time, ranging from months to millions of years (the classical period is 30 years)” (Le Treut et al., 2007, p.96).

The unimpeded growth of greenhouse gas emissions is raising global average temperatures. The consequences include changes in precipitation patterns, more extreme weather events, and shifting seasons. The accelerating pace of climate change, combined with global population and income growth, threatens food security everywhere.

Agriculture is vulnerable to climate change in a number of dimensions. Higher temperature and humidity eventually reduce yields of agricultural crops (Lobell and Gourdji, 2012; Lobell et al., 2013) and tend to encourage weed and pest proliferation (Oerke, 2006). Greater variations in precipitation patterns increase the likelihood of short-run crop failures and long-run production declines. Higher CO₂ concentrations favor weeds more than agricultural crops. Although there might be near-term gains in some crops in some regions of the world, the overall impacts of climate change on agriculture are expected to be negative, threatening global food security. The impacts are:

- Direct, on crops and livestock productivity domestically

- Indirect, on availability/prices of food domestically and in international markets
- Indirect, on income from agricultural production both at the farm and country levels

While the general consequences of climate change are becoming increasingly well known, great uncertainty remains about how climate change effects will play out in specific locations. To quantify uncertainty in future climate we use results from four global climate (or general circulation) models (GCMs) that numerically simulate the physics and chemistry of the atmosphere and its interactions with oceans and the land surface. These models provide future climate scenarios consistent with scenarios of future human contributions to concentrations of greenhouse gases (carbon dioxide, methane and nitrous oxide are the most important). All models use the same basic set of physics equations, but each has slightly different ways of representing land surface, cloud, and precipitation processes. Over multi-decadal time periods used in this application, the accumulated differences are large but still well within plausible limits. Since all are consistent with the basic physics of climatic conditions, we interpret these to be different possible realizations of the climate of mid-21st Century. By using all four models to provide input to crop models we create an ensemble of possible yields consistent with this ensemble of possible climates. The range of yields produced by these four climate models can be interpreted as one (maybe not the only one) measure of uncertainty in future yields due to uncertainty (but within the range of physical consistency) in climate model representation of the mid-21st century.

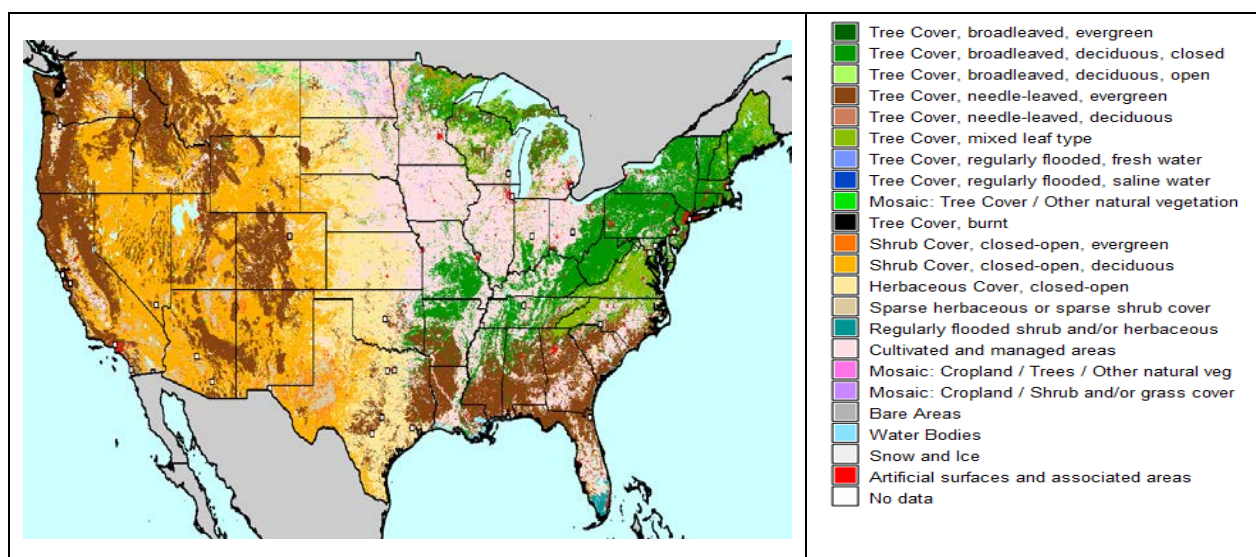
Changes in temperature and precipitation between 2000 and 2050 as projected by four Global Climate Models (GCMs) (CNRM-CM3 France, CSIRO-MK3 Australia, DCHM5 Germany, and MIROC3.2 Japan), each using the A1B scenario, were used to simulate the change in US climate. These were chosen because their output datasets include the daily maximum and minimum temperatures required by the IMPACT modeling suite and they span the ranges of variability exhibited by the entire suite of models in the IPCC AR4 archive.

Substantial differences among these model results exist despite the fact that all models use the same widely accepted laws of physics to simulate large-scale motions and thermal processes. Differences in how models account for features of

the atmosphere and surfaces smaller than about 200 km (principally clouds and surface interactions) account for differences in temperature and precipitation. Each model's smaller scale particulars eventually interact with the global flow to create different regional climate features among the models.

Agricultural production is dependent on the availability of land that has sufficient water, soil resources, low enough slope that allows for agronomic practices, and an adequate growing season. Figure 1 shows land cover as of 2000.

Figure 1. Land cover, 2000



Source: GLC2000 (JRC 2000).

2.1 Agriculture Overview

Tables 1 and 2 show key agricultural commodities in terms of area harvested and value of the harvest for the period centered around 2006–2008.

Shown in Figures 2–6 are the estimated yield and growing areas for five key US crops: cotton, maize, rice, soybeans, and wheat. These figures represent the results of the Spatial Production Allocation Model (SPAM) data

Table 1. Harvest area of leading agricultural commodities, average of 2006–2008

Rank	Crop	% of total	Area harvested (000 hectares)
1	Maize	32.1	31,809
2	Soybeans	29.0	28,786
3	Wheat	20.9	20,707
4	Seed cotton	4.2	4,175
5	Sorghum	2.6	2,563
6	Barley	1.4	1,379
7	Rice, paddy	1.2	1,153
8	Sunflower seed	0.8	833
9	Beans, dry	0.6	602
10	Oats	0.6	591
	Total	100.00%	99,119

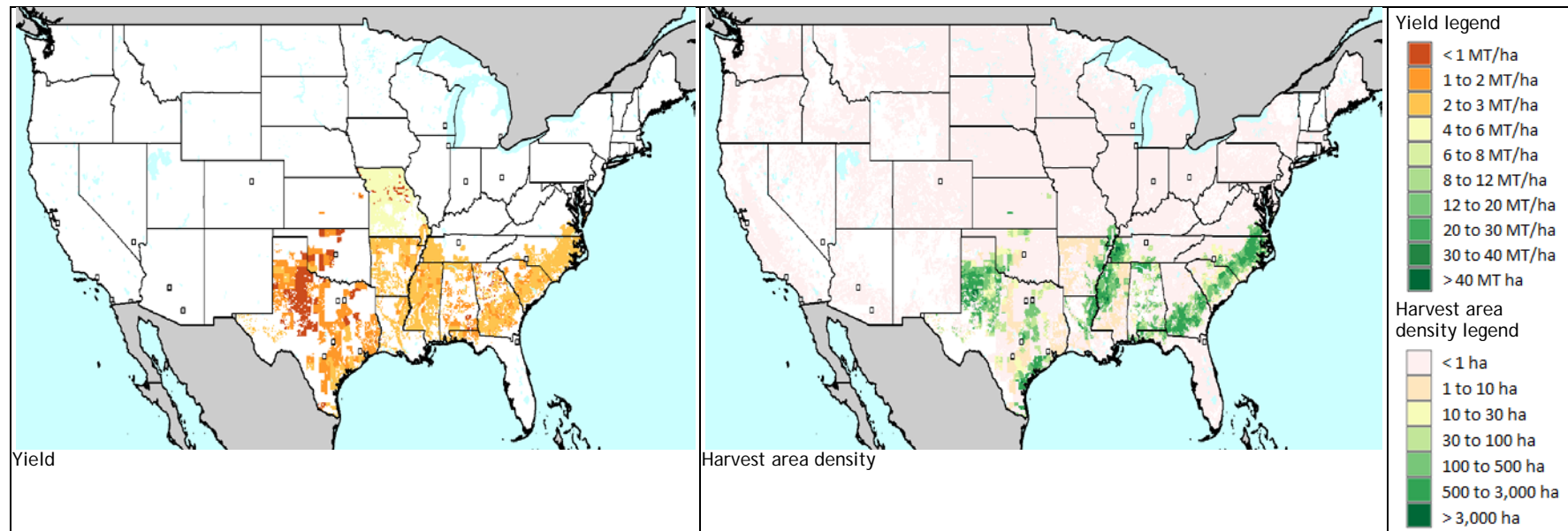
Source: FAOSTAT (FAO 2010)

Table 2. Value of production for leading agricultural commodities, average of 2006–2008

Rank	Crop	% of total	Value of Production (billion US\$)
1	Maize	28.3	35.5
2	Soybeans	17.3	21.6
3	Tomatoes	8.7	10.9
4	Wheat	7.5	9.4
5	Seed cotton	4.7	5.9
6	Almonds, with shell	3.1	3.92
7	Grapes	2.7	3.41
8	Potatoes	2.5	3.13
9	Apples	1.8	2.22
10	Rice, paddy	1.6	2.06
	Total	100.0	125.19

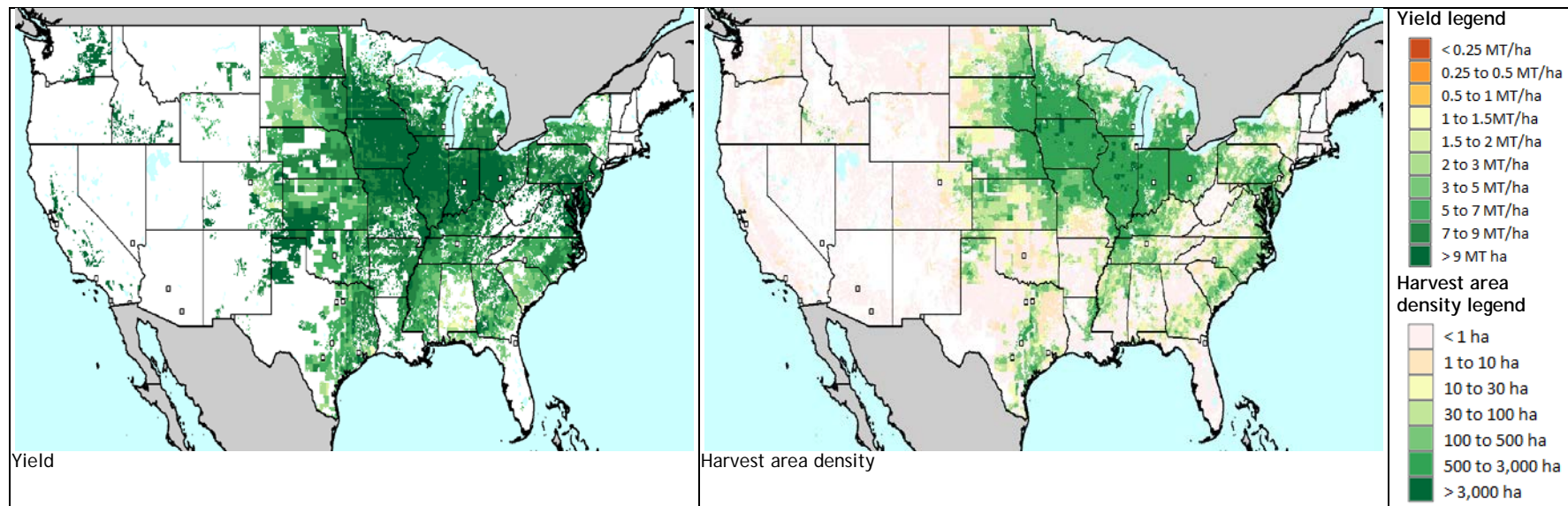
Source: FAOSTAT (FAO 2010)

Figure 2. 2000 Yield and harvest area density for main crops: rainfed cotton



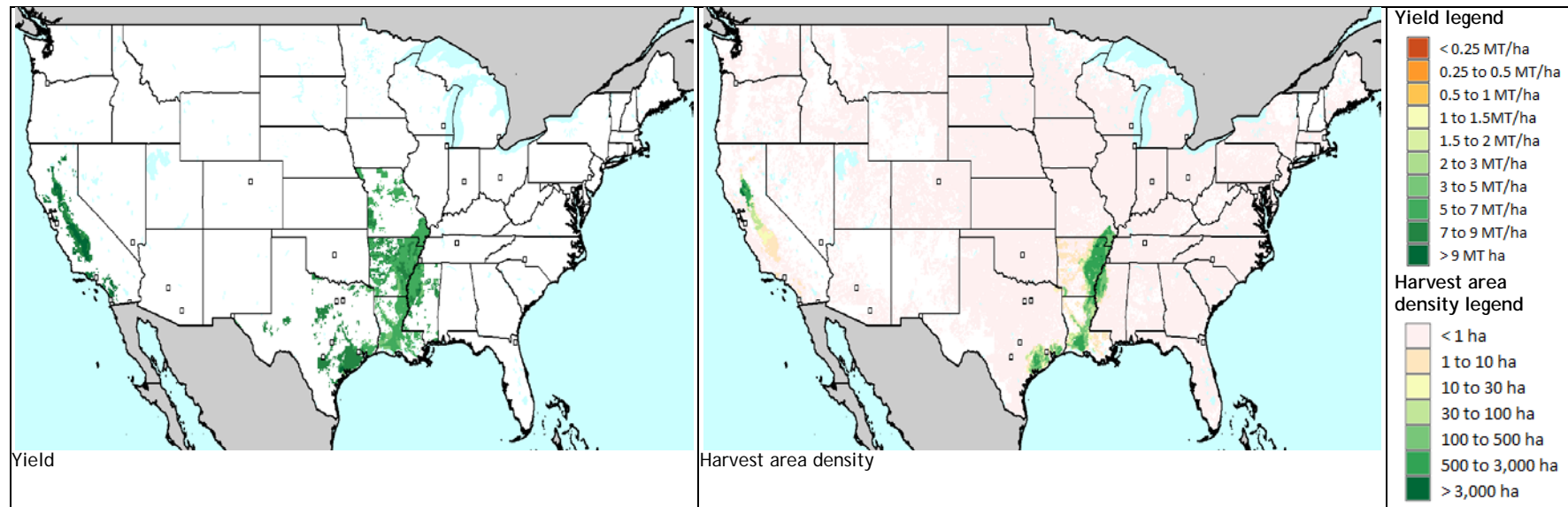
Source: SPAM Dataset (You et al., 2009)

Figure 3. 2000 Yield and harvest area density for main crops: rainfed maize



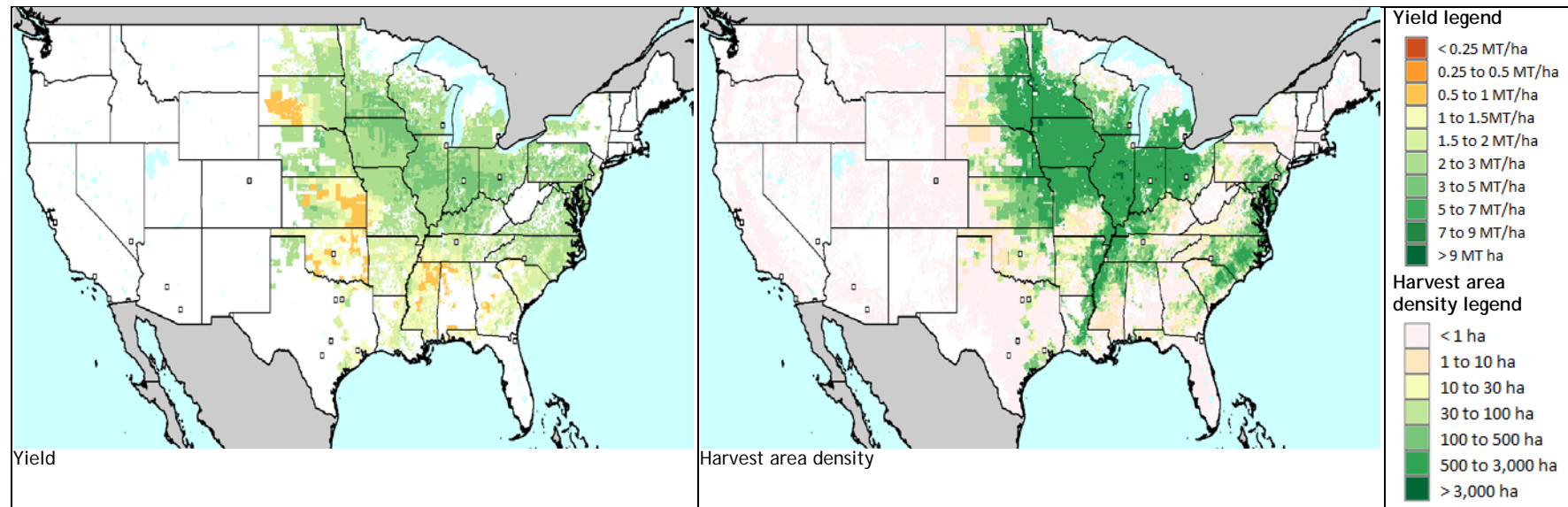
Source: SPAM Dataset (You et al., 2009)

Figure 4. 2000 Yield and harvest area density for main crops: irrigated rice



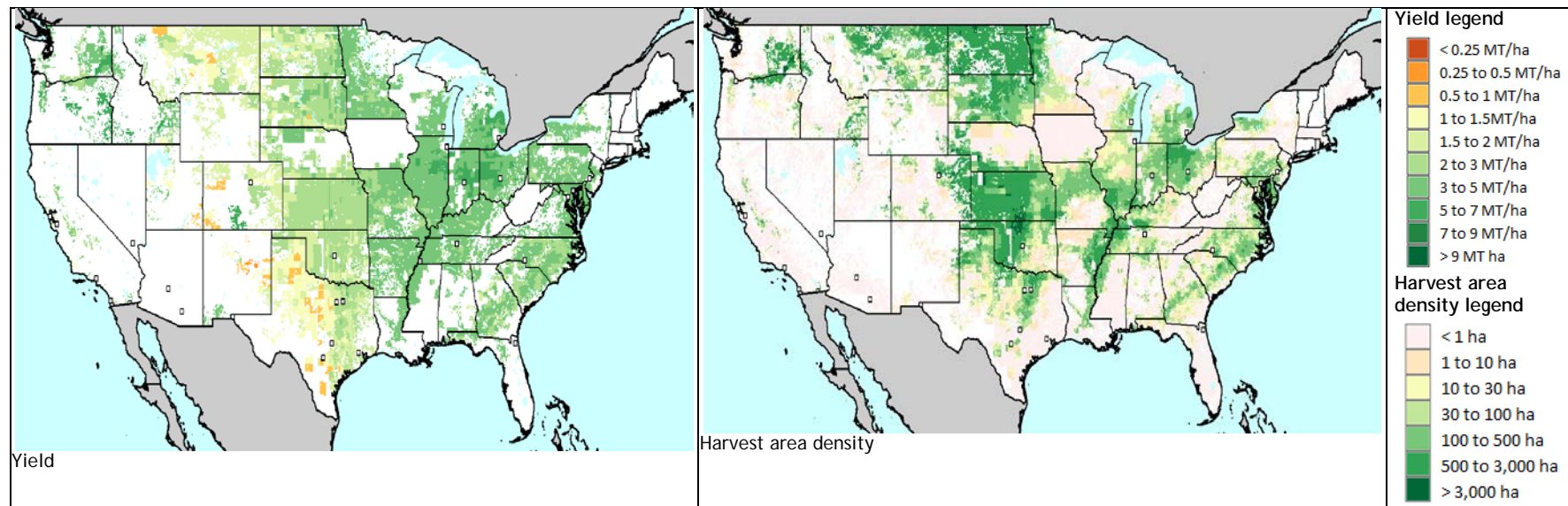
Source: SPAM Dataset (You et al., 2009)

Figure 5. 2000 Yield and harvest area density for main crops: rainfed soybeans



Source: SPAM Dataset (You et al., 2009)

Figure 6. 2000 Yield and harvest area density for main crops: rainfed wheat



Source: SPAM Dataset (You et al., 2009)

set (You et al., 2009), which takes data from international, national, and subnational sources as well as land quality and crop suitability maps and attempts to reconcile them using an entropy method to estimate where the crops are likely grown within a country. This spatial allocation of crop production is used as an input to the IMPACT model, to allow us to correctly assign production from FAO's national statistics to the Food Production Units (FPUs – intersection of national boundary and watershed) within IMPACT. The correct allocation of crops to subnational levels is also essential with respect to climate change, as climatic change has an obvious local effect on agriculture, and better spatial disaggregation will improve the capacity to model climate change's effects on agriculture. Note that the production (MT) for a particular location is the product of the yield (MT/ha) times the area harvested (ha).

3 Scenarios for Adaptation

To better understand the possible vulnerability to climate change, it is necessary to develop plausible scenarios. The Millennium Ecosystem Assessment (2005, Volume 2, Chapter 2) provides a useful definition: “Scenarios are plausible, challenging, and relevant stories about how the future might unfold, which can be told in both words and numbers. Scenarios are not forecasts, projections, predictions, or recommendations. They are about envisioning future pathways and accounting for critical uncertainties” (Raskin et al., 2005).

For this report, combinations of economic and demographic drivers have been selected that collectively result in three pathways – a baseline scenario that is “middle of the road”, a pessimistic scenario that chooses driver combinations that, while plausible, are likely to result in more negative outcomes for human well-being, and an optimistic scenario that is likely to result in improved outcomes relative to the baseline. These three overall scenarios are further qualified by four climate scenarios: plausible changes in climate conditions consistent with future scenarios of greenhouse gas emissions.

3.1 Biophysical Scenarios

This section presents the climate scenarios used in the analysis and the crop physiological response to the changes in climate between 2000 and 2050.

3.1.1 Climate Scenarios

We used downscaled results from 4 GCMs driven by the A1B scenario and additionally the downscaled results from 2 GCMs (ECHAM and MIROC, having the highest and lowest precipitation for the US, respectively) driven by the B1 emissions scenario.

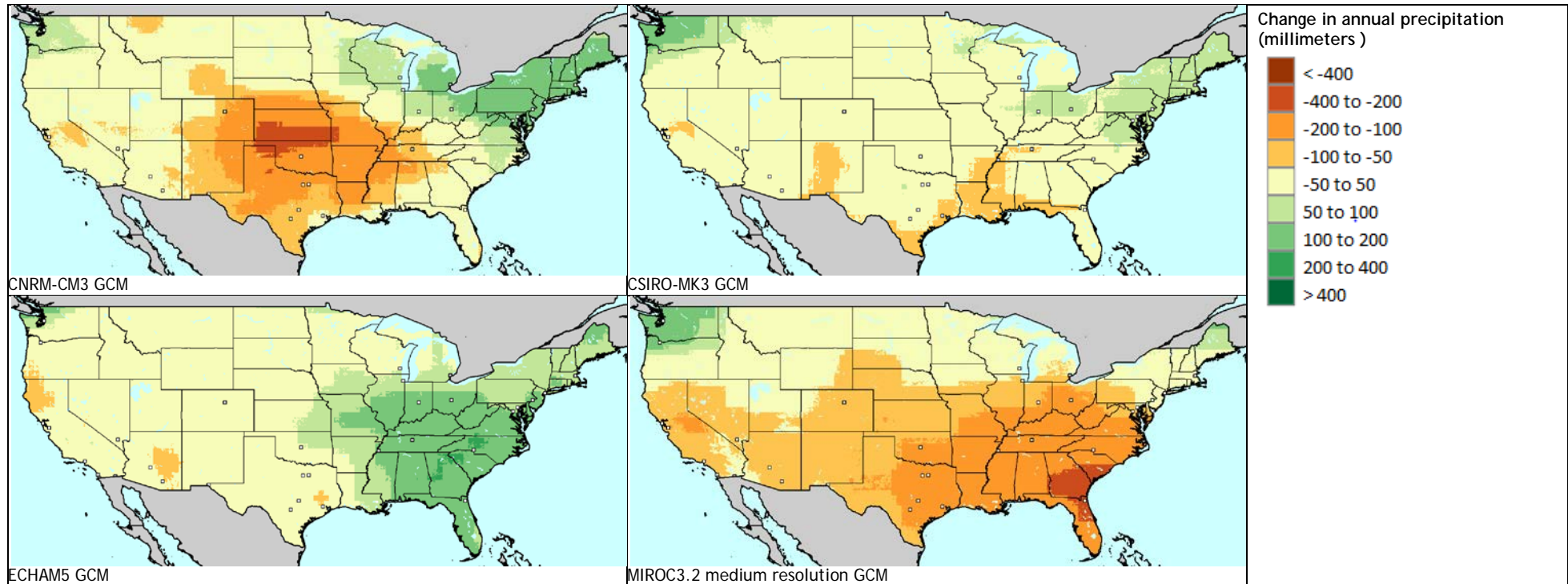
Figure 7 shows precipitation changes for USA under 4 downscaled climate models using the A1B scenario. Global temperatures tend to rise most in mid-continental areas, and this is evident in Figure 7 for the US as well. Precipitation changes in Figure 7 are presented in mm, which is the important metric for crop growth. However, it is important to recognize that the overall climate of the western half of the US is much drier than the eastern half so the percentage change of a 50-mm decline is much higher in the western half than the eastern half. Regardless of plotting method, the western US, particularly the US Southwest, is projected to be impacted by climate change much more than the eastern half.

Figure 8 shows changes in maximum temperature for the month with the highest mean daily maximum temperature.

3.1.2 Exogenous Rate of Crop Yield Gains for Cotton, Maize, and Soybeans

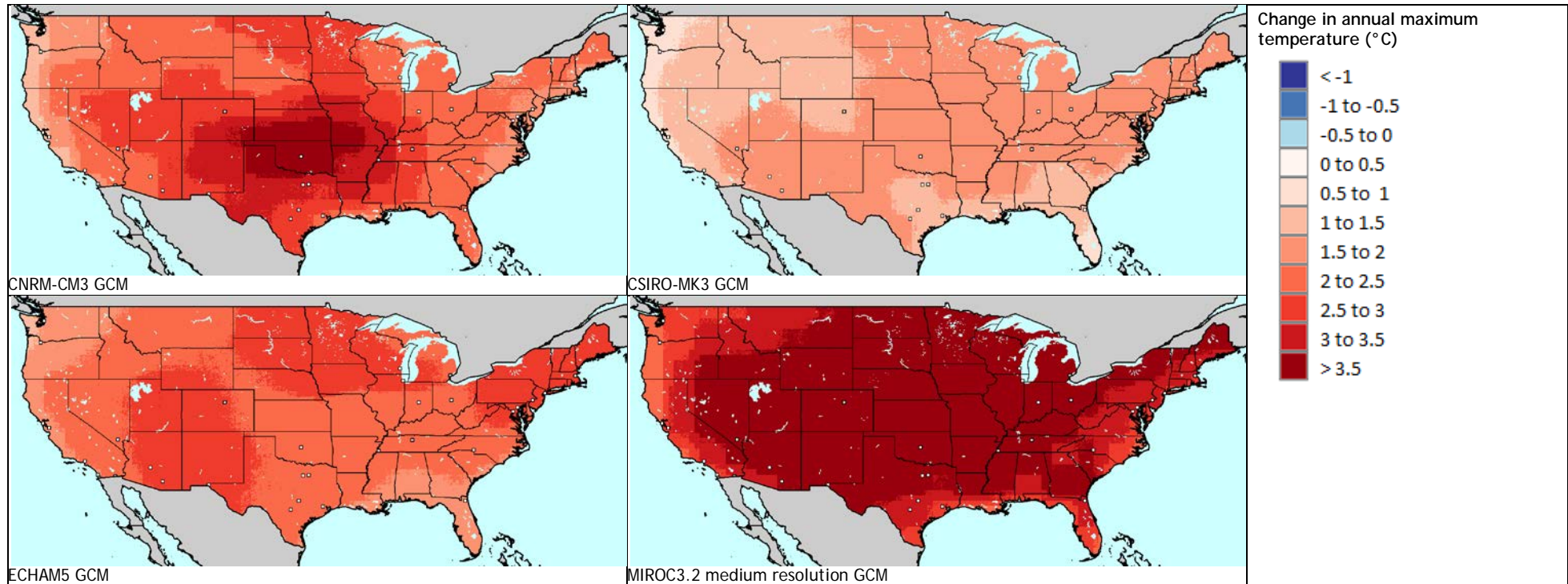
Observed (1860 to present) and projected (2000–2050) yields for cotton, maize, soybean are plotted in Figures 9–11. Extensive private sector resources are being expended to increase the rate of yield gain for three key US crops: cotton, maize, and soybeans. These efforts include advanced breeding techniques, improved agronomic practices, and applications of biotechnology. These yield gains are defined within this paper as “exogenous” rates of yield

Figure 7. Changes in mean annual precipitation for USA between 2000 and 2050 using the A1B scenario (millimeters)



Source: IFPRI calculations based on downscaled climate data available at <http://ccaifs-climate.org/>

Figure 8. Changes in normal annual maximum temperature for USA between 2000 and 2050 using the A1B scenario (°C)



Source: IFPRI calculations based on downscaled climate data available at <http://ccafs-climate.org/>

gain. Cumulatively, these efforts have produced compound annual growth rates in crop yield of 1.53% for cotton, 1.63% for maize, and 1.29% for soybeans over the period 1970 to present (exponential fit in Figures 9–11). Projected future yields are derived from DSSAT for maize and soybeans. For crops like cotton that are not currently being modeled in DSSAT we apply the average climate effects of the commodities that are modeled by DSSAT and apply this average climate effect to the cotton yields.

Figure 9. Observed (1860 to present) and projected (2000–2050) US cotton yields

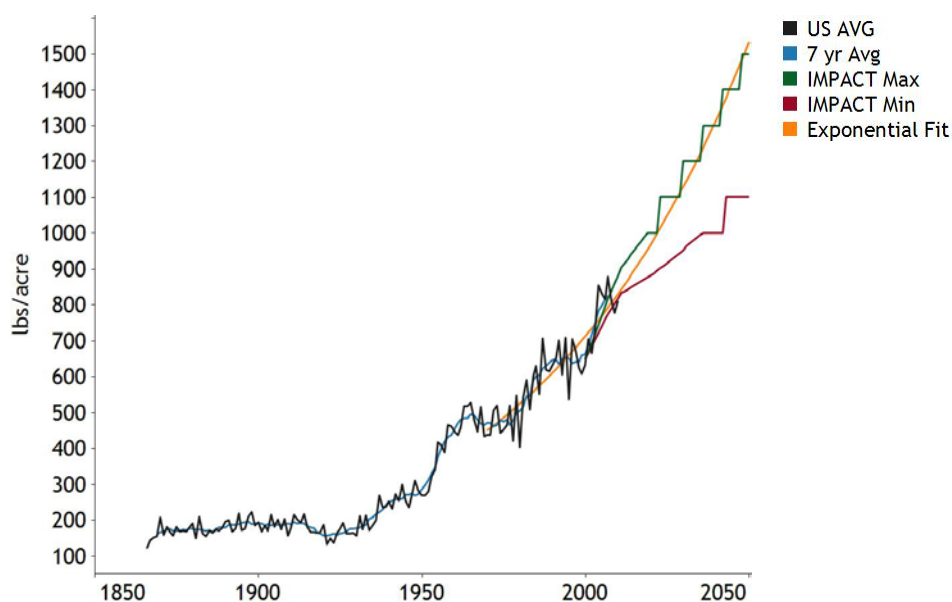


Figure 10. Observed (1860 to present) and projected (2000–2050) US maize yields

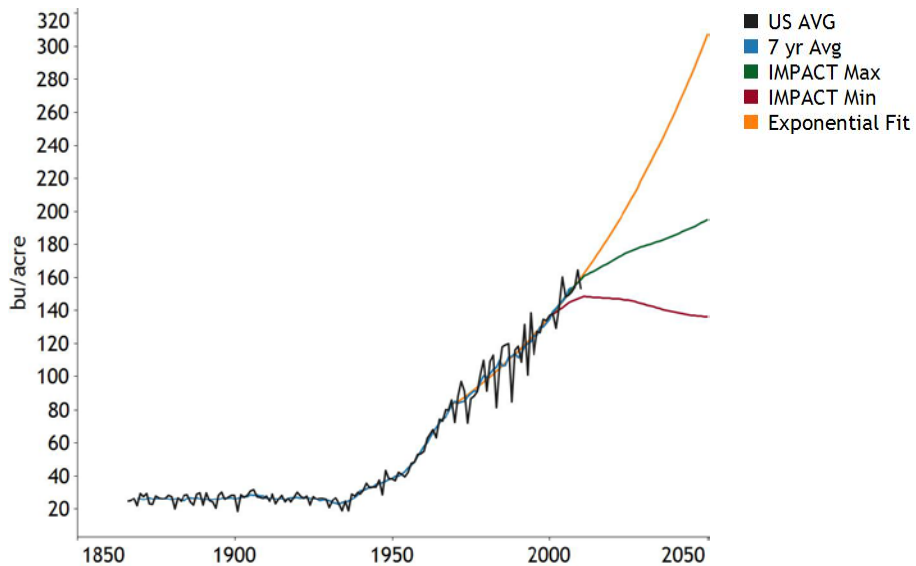
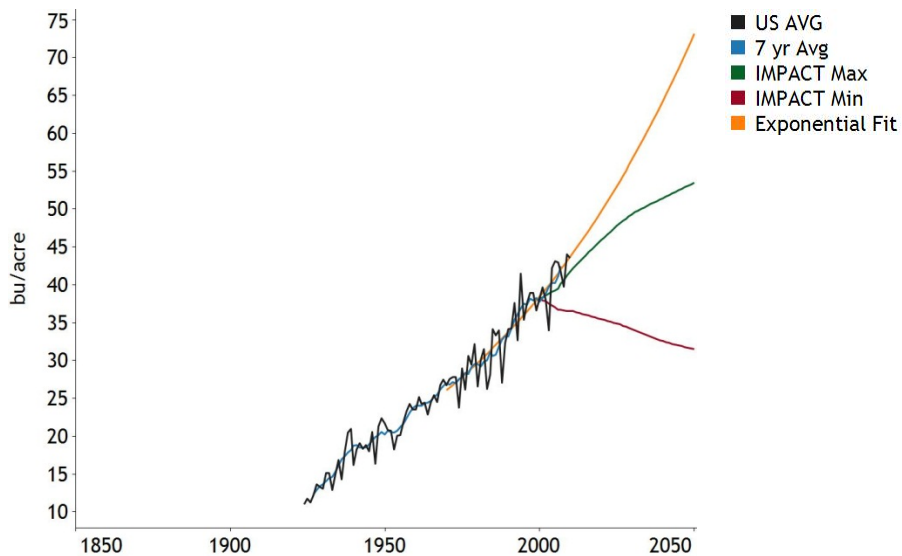


Figure 11. Observed (1930 to present) and projected (2000–2050) US soybean yields



3.1.3 Crop Physiological Response to Climate Change

The DSSAT crop modeling system (Jones et al., 2003) is used to simulate responses of five important crops (rice, wheat, maize, soybeans, and groundnuts) to climate, soil, and nutrient availability, at current locations based on the SPAM dataset of crop location and management techniques (You and Wood 2006). In addition to temperature and precipitation, we also input soil data, assumptions about fertilizer use and planting month, and additional climate data such as days of sunlight each month.

We then repeated the exercise for each of the 4 future climate scenarios for the year 2050. For all locations, variety, soil and management practices were held constant. We then compared the future yield results from DSSAT (using multiple runs for each location) to the current or baseline yield results from DSSAT.

Downscaling climate change as modeled by GCMs to local scale is essential to trying to model the effects of climate change on agriculture. Using the spatial allocation of crops from SPAM, we downscale climate effects to the pixel level and then use DSSAT model crop production at the pixel under the downscaled climate effects in 2050 from four GCMs. These results are then compared to the crop yields that were modeled for the 2000 climate. The output for key crops is mapped in Figures 12–15. Each figure overlays these results on a map to show the changes in crop yield between 2050 and 2000 as a consequence of the different GCMs. Each GCM projects different changes in local temperature and precipitation, and these figures illustrate how these differences can create even greater variability of its effect on agriculture.

Regions already marginally too dry and/or too warm for rain-fed maize (on the southern and western boundaries of high producing areas shown in Figure 3) experience significant yield loss under reduced precipitation (Figure 7) and/or high temperatures (Figure 8) associated with the CNRM and MIROC model results for 2050. For instance, the Canadian model (CNRM) results show significant drying (Figure 7) and much warmer conditions (Figure 8) in southern Kansas and Missouri. Tracing the impact of this pronounced climate change onto yields reveals that the 2050 climate of this region will be unsuitable for maize (Figure 12) and soybean (Figure 14) production if the Canadian model is correct. Other models disagree, however.

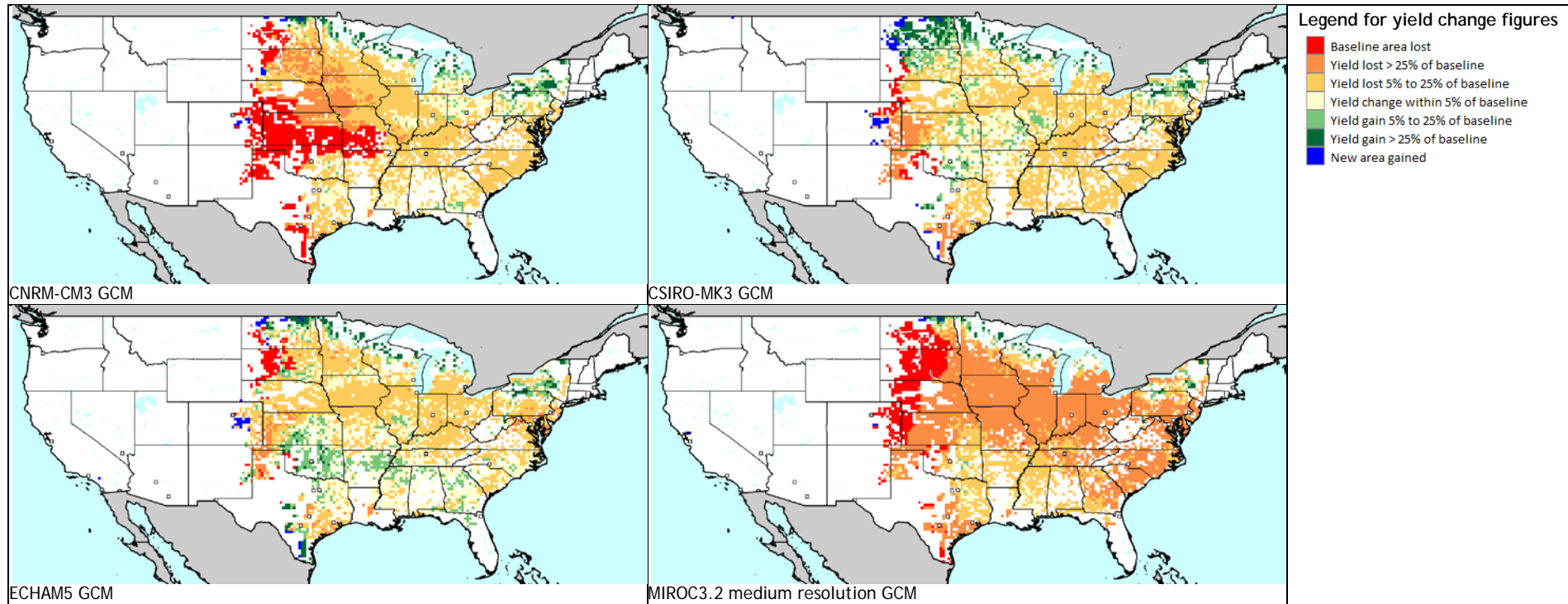
Production of soybean varieties that are more heat-tolerant than other varieties, by contrast, declines somewhat less with increased temperature but substantially increases north of 42°N latitude where warmer 2050 temperatures, combined with high levels of precipitation, create a longer and more favorable growing season. All models are in general agreement with the need to develop heat-tolerant crop varieties.

It is important to observe from these graphs that baseline area lost for most crops (see for example soybean) is at the margins and not the high yielding part of growing area and that production (yield x area harvested) in new areas added compensates for lost production due to lost baseline area. This leads to resilience in total national production under changing climate.

3.1.4 From biophysical scenarios to socioeconomic outcomes: The IMPACT modeling suite

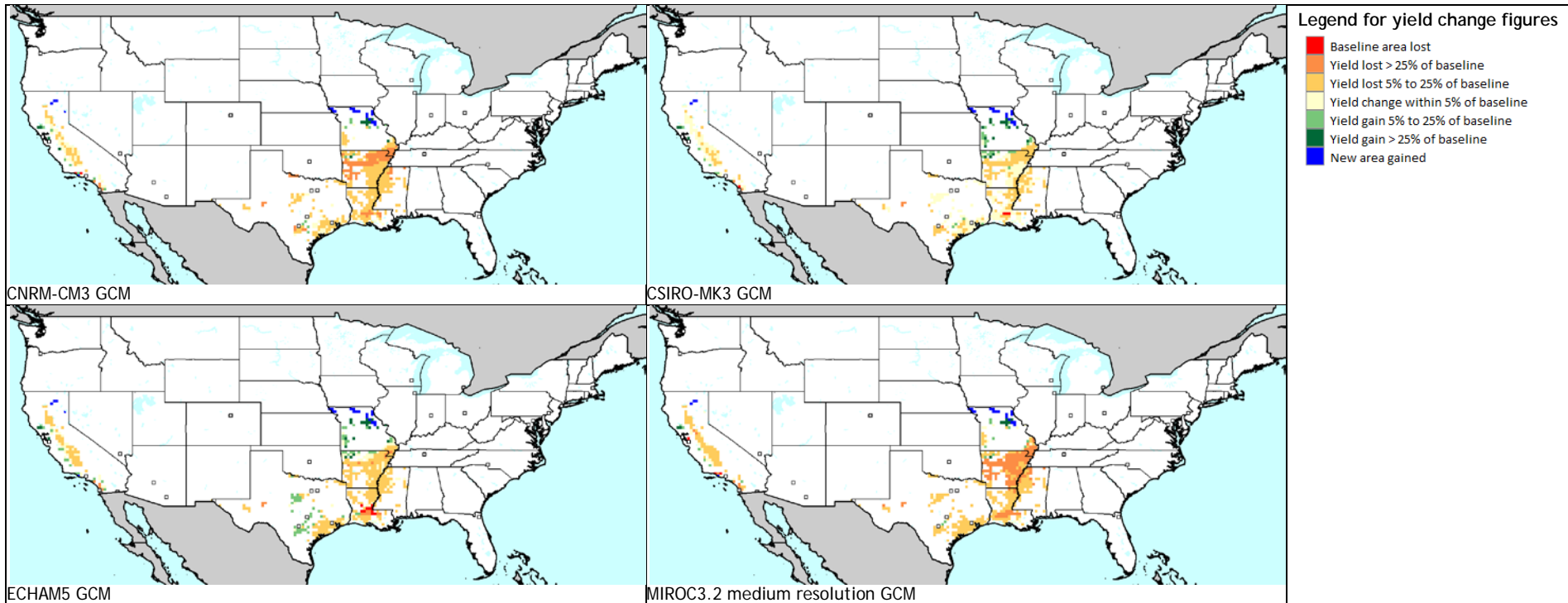
Figure 16 describes the interaction of different drivers within the IMPACT modeling suite. IMPACT is an iterative model that dynamically solves for the world prices that ensure global supply equals global demand (Rosegrant et al., 2012). The schematic shows the interaction of different drivers, both endogenous and exogenous. The orange arrows describe where exogenous inputs define the behavior of the dynamic actors (elasticities) and how they change over time (growth rates). The black arrows show the interplay of dynamic actors in determining equilibrium. To model results for multiple years, the model must be shocked exogenously (growth rates) to force it out of equilibrium, and cause the dynamic drivers within the model (supply, demand, prices) to adjust to create a new equilibrium. The modeling methodology reconciles the limited spatial resolution of macro-level economic models that operate through equilibrium-driven relationships at a national level with detailed models of biophysical processes at high spatial resolution. The DSSAT system is used to simulate responses of five important crops (rice, wheat, maize, soybeans, and groundnuts) to climate, soil, and nutrient availability, at current locations based on the SPAM dataset of crop location and management techniques. This analysis is done at a spatial resolution of 15 arc minutes, or about 30 km at the equator. These results are aggregated up to

Figure 12. Yield change map under climate change scenarios: rainfed maize



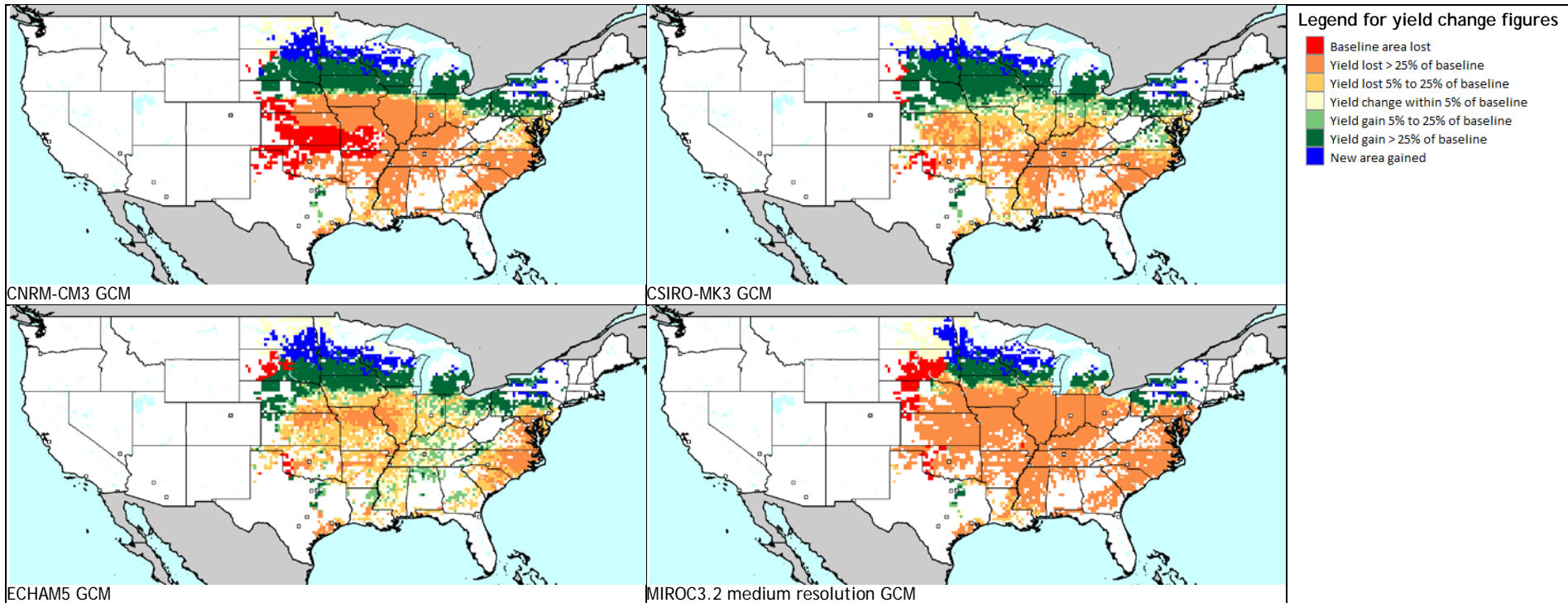
Source: IFPRI calculations based on downscaled climate data and DSSAT model runs

Figure 13. Yield change map under climate change scenarios: irrigated rice



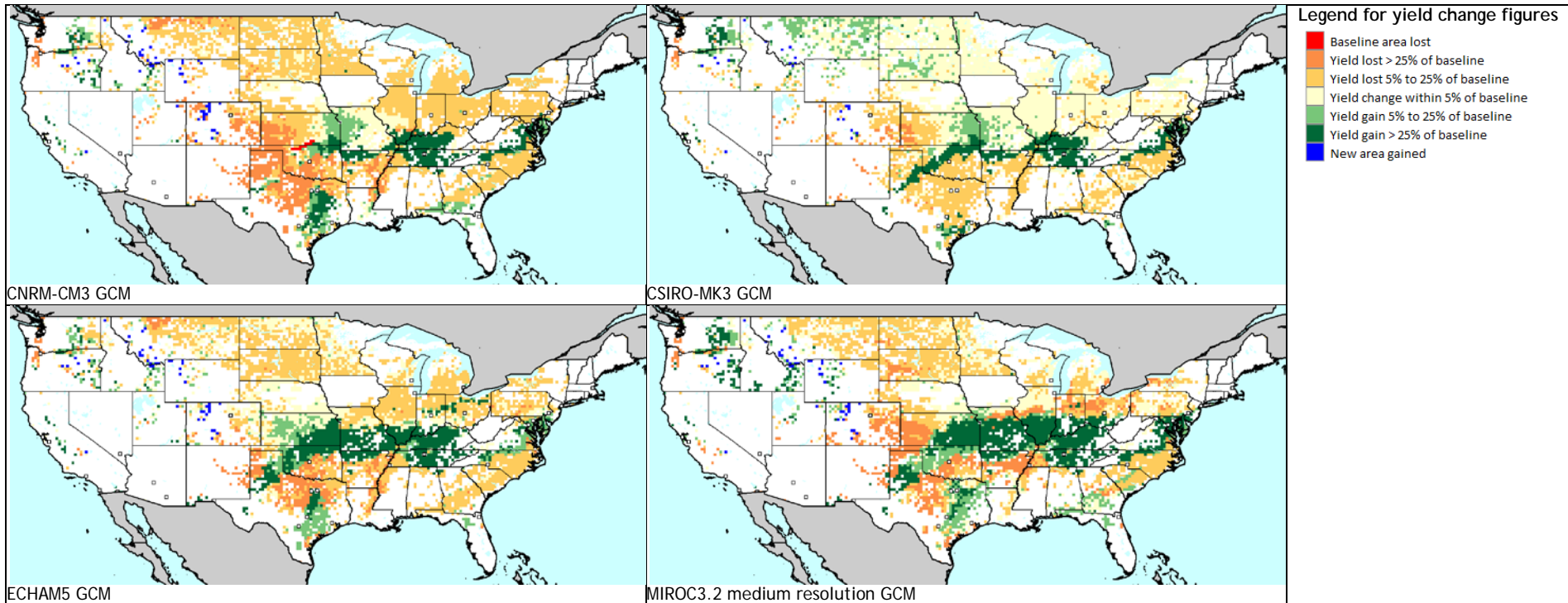
Source: IFPRI calculations based on downscaled climate data and DSSAT model runs

Figure 14. Yield change map under climate change scenarios: rainfed soybeans



Source: IFPRI calculations based on downscaled climate data and DSSAT model runs

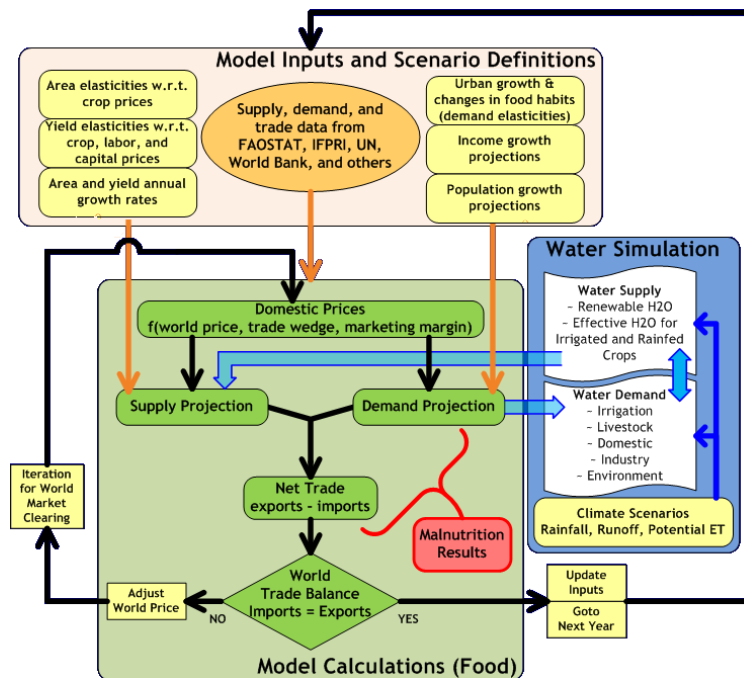
Figure 15. Yield change map under climate change scenarios: rainfed wheat



Source: IFPRI calculations based on downscaled climate data and DSSAT model runs

the IMPACT model's 281 spatial units, called food production units (FPUs) (see Figure 17). The FPUs are defined by political boundaries and major river basins.

Figure 16. The IMPACT modeling framework



Source: Nelson et al. (2010).

Figure 17. The 281 FPU in the IMPACT model



Source: Nelson et al. (2010).

3.2 Agricultural Vulnerability Scenarios (Crop-specific)

Several of the figures below use box and whisker plots to present the effects of the climate change scenarios in the context of each of the economic and demographic scenarios. Each box has 3 lines. The top line represents the 75th percentile, the middle line is the median, and the bottom line is the 25th percentile.¹ IMPACT is a dynamic model, and changing any input in the model can create different countervailing reactions. In the case of maize, a pessimistic world would see an increase in global population, and lower global GDP; increases in population of lower income consumers would stimulate the demand for staples like maize. In an optimistic world we would see increases in income, which would lead to improving diets and a larger demand for high value products like meat. Higher demand for meat would stimulate the livestock feed demand for maize. Therefore, one might get similar results for a single commodity market, but derived with very different variables.

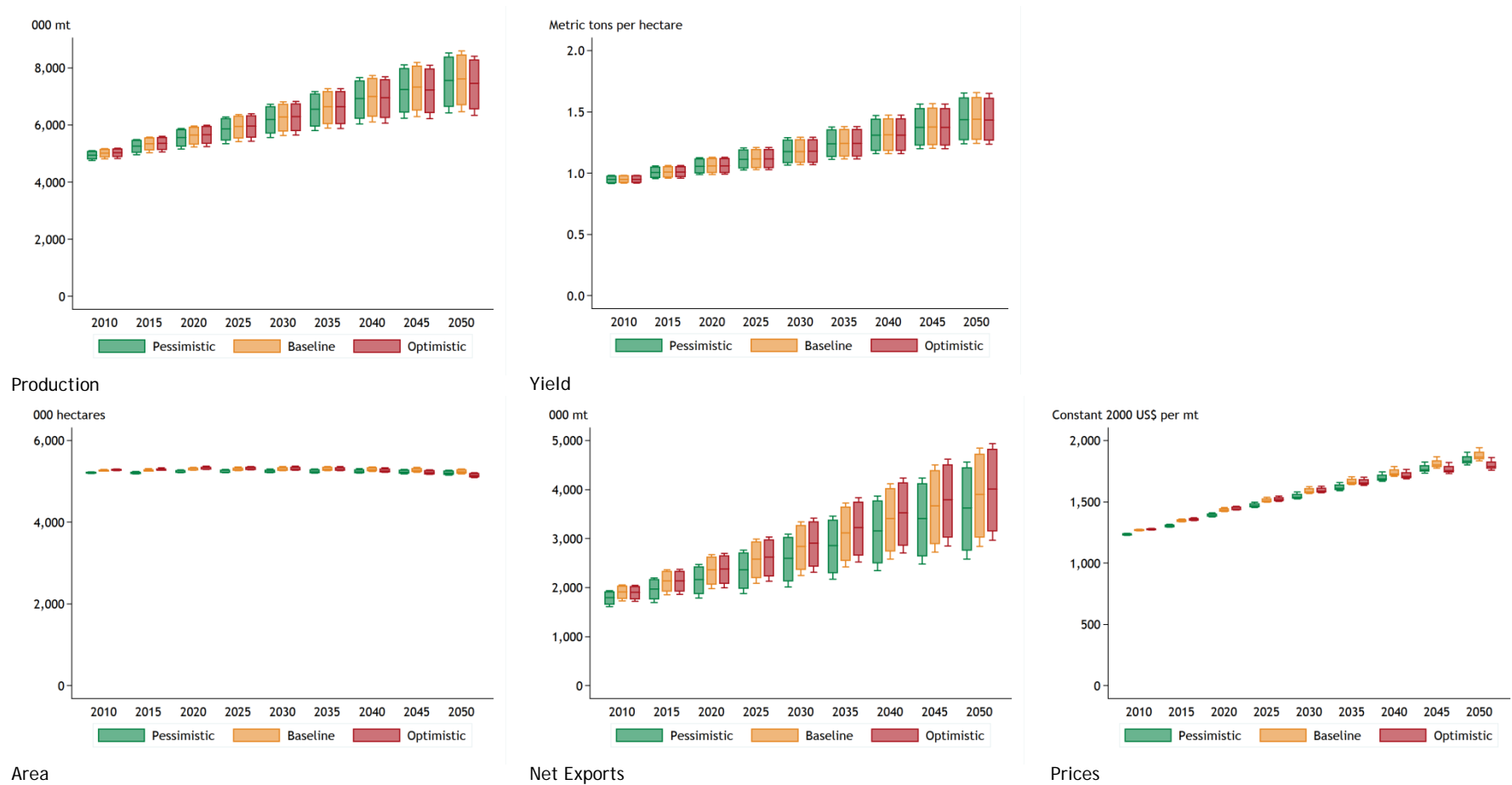
¹ These graphs were generated using Stata with Tukey's (Tukey 1977) formula for setting the whisker values. If the interquartile range (IQR) is defined as the difference between the 75th and 25th percentiles, the top whisker is equal to the 75th percentile plus 1.5 times the IQR. The bottom whisker is equal to the 25th percentile minus 1.5 times the IQR (StataCorp 2009).

Figures 18–23 show simulation results from the IMPACT model for cotton, maize, rice, soybeans, wheat, and other grains. Each crop has five graphs: one each showing production, yield, area, net exports, and world price. Closer examination of trends for maize and soybean illustrate the 50–year projected trends. For maize, lack of growth in yields due to exogenous assumptions, coupled with a leveling out of harvested area creates a concurrent leveling of production after 2030. Prices experience a greater rate of increase after 2030, and net exports become much more volatile. By contrast, soybean yields increase slightly but experience higher volatility and no growth in area harvested until near mid-century. Prices increase at a higher rate than production, but mean annual net exports change little. Net exports by 2050 may vary by a factor of five or more from one year to the next.

An overview of Figures 18–23 shows that economic and demographic factors (optimistic vs. pessimistic) have quite limited impacts, except on exports, on all grains except rice. The range of climate effects is revealed in the box and whisker plots. In most cases the range of possible climates introduces more uncertainty in predictions than do economic/demographic factors. The graphs show that, compared to a pessimistic future, an optimistic economic/demographic future predicts higher exports for cotton, soybean and “other grains” but lower exports for maize, rice, and wheat. Furthermore, an optimistic future creates lower prices for all commodities except soybeans.

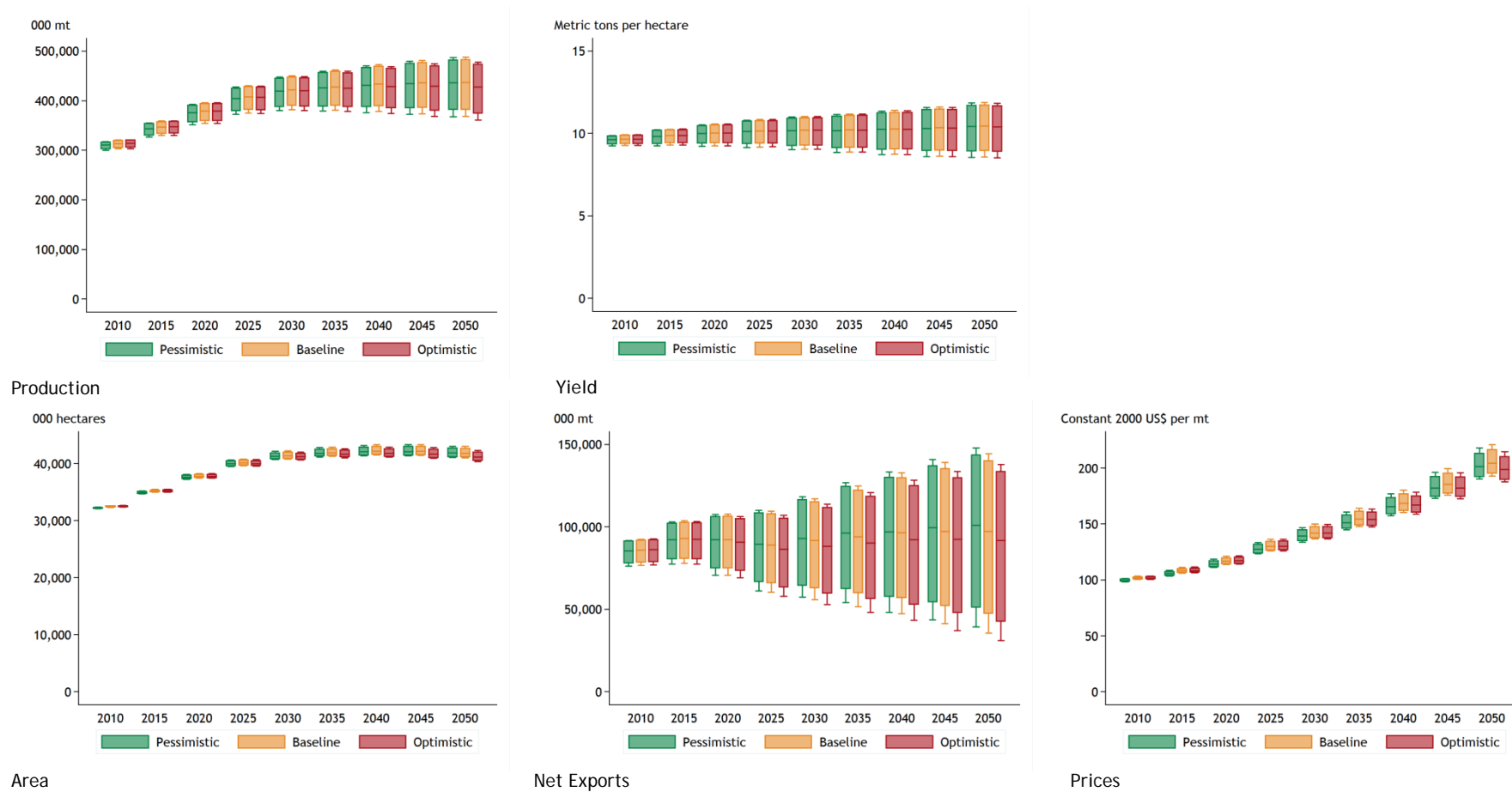
We demonstrate the full range of IMPACT-simulated future yields, in comparison with exponential yield trends since 1970 (Figures 9–11), by plotting (on these figures) the maximum and minimum yields within the simulation ensemble. To be specific, of the fifteen scenarios created by three socio-demographic options x 5 climate options (four climate models and one no-climate-change option), we choose the one scenario having highest yield trend to 2050 and the one have the lowest trend. Note that, even for the most optimistic socio-demographic and climate-favorable future predicted by the IMPACT model, maize and soybean yields (Figures 10 and 11) fall far short of the extrapolated trend from the 20th Century that has been and will continue to be a target for meeting global demand for these commodities. These results are consistent with a recent summary (Walthall et al., 2012) that continued

Figure 18. Scenario outcomes for cotton area, yield, production, net exports, and prices



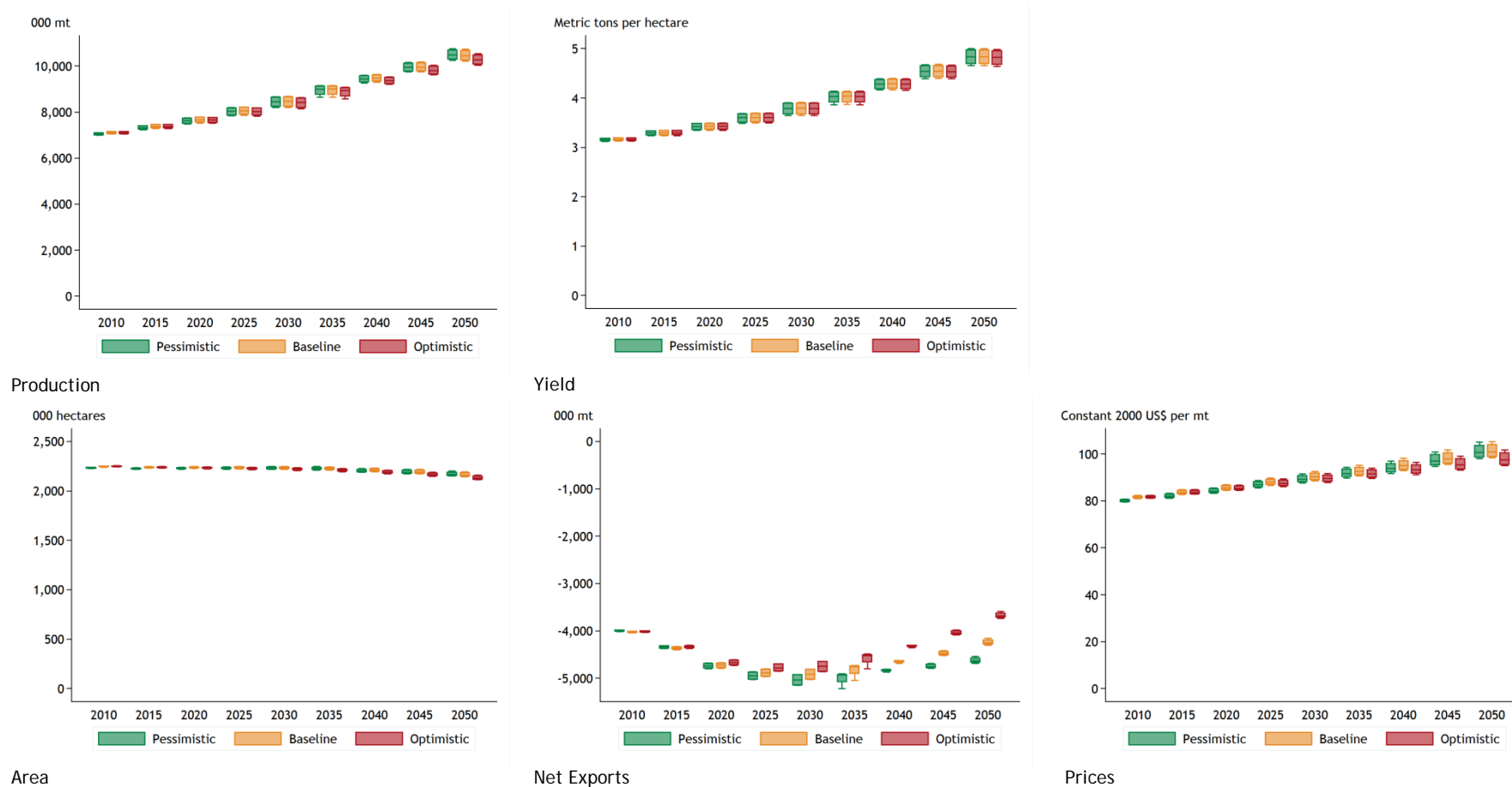
Source: Based on IMPACT results of July 2011. The box and whiskers plot for each socioeconomic scenario shows the range of effects from the four future climate scenarios. GDP = gross domestic product; US\$ = US dollars.

Figure 19. Scenario outcomes for maize area, yield, production, net exports, and prices



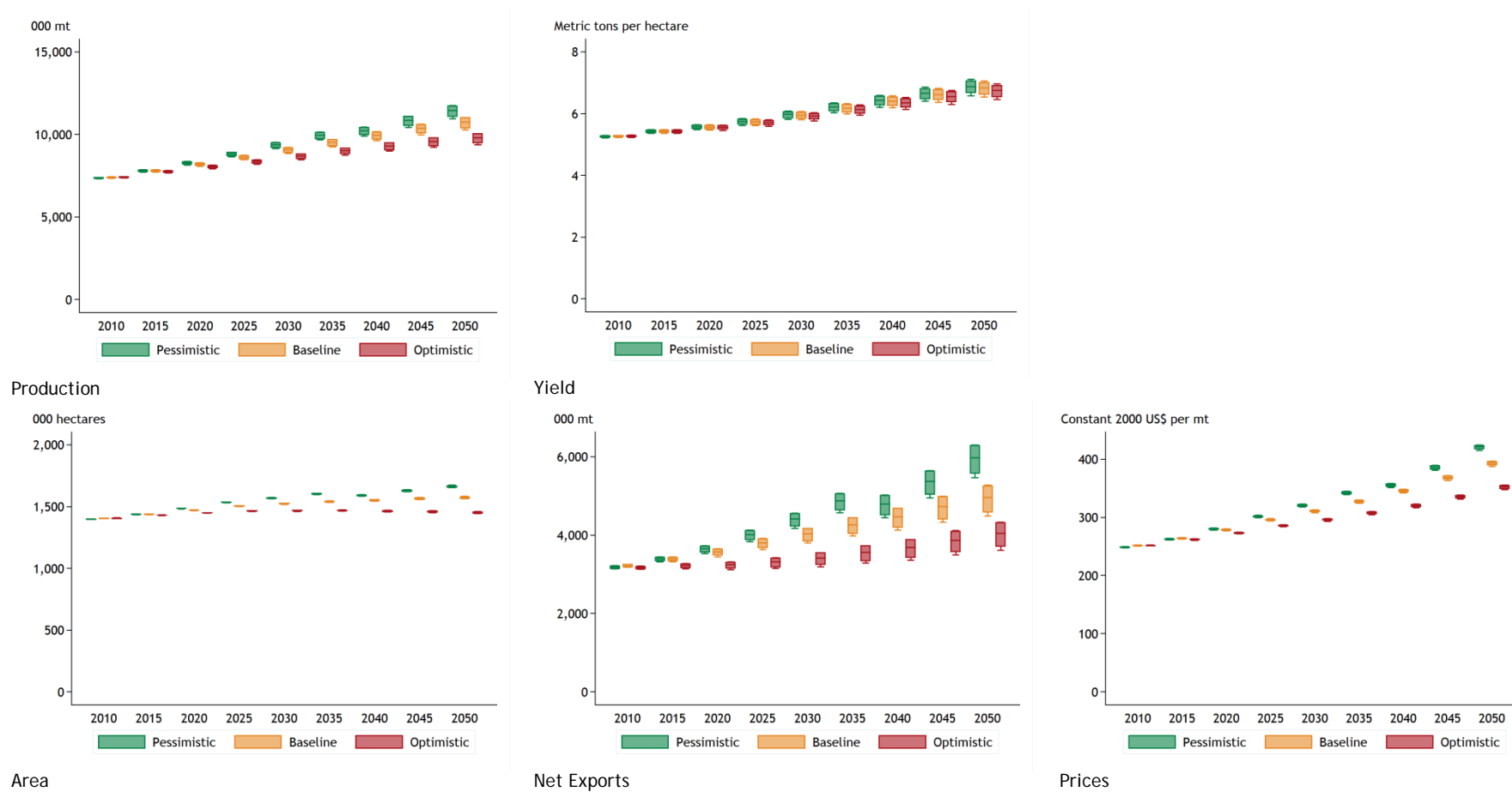
Source: Based on IMPACT results of July 2011.

Figure 20. Scenario outcomes for other grains area, yield, production, net exports, and prices



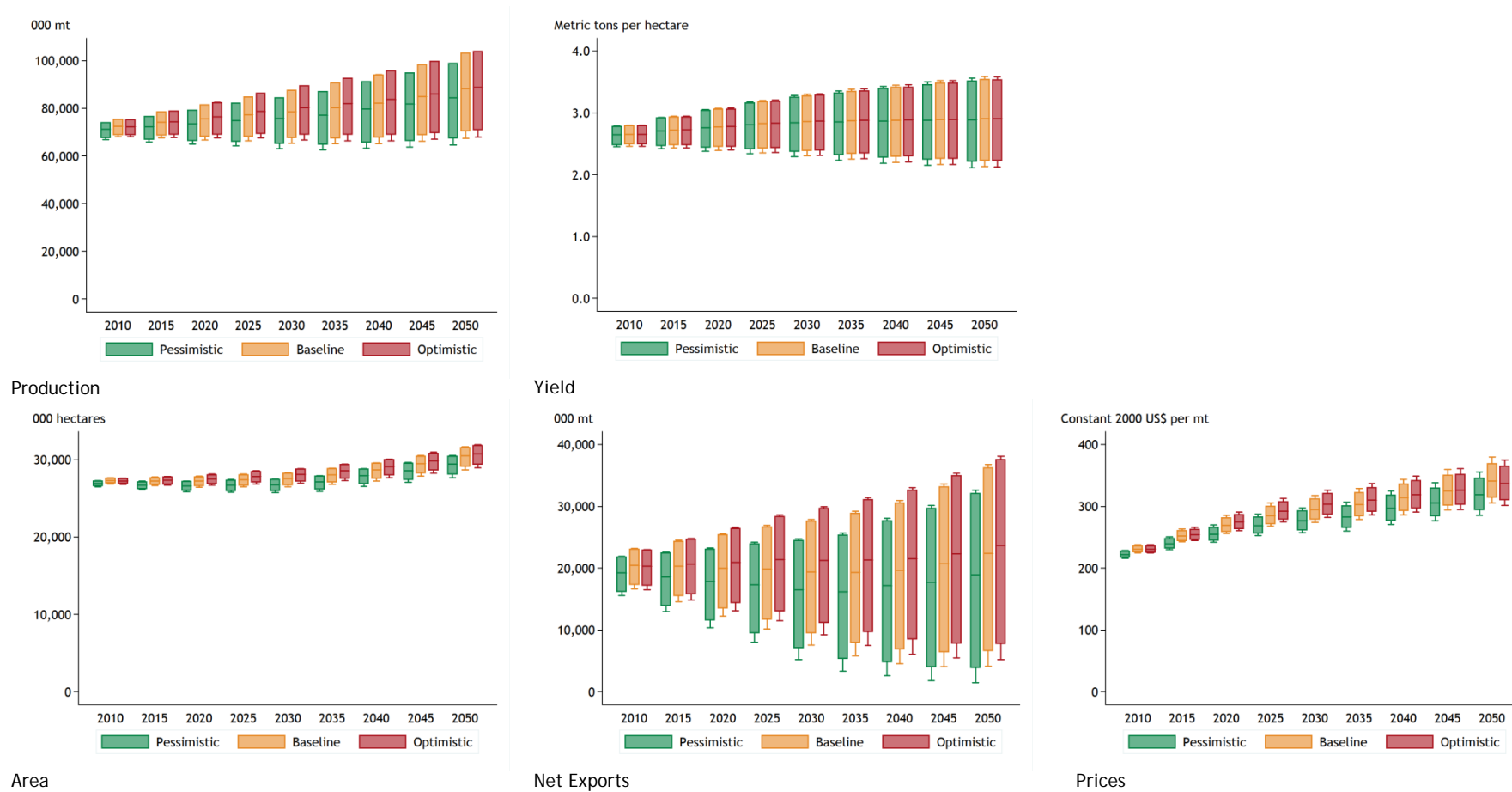
Source: Based on IMPACT results of July 2011. The box and whiskers plot for each socioeconomic scenario shows the range of effects from the four future climate scenarios. GDP = gross domestic product; US\$ = US dollars.

Figure 21. Scenario outcomes for rice area, yield, production, net exports, and prices



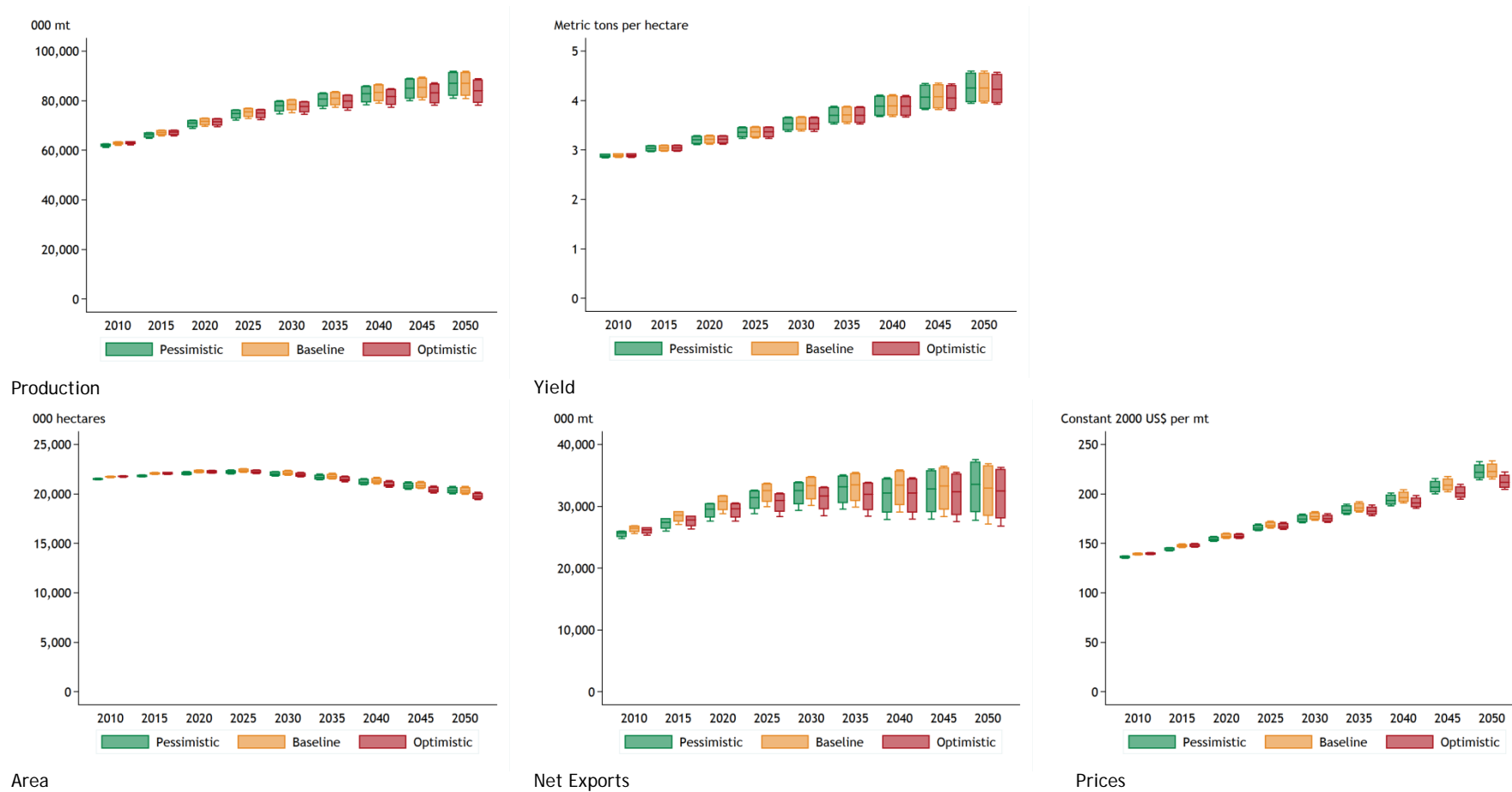
Source: Based on IMPACT results of July 2011.

Figure 22. Scenario outcomes for soybeans area, yield, production, net exports, and prices



Source: Based on IMPACT results of July 2011. The box and whiskers plot for each socioeconomic scenario shows the range of effects from the four future climate scenarios. GDP = gross domestic product; US\$ = US dollars.

Figure 23. Scenario outcomes for wheat area, yield, production, net exports, and prices



Source: Based on IMPACT results of July 2011. The box and whiskers plot for each socioeconomic scenario shows the range of effects from the four future climate scenarios. GDP = gross domestic product; US\$ = US dollars

climate change in the U. S. will have overall detrimental effects on most crops by mid-century and beyond. Although some recent declines in maize yields in many countries have been attributed to warmer temperatures associated with climate change (Lobell et al., 2011; 2013), reduction in daily maximum temperatures in the U. S. Midwest (Takle, 2011) likely has contributed to yield gains for maize and soybeans (Lobell and Asner, 2003).

3.3 Opportunities and Constraints of Adaptation to Climate Change

A review of trends in producer management changes over the past 40 years provides a glimpse of adaptation to recent climate change in Iowa, the largest corn-producing state in the US Midwest (Takle 2011). Farmers in Iowa are planting corn about 3 weeks earlier than 40 years ago because they use improved seed and seed treatment that better tolerate cold soil temperatures and because of the longer growing season due to climate change. They plant higher-yielding, longer season hybrids and harvest later, taking advantage of warmer and dryer autumn conditions that provide natural dry-down for the crop. Farmers adapt to higher rainfall amounts in spring and early summer due to climate change by purchasing larger machinery to plant more in smaller windows for field work. More abundant spring rains recharge deep soil moisture, providing a critical reservoir of moisture for dry August periods when grain is filling in the ear, allowing for planting more plants per hectare. Farmers have responded to wetter springs and early summer by installing more subsurface drainage tile at closer spacing and even on sloped surfaces to reduce water-logging of soils. Higher summer humidity levels require chemical response to new pests and pathogens. Recent high commodity prices have enabled producers to make investments in machinery, chemicals and crop genetics to respond to climate change. On balance, these recent climate changes have been favorable for agricultural production in Iowa. The resilience of future food security in the US in the face of climate change assumes that producers will continue to have financial resources to respond as they have in the past 40 years and that fundamental biophysical processes are not constrained by extremes of climate change in the next 40 years. Burke et al. (2011) conclude that, by mid- to late 21st Century, US maize yields and

farm profits would decline under a range of climate scenarios, which would constrain adaptation options. Furthermore, Malcolm et al. (2012) point out that both public and private investments will be needed to adapt agricultural production and infrastructure to climate change. If producers cannot cover increasing adaptation costs, or if extremes of climate change (not well modeled by current global climate models) constrain crop production, US food security may be challenged before mid-century.

3.4 Uncertainties in Climate Change Projections

Growing season water availability is the largest uncertainty to interannual production of maize and soybeans. Recent trends and future projections of climate change indicate changes in frequency of both extreme high and extreme low precipitation (USGCRP, 2008). For example, the statewide average precipitation for Iowa (Figure 24), centrally located in the US maize and soybean production region (Figures 3 and 5, respectively) shows a tendency toward more years with annual precipitation greater than 40 inches *and* more years with less than 25 inches, either of which could likely lead to reduced yields (Takle 2011).

The four future global climate precipitation projections used in this study (Figure 7) show mixed results for future scenario precipitation for the major maize and soybean producing regions, with ECHAM showing increase, CSIRO projecting very little change, MIROC projecting a decrease, CNRM having decreases in the southwest and increases in the northeast over the maize-soybean region.

Higher resolution simulations of future climates with multiple regional climate models recently have become available under the North American Regional Climate Change Assessment Program (NARCCAP 2013). These models are imbedded in global models and produce climate variables at the county scale across North America. Although finer scale climates for driving crop production models should, in principle reduce uncertainty they reveal several plausible results even for a single global model. For instance as shown in the top four panels of Figure 25, the model (CCSM) of the US National Center for Atmospheric Research simulates uniformly wetter

Figure 24. Annual state-wide average precipitation for Iowa

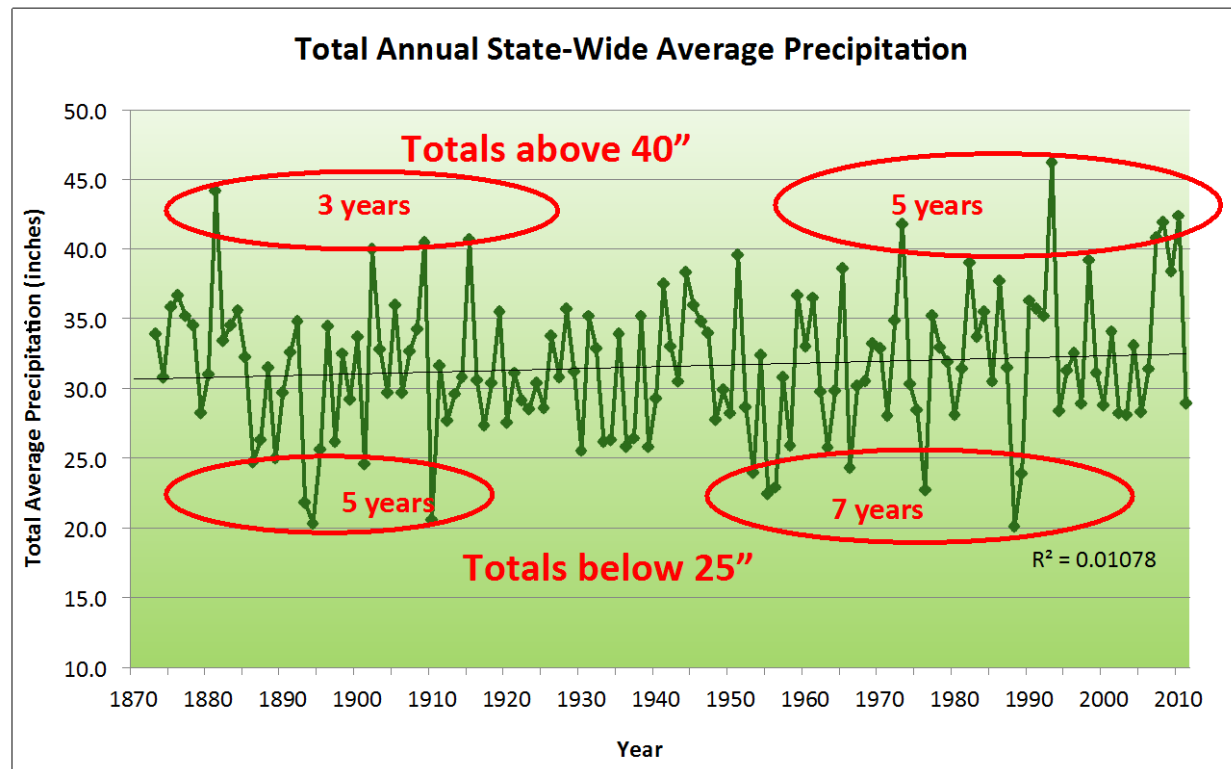
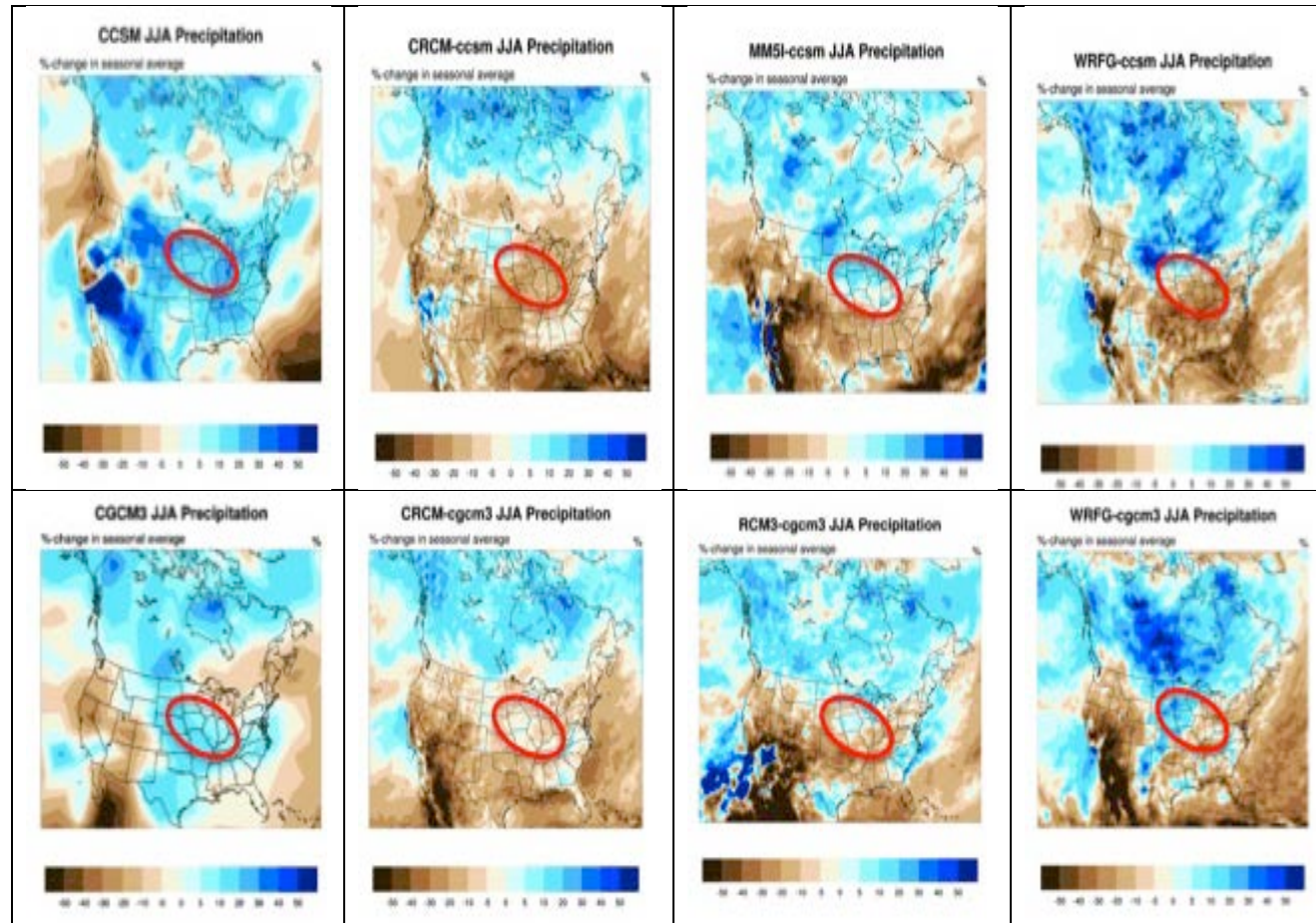


Figure 25. Global climate model simulations of changes in future scenario precipitation patterns for North America by two different global climate models (left hand panels) and precipitation simulations from three different regional climate models (right hand three panels), each driven by the global model to the left



Source: (NARCCAP 2013)

conditions over the maize-soybean region in the future (left top panel), but when results of this model are downscaled by three different regional models (three right top panels) drier conditions are produced. A similar result is obtained by downscaling the global model of the Canadian Climate Center (CGCM3) (lower left panel) with three different regional climate models (three lower right panels). Zhang et al. (2007) report that the observed changes are larger than estimated from model simulations, which suggests that climate conditions for individual years at mid 21st century might depart significantly from conditions of multi-year averages.

4 Conclusions

The analysis presented herein suggests that U. S. food insecurity due to climate change, as reflected in production of commodity crops, may be avoided in the first half of the 21st century by continuing adaptation measures of the past and by shifting cropping regions. Although trends in yields, production, and exports generally are up in the near term, some leveling off is projected by mid-century. Furthermore, a wider range of uncertainty, particularly for maize and soybeans, is estimated in export markets. This range could be exacerbated by increases in climate extremes that are widely predicted by U. S. and international climate science assessments. Both recent observations and future projections point to more areas experiencing both droughts and precipitation periods of increased intensity. By diverting financial resources from other areas, producers have successfully adapted to most changes in climate over the last 40 years, and likely will continue to adapt in next decade or two. Large differences among global models (e.g., annual precipitation produced by ECHAM vs. MIROC models for the central US as shown in Figure 7) allow for a wide variety of future precipitation regimes in major grain-producing regions. This report did not examine climate trends for the latter half of the 21st century. However, Walthall et al. (2012) report that temperature trends by mid century are projected to continue through 2100 unless effective mitigation measures are instituted soon.

Acknowledgments We thank reviewers, both online and anonymous, for very constructive comments that led to improvements in the manuscript. Partial support for EST was provided by USDA-NIFA award no. 2011-68002-30220. Support also was provided by the EU through its support for the Climate Change, Agriculture, and Food Security Research

Program of the CGIAR (CCAFS). NARCCAP is funded by the National Science Foundation (NSF), the U.S. Department of Energy (DoE), the National Oceanic and Atmospheric Administration (NOAA), and the U.S. Environmental Protection Agency Office of Research and Development (EPA).

References

- Burke, M., J. Dykema, D. Lobell, E. Miguel, and S. Satyanath (2011). Incorporating climate uncertainty into estimates of climate change impacts, with applications to US and African agriculture. NBER Working Paper Series, Working Paper 17092.
<http://www.nber.org/papers/w17092>
- FAO, (2010). FAOSTAT. *Online database*. <http://faostat.fao.org/site/291/default.aspx>.
- Hamlin, J. (2012). 2012 Outlook report: Nighttime heat stress impact on corn crop. The Climate Corporation. <http://www.climate.com/2012outlook/nighttime-heat-stress>.
- Hatfield, J., K. Boote, B.A. Kimball, R., Izaurralde, D. Ort, A. Thomson, and D. Wolfe (2011). Climate impacts on agriculture: Implications for crop production. *Agronomy Journal* 103: 351–370.
<https://dl.sciencesocieties.org/publications/aj/abstracts/103/2/351>
- IPCC (2007). Summary for policymakers. In S. Solomon, D. Qin, M. Manning, Z. Chen, M. Marquis, K.B. Averyt, M. Tignor, and H.L. Miller (eds.), *Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change*. Cambridge, UK and New York, NY, USA: Cambridge University Press.
http://www.ipcc.ch/publications_and_data/publications_ipcc_fourth_assessment_report_wg1_report_the_physical_science_basis.htm
- 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). The DSSAT cropping system model. *European Journal of Agronomy* 18: 235–265.
<http://www.sciencedirect.com/science/article/pii/S1161030102001077>
- JRC (2000). Global Land Cover 200. Joint Research Centre. Global Management Unit. European Commission. <http://bioval.jrc.ec.europa.eu/products/glc2000/glc2000.php>
- Le Treut, H., R. Somerville, U. Cubasch, Y. Ding, C. Mauritzen, A. Mokssit, T. Peterson, and M. Prather (2007). Historical overview of climate change. In S. Solomon, D. Qin, M. Manning, Z. Chen, M. Marquis, K.B. Averyt, M. Tignor, and H.L. Miller. *Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change*, Cambridge, UK and New York, NY, USA: Cambridge University Press.
http://www.ipcc.ch/publications_and_data/publications_ipcc_fourth_assessment_report_wg1_report_the_physical_science_basis.htm
- Lobell, D.B., and G.P. Asner (2003). Climate and management contributions to recent trends in U. S. agricultural yields. *Science* 299 (5609): 1032.

- Lobell, D.B. and S.M. Gourdjji (2012). The influence of climate change on global crop productivity. *Plant Physiology* 160: 1686–1697.
<http://www.plantphysiol.org/content/160/4/1686>
- 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: 497–501. doi:10.1038/nclimate1832
<http://www.nature.com/nclimate/journal/v3/n5/full/nclimate1832.html>
- Lobell, D.B., W. Schlenker, and J. Costa-Roberts (2011). Climate trends and global crop production since 1980. *Science* 333: 208–218.
- Malcolm, S., E. Marshall, M. Aillery, P. Heisey, M. Livingston, and K. Day-Rubenstein (2012). Agricultural adaptation to a changing climate: Economic and environmental implications Vary by U.S. Region ERR-136, U.S. Department of Agriculture, Economic Research Service.
- Millennium Ecosystem Assessment (2005). Ecosystems and human well-being: Scenarios. Washington, DC. Island Press.
- NARCCAP. North American Regional Climate Change Assessment Program (2013).
<http://www.narccap.ucar.edu/>
- Nelson, G.C., M.W. Rosegrant, A. Palazzo, I. Gray, C. Ingersoll, R. Robertson, S. Tokgoz, et al. (2010). *Food security, farming, and climate change to 2050: Scenarios, results, policy options*. Washington, DC: International Food Policy Research Institute.
- Oerke, E.C. (2006). Crop losses to pests. *Journal of Agricultural Sciences* 144: 31–43.
<http://journals.cambridge.org/action/displayAbstract?fromPage=online&aid=431724>
- Pardey P.G., and J.M. Alston (2010). *U.S. Agricultural research in a global food security setting*. Center for Strategic and International Studies, Washington DC.
- Peters, D.B., J.W. Pendleton, R.H. Hageman, and C.M. Brown (1971). Effect of night air temperature on grain yield of corn, wheat, and soybeans. *Agronomy Journal* 63: 809–809.
<https://www.agronomy.org/publications/aj/abstracts/63/5/AJ0630050809a?access=0&view=pdf>
- Raskin, P., F. Monks, T. Ribeiro, D. van Vuuren, and M. Zurek (2005). Global scenarios in historical perspective. In R. Carpenter, S. Prabhu Pingali, E.M. Bennett, and M. Zurek (eds), *Ecosystems and human well-being: Scenarios*, Volume 2, 35–44. Washington, D.C. Island Press.
- Rosegrant, M.W, and IMPaCT Development Team (2012). International model for policy analysis of agricultural commodities and trade (IMPACT) Model Description. Washington D.C.

- StataCorp (2009). Stata. College Station, TX: StataCorp LP.
- Takle, E. S. (2011). Assessment of potential impacts of climate changes on Iowa using current trends and future projections.
<http://climate.engineering.iastate.edu/CSPPublications.html>
- Tukey, J. W. (1977). *Exploratory data analysis*. Reading, MA: Addison-Wesley.
- US Global Change Research Program (USGCRP) (2008). Weather and climate extremes in a changing climate. CCSP SAP 3.3.
<http://library.globalchange.gov/products/assessments/2004-2009-synthesis-and-assessment-products/sap-3-3-weather-and-climate-extremes-in-a-changing-climate>.
- Walthall, C.L., J. Hatfield, P. Backlund, L. Lengnick, E. Marshall, M. Walsh, S. Adkins, M. Aillery, E.A. Ainsworth, C. Ammann, C.J. Anderson, I. Bartomeus, L.H. Baumgard, F. Booker, B. Bradley, D.M. Blumenthal, J. Bunce, K. Burkey, S.M. Dabney, J.A. Delgado, J. Dukes, A. Funk, K. Garrett, M. Glenn, D.A. Grantz, D. Goodrich, S. Hu, R.C. Izaurralde, R.A.C. Jones, S-H. Kim, A.D.B. Leaky, K. Lewers, T.L. Mader, A. McClung, J. Morgan, D.J. Muth, M. Nearing, D.M. Oosterhuis, D. Ort, C. Parmesan, W.T. Pettigrew, W. Polley, R. Rader, C. Rice, M. Rivington, E. Rosskopf, W.A. Salas, L.E. Sollenberger, R. Srygley, C. Stöckle, E.S. Takle, D. Timlin, J.W. White, R. Winfree, L. Wright-Morton, L.H. Ziska. (2012). Climate change and agriculture in the United States: Effects and adaptation. USDA Technical Bulletin 1935. Washington, DC.
http://www.usda.gov/oce/climate_change/effects_2012/effects_agriculture.htm
- You, L., and S. Wood (2006). An entropy approach to spatial disaggregation of agricultural production. *Agricultural Systems* 90: 329–347.
<http://www.sciencedirect.com/science/article/pii/S0308521X06000096>
- You, L., S. Wood, and U. Wood-Sichra (2009). Generating plausible crop distribution and performance maps for Sub-Saharan Africa using a spatially disaggregated data fusion and optimization approach. *Agricultural Systems* 99: 126–140.
<http://ideas.repec.org/a/eee/agisys/v99y2009i2-3p126-140.html>
- Zhang, X., F.W. Zwiers, G.C. Hegerl, F.H. Lambert, N.P. Gillett, S. Solomon, P.A. Stott, and T. Nozawa (2007). Detection of human influence on twentieth-century precipitation trends. *Nature* 448: 461–465.
<http://dx.doi.org/10.1038/nature06025>

Please note:

You are most sincerely encouraged to participate in the open assessment of this article. You can do so by either recommending the article or by posting your comments.

Please go to:

<http://dx.doi.org/10.5018/economics-ejournal.ja.2013-34>

The Editor