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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. The lack of additional arable land and availability of freshwater have long been constraints on agriculture. However, the increased frequency of extreme and unpredictable weather events, in a manner consistent with the changes predicted by global climate models, is expected to exacerbate the global food challenge as we move toward the middle of the 21st century. 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. The present report projects the impact of climate change on food security through the year 2050. The analysis presented here suggests that climate change in the first half of the 21st century does not represent a near-term threat to food security in the US due to the availability of adaptation strategies. However, as climate continues to trend away from 20th century norms current adaptation measures will not be sufficient to enable agriculture to meet growing food demand. High-end projections on carbon emissions will exacerbate the food shortfall, although uncertainty in climate model projections (particularly precipitation) is a limitation to impact studies.

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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. 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.

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, pg.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 and tend to encourage weed and pest proliferation. 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

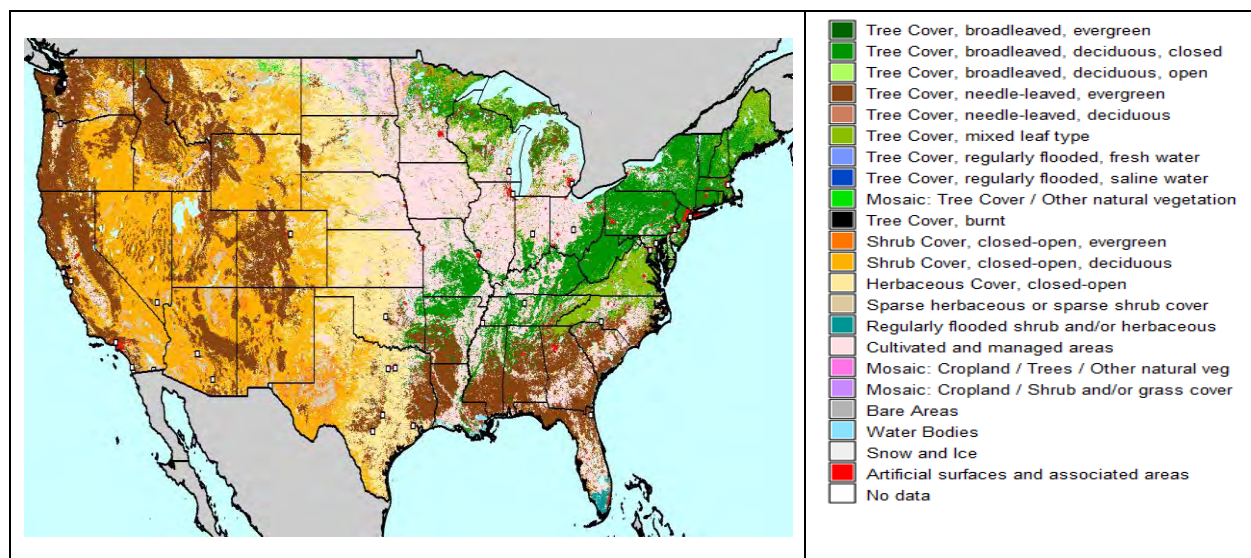
While the general consequences of climate change are becoming increasingly well known, great uncertainty remains about how climate change effects will play out in specific locations. To understand the significant uncertainty in how these effects play out globally it is useful to describe briefly the process by which the results depicted in the figures are derived. They start with 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). Several GCMs have been developed independently around the world. 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 gasses. Several independent IAMs exist as well. 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.

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: Source: GLC2000 (JRC 2000).

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.

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)

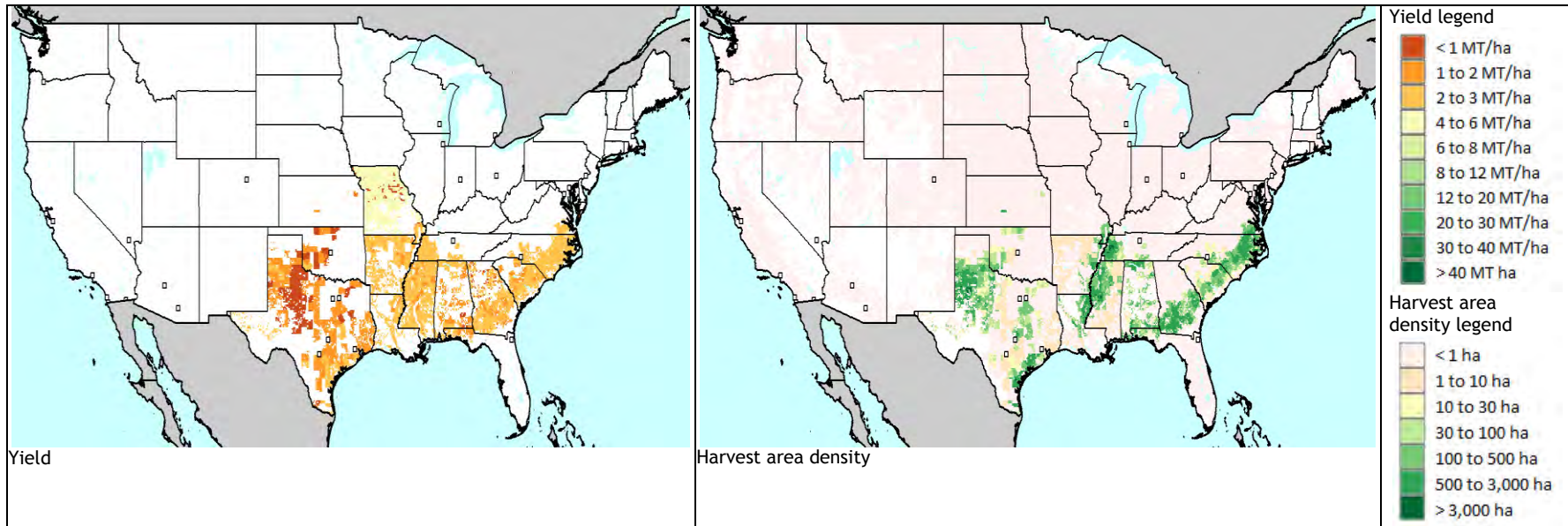
Table 2. Value of production for leading agricultural commodities, average of 2006-2008

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)

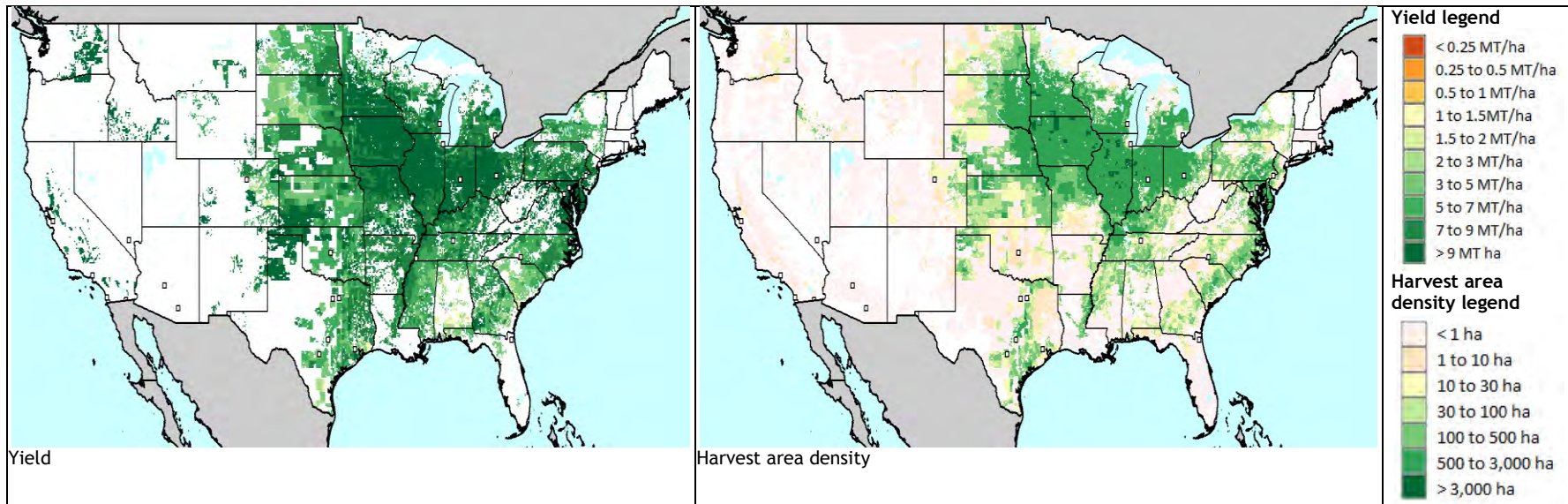
Shown in Figures 2-6 are the estimated yield and growing areas for five key US crops: cotton, maize, rice, soybeans, and wheat. These figures are based on the SPAM data set (You et al. 2009), a plausible allocation of national and sub-national data on crop area and yields. Note that the production (MT) for a particular location is the product of the yield (MT/ha) times the area harvested (ha).

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



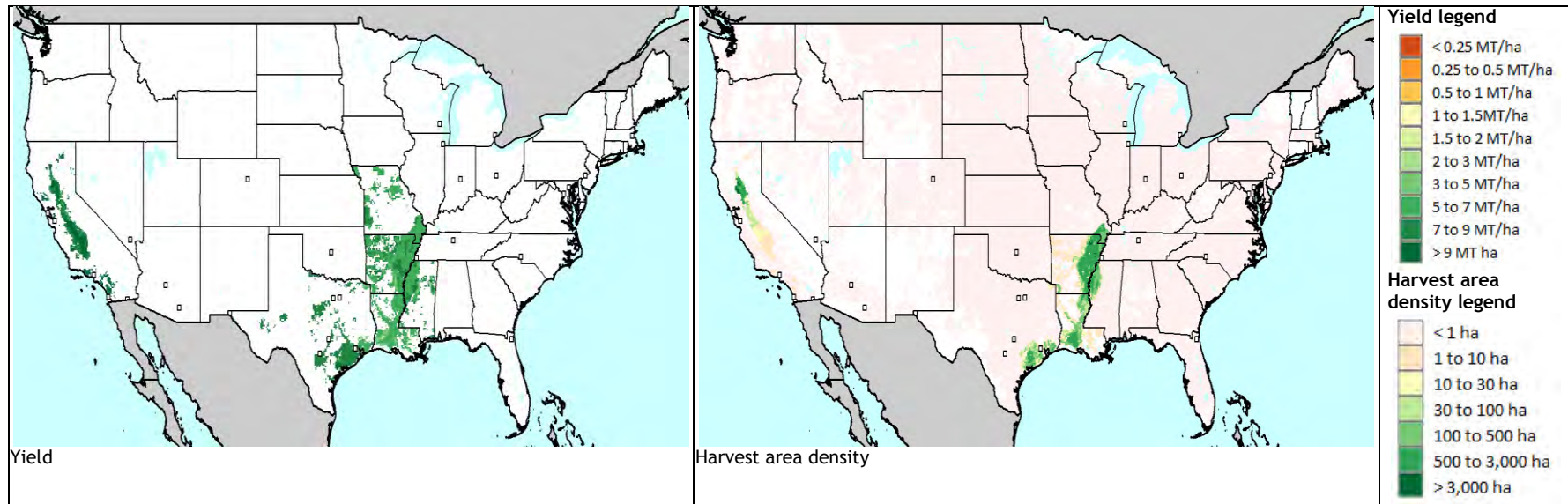
Source: SPAM Dataset (You et al. 2009)

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



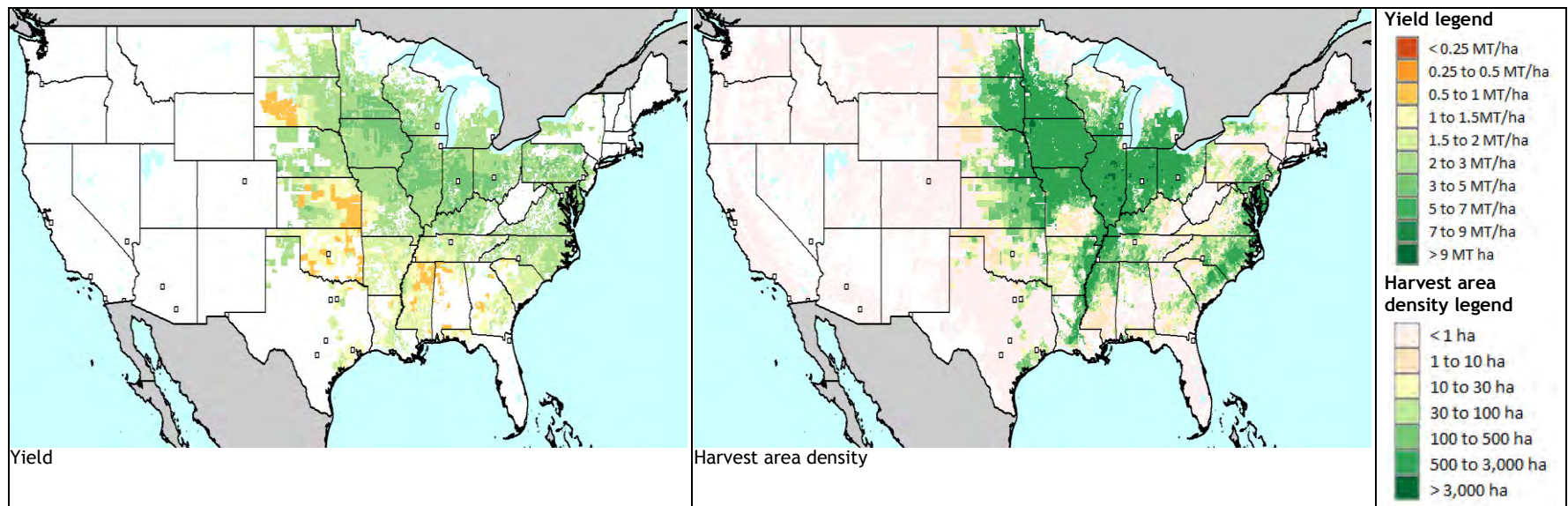
Source: SPAM Dataset (You et al. 2009)

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



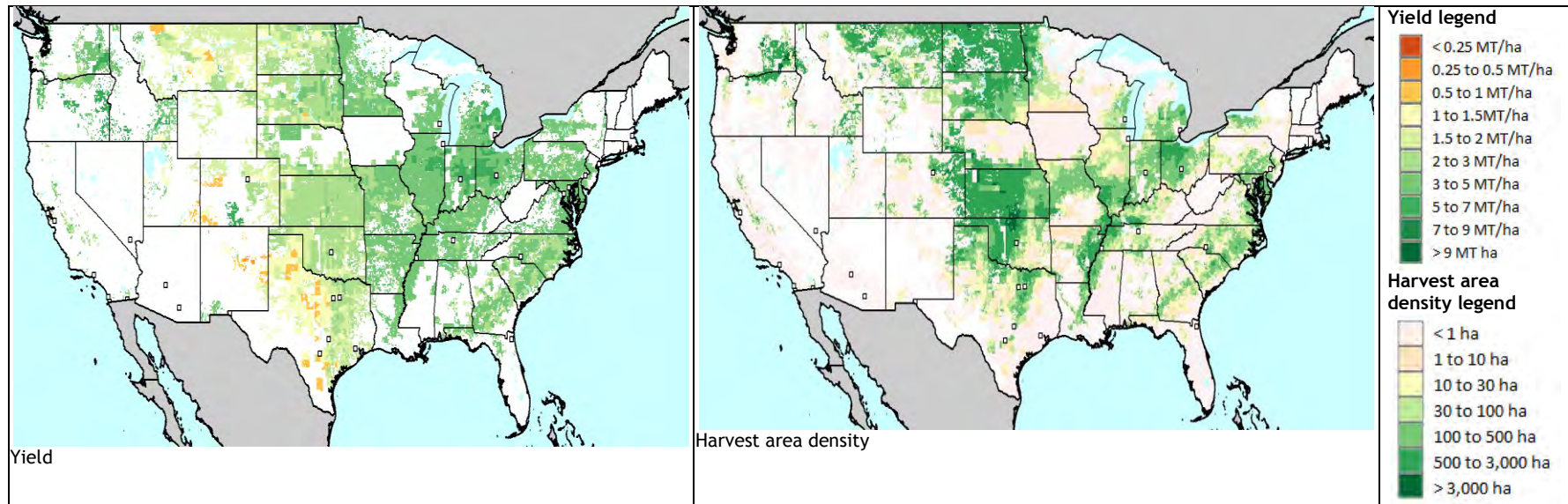
Source: SPAM Dataset (You et al. 2009)

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)

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.

Biophysical Scenarios

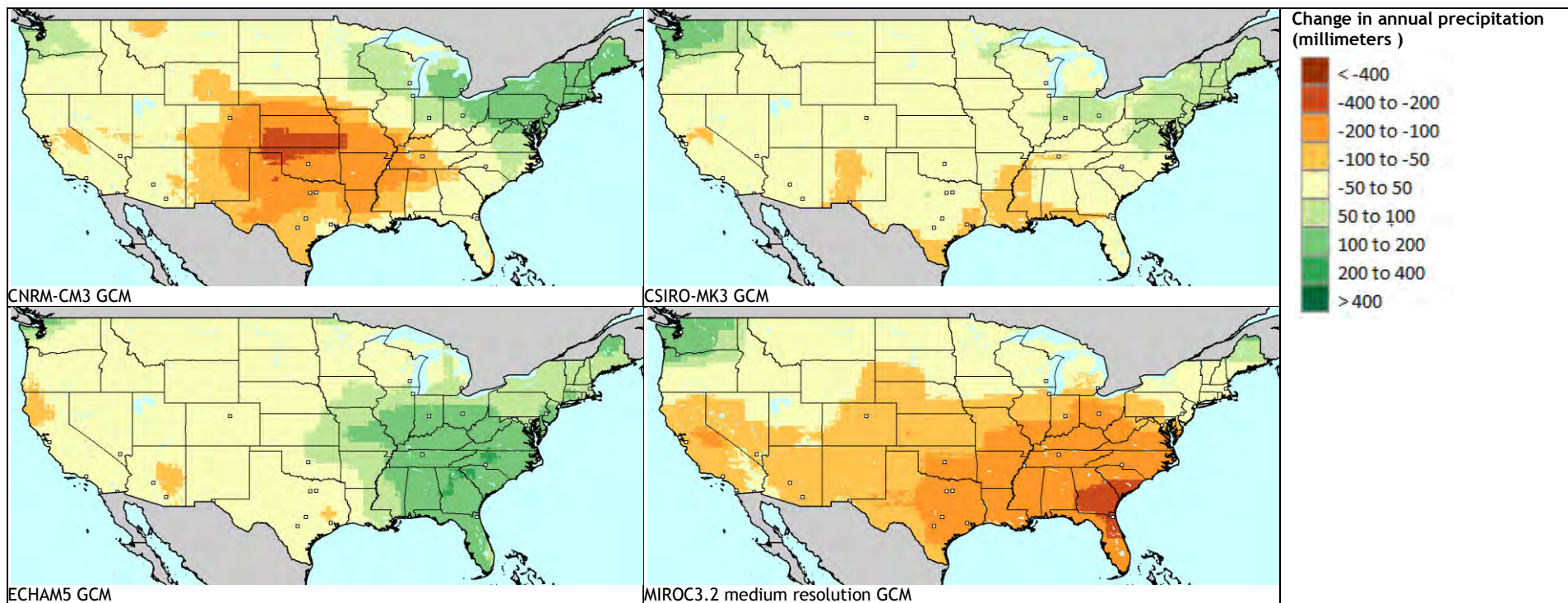
This section presents the climate scenarios used in the analysis and the crop physiological response to the changes in climate between 2000 and 2050.

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.

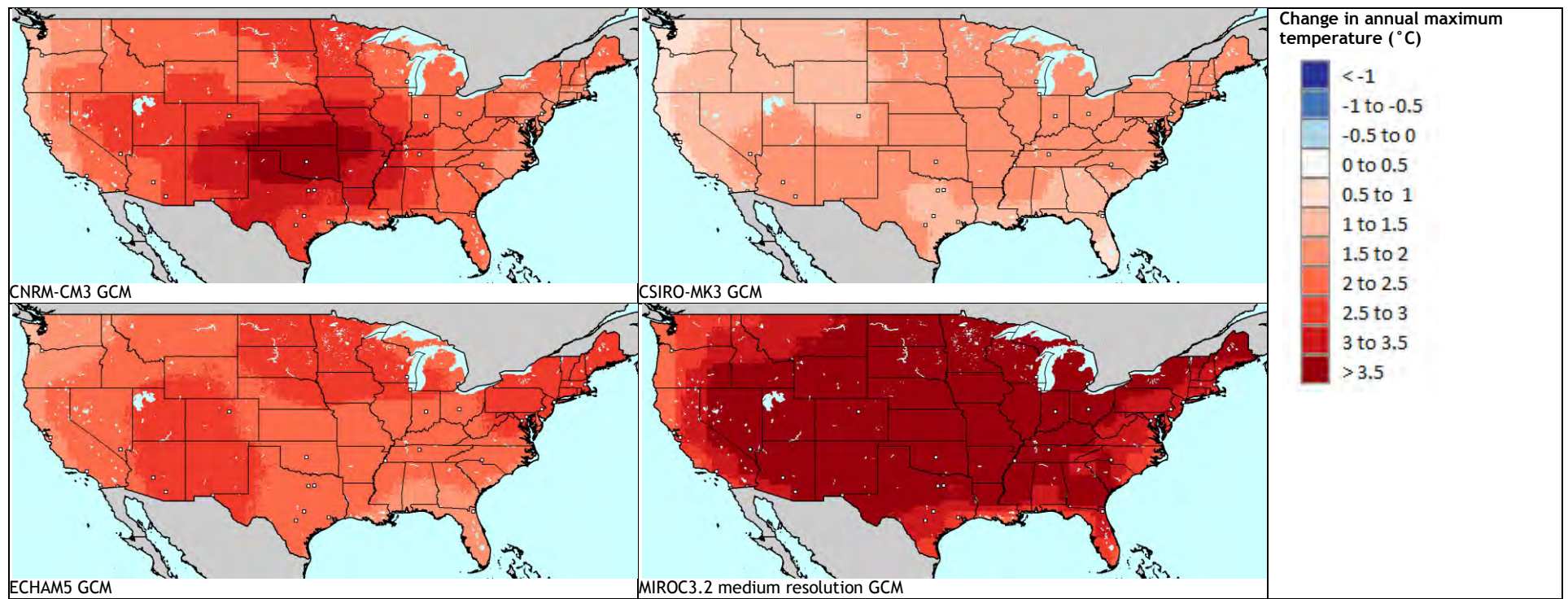
Figure 7 Changes in mean annual precipitation for USA between 2000 and 2050 using the A1B scenario (millimeters)



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

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

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/>

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

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 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).

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 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. The output for key crops is mapped in Figures 12-15. The comparison is between the crop yields for 2050 with climate change compared to the yields with 2000 climate. 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.

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

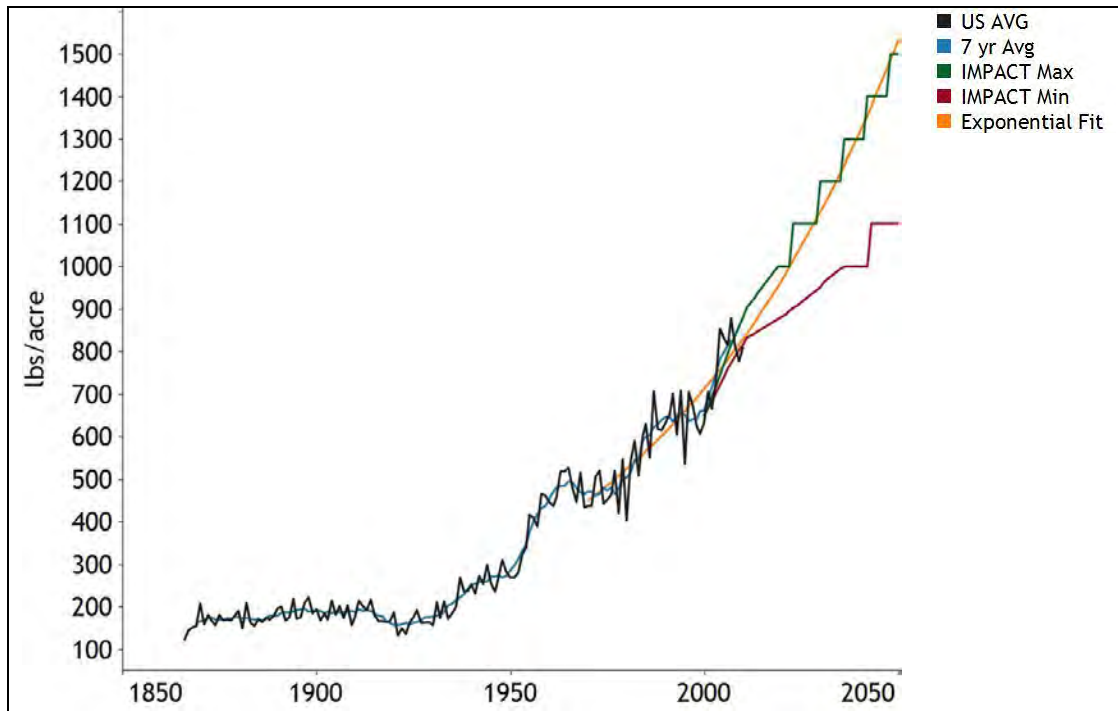


Figure 10 Observed (1860 to present) and projected (2000-2050) US maize yields

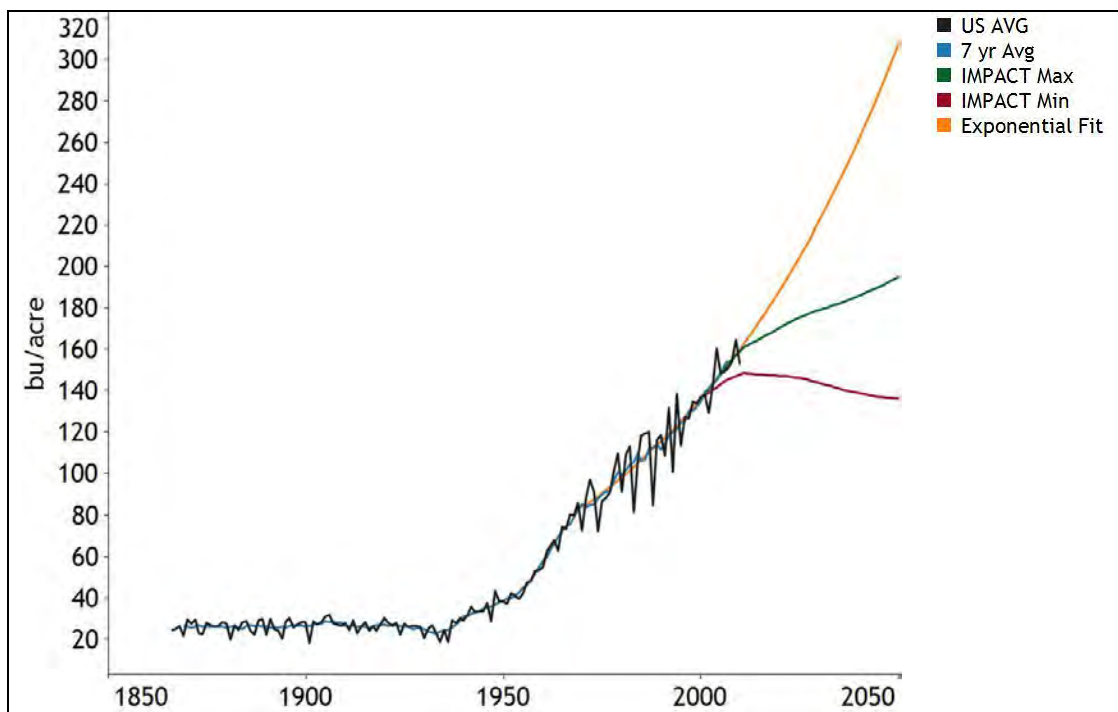


Figure 11 Observed (1930 to present) and projected (2000-2050) US soybean yields

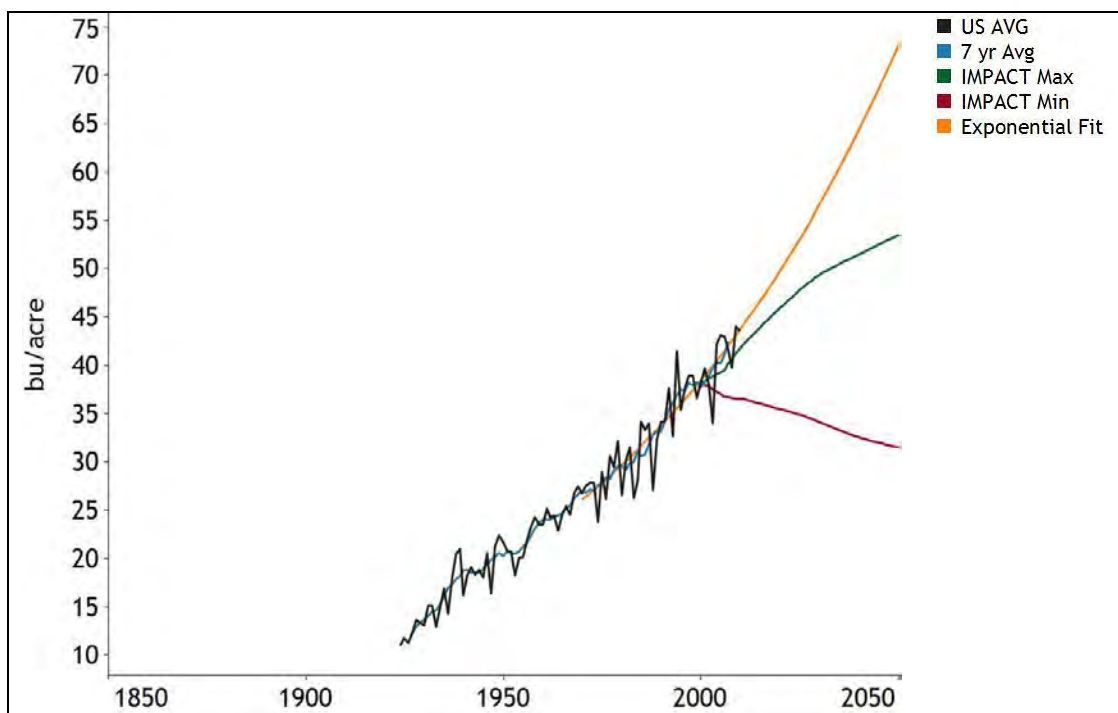
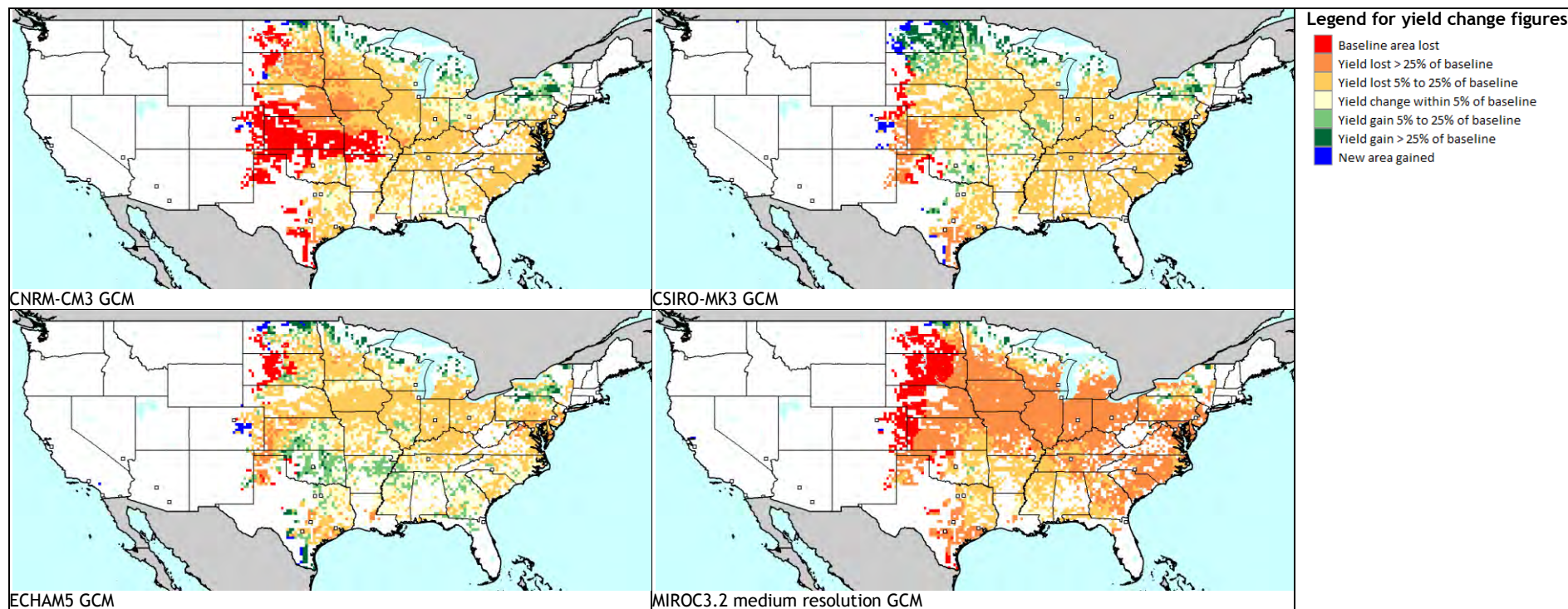
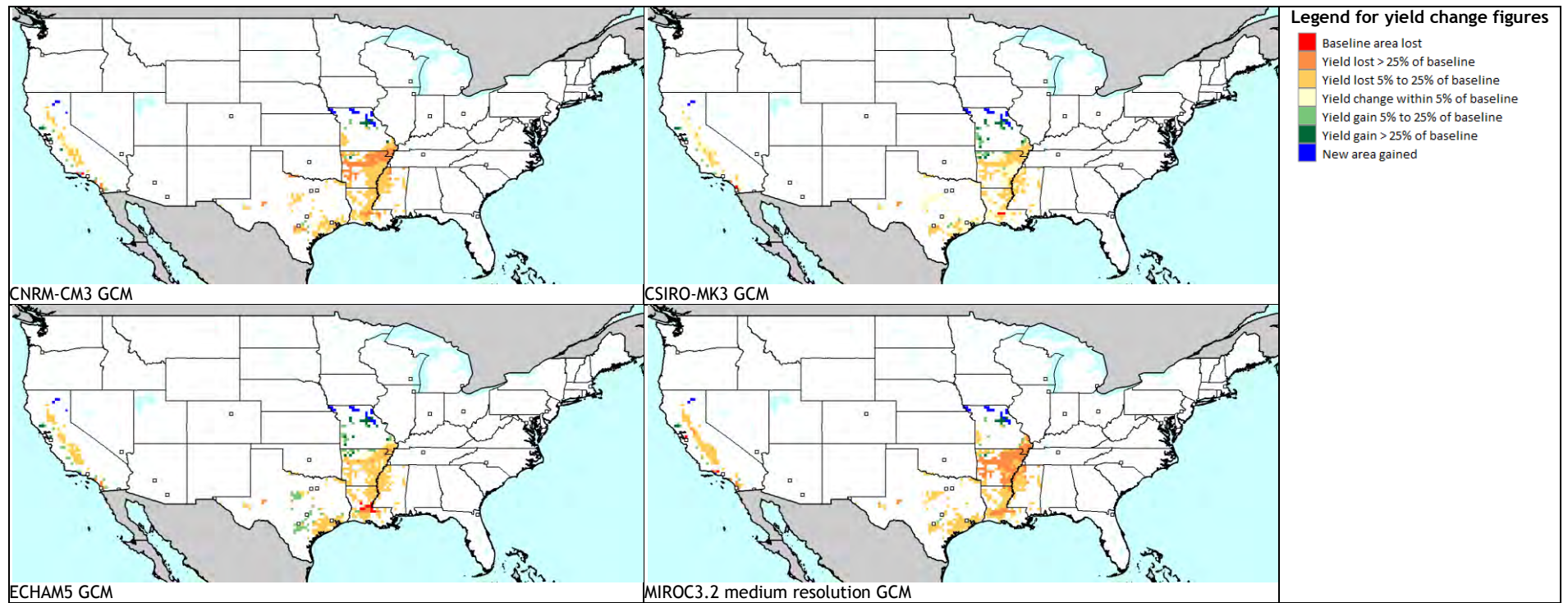


Figure 12 Yield change map under climate change scenarios: rainfed maize



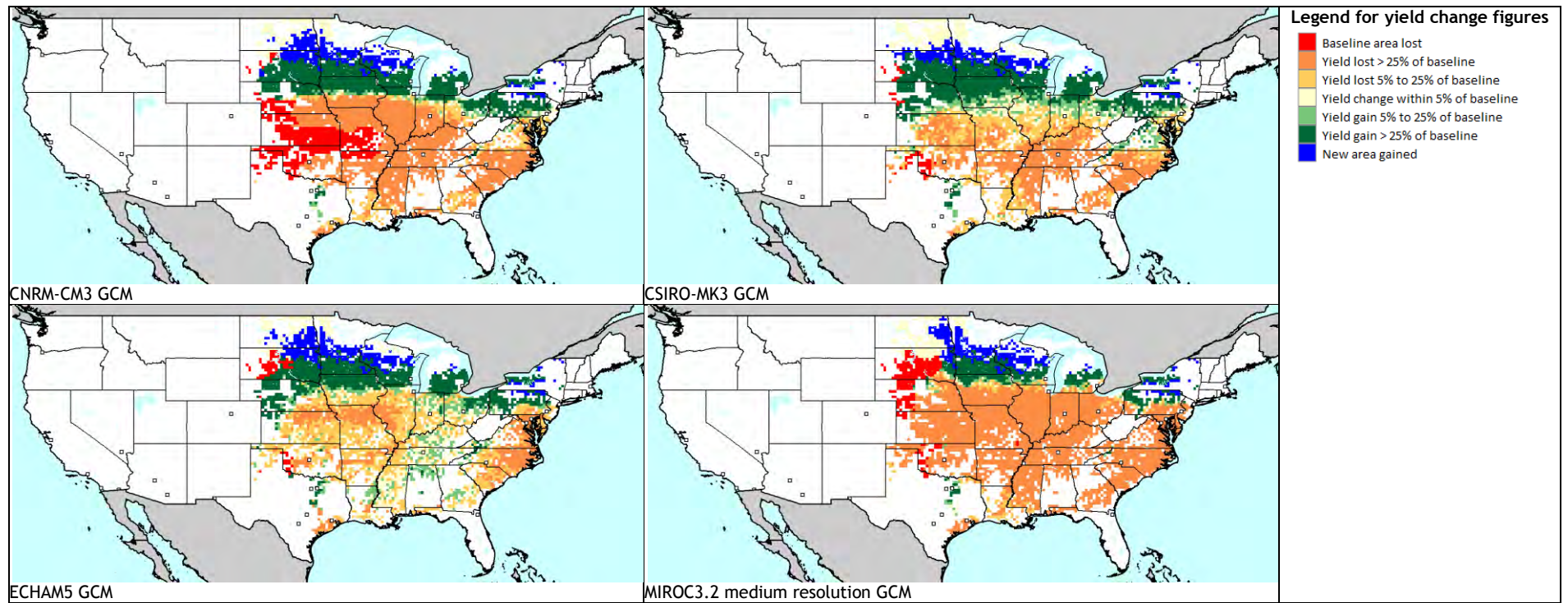
Source: IFPRI calculations based on downscaled climate data and DSSAT model runs

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



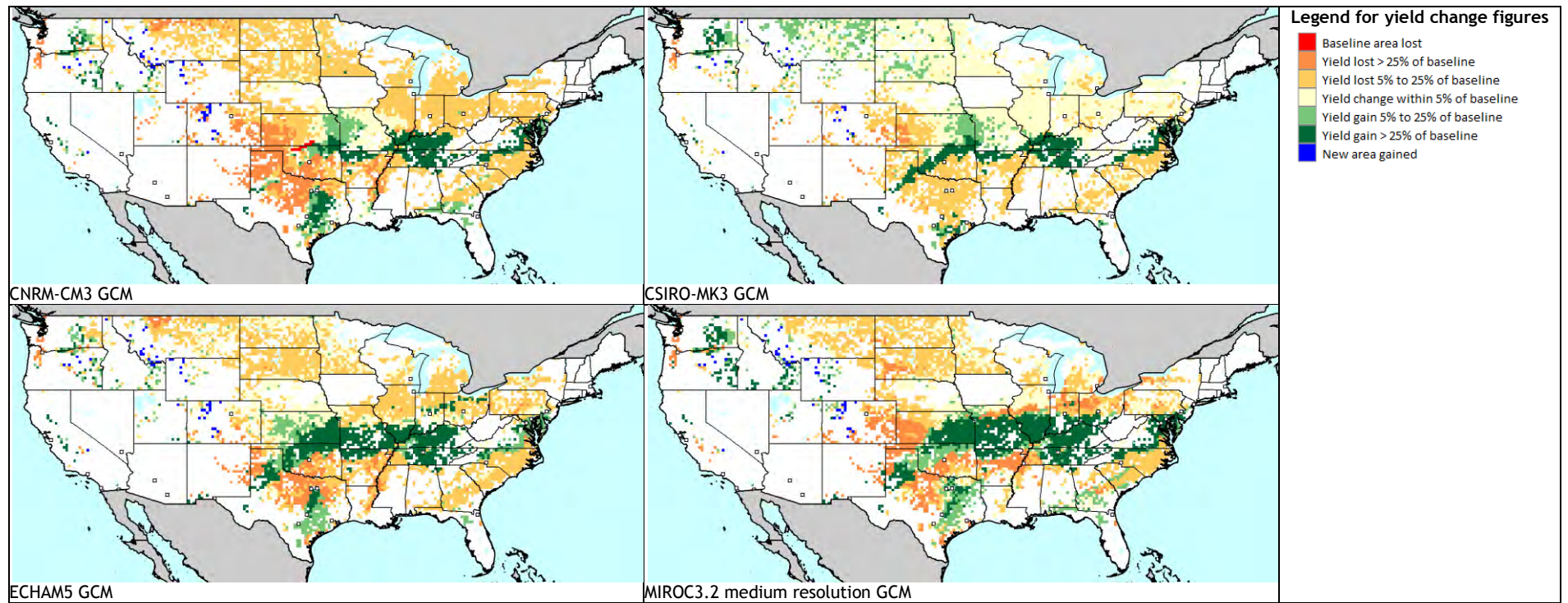
Source: IFPRI calculations based on downscaled climate data and DSSAT model runs

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

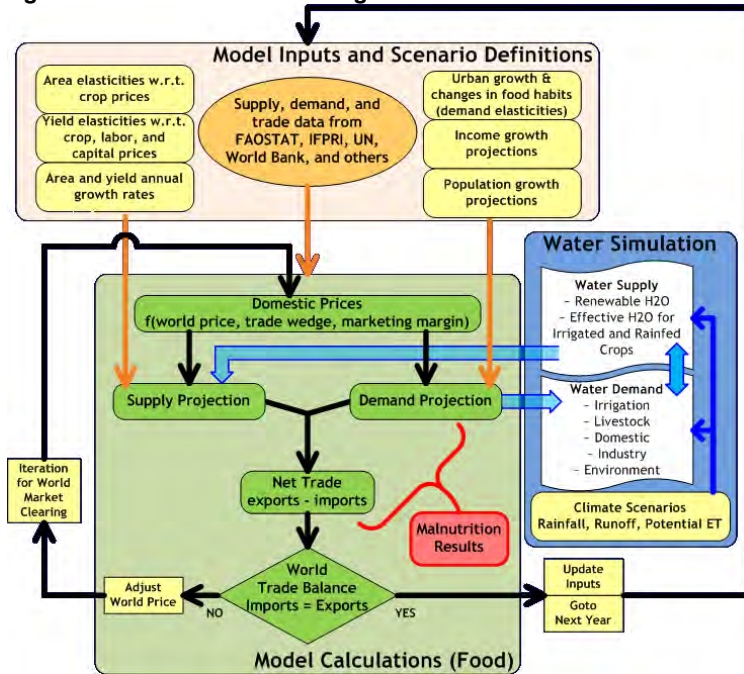


Source: IFPRI calculations based on downscaled climate data and DSSAT model runs

From biophysical scenarios to socioeconomic consequences: The IMPACT Model

Figure 16 describes the links among the three models used in this analysis: IFPRI's IMPACT model (Cline 2008), a partial equilibrium agriculture model that emphasizes policy simulations; a hydrology model and an associated water-supply demand model incorporated into IMPACT; and the DSSAT crop modeling suite (Jones et al. 2003) that estimates yields of selected crops under varying management systems and climate change scenarios. 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 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 FPUs in the IMPACT model



Source: Nelson et al. 2010

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

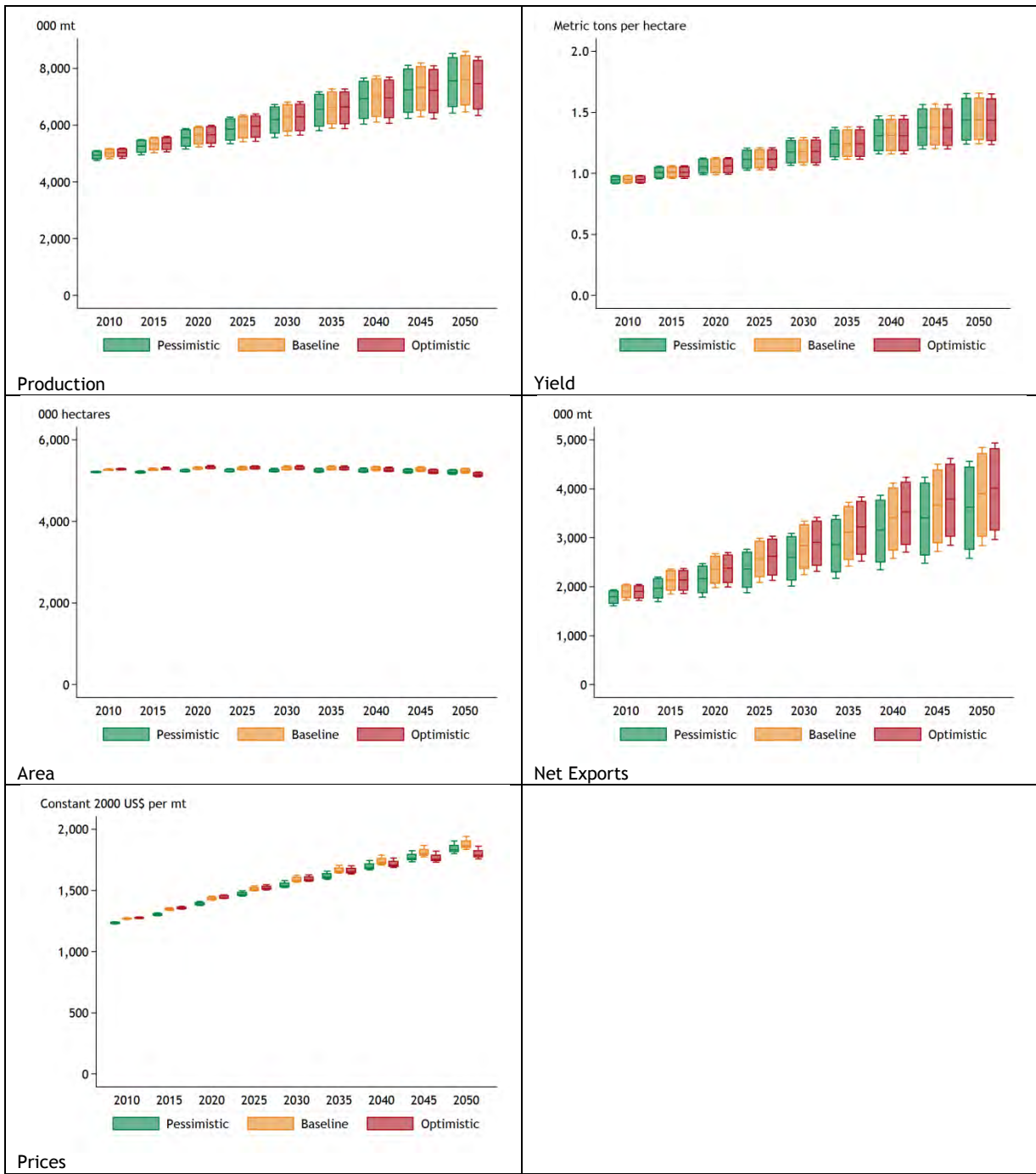
Figures 18-23 show simulation results from the IMPACT model for cotton, maize, rice, soybeans, wheat, and other grains. Each crop has five graphs: one each showing production, yield, area, net exports, and world price. Closer examination of trends for maize and soybean illustrate the 50-year projected 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.

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 IMPACT model's most optimistic socio-demographic and climate-favorable future, maize and soybean yields (Figures 10 and 11, respectively) fall far short of the late 20th century.

Shown in Figures 24-26 are IMPACT-predicted changes in US cotton, maize, and soybean yields in 2050 implied by the higher exogenous yield assumptions described earlier (in Figures 9-11). The figures compare yields predicted by the IMPACT baseline model, and 4 different productivity scenarios, while comparing them to the initial value in 2010 (PM - is perfect mitigation or no climate change). Yield growth in the IMPACT model is determined by the intrinsic yield growth rates, as well as responding to changes in prices. Therefore, in productivity scenarios that directly affect the crop (i.e. maize yield and the maize productivity scenario) we can expect to see a clear difference in the yield between the baseline model (no productivity scenario) and the results of the IMPACT model with a productivity scenario, because we are directly changing the yield growth assumption. In productivity scenarios that do not change own-crop yield (i.e. maize yield and the soybean productivity scenario) we should expect to see much smaller changes to own-crop yields. This is because changes in own-crop yield would be different from the baseline in so much as the changes in the yields in another crop affect world crop prices, leading to changes in incentives in planting different crops. Using the maize yield and soybean productivity example, any changes in maize yield under the soybean productivity scenario occur because increased productivity of soybean leads to changes in production and/or prices of soybeans, which leads to changes in demand and/or prices of other crops including maize. On average we should expect these indirect effects on maize yield from changes in soybean yields to be fairly small.

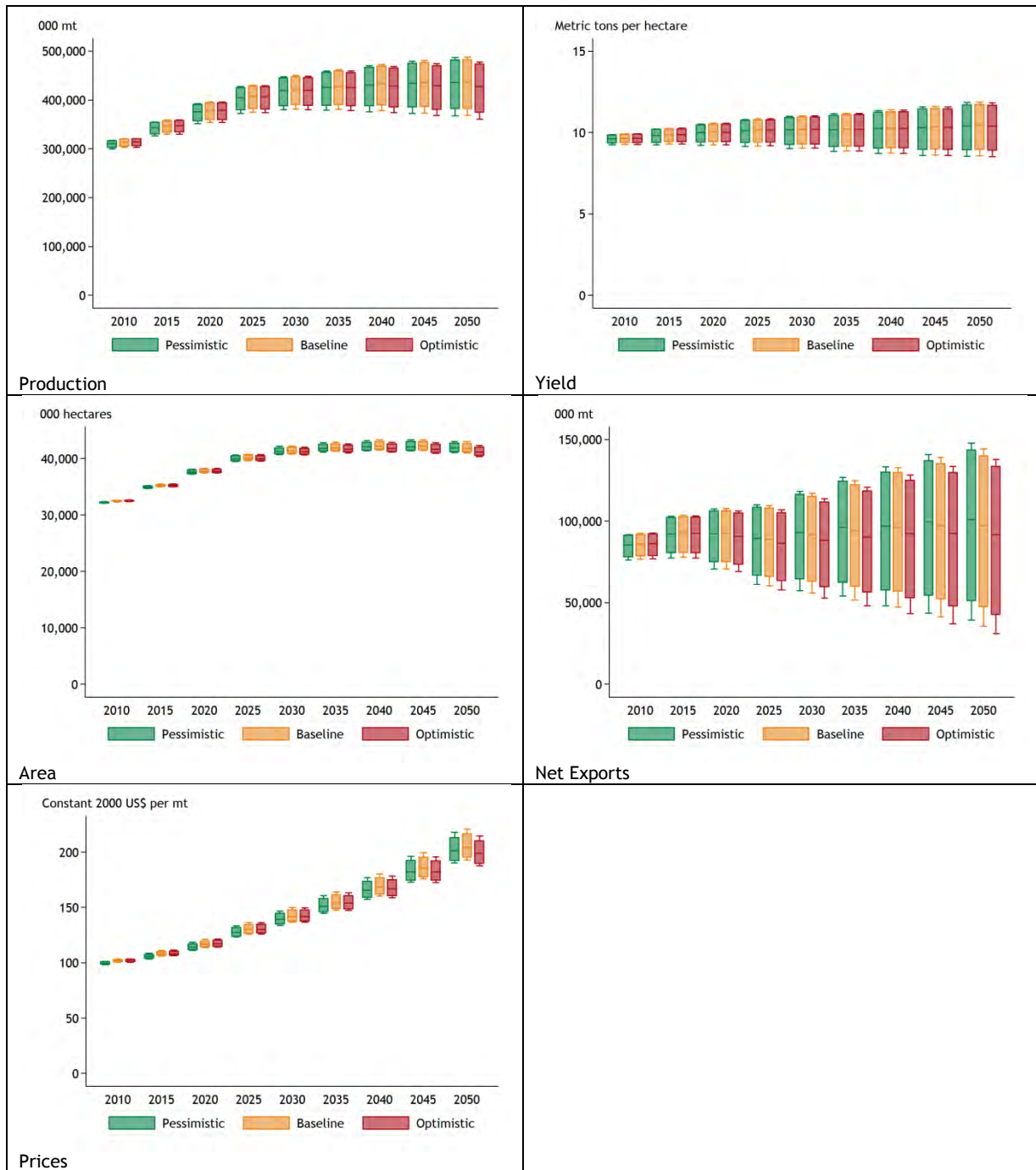
¹ These graphs were generated using Stata with Tukey's (Tukey 1977) formula for setting the whisker values. If the interquartile range (IQR) is defined as the difference between the 75th and 25th percentiles, the top whisker is equal to the 75th percentile plus 1.5 times the IQR. The bottom whisker is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

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



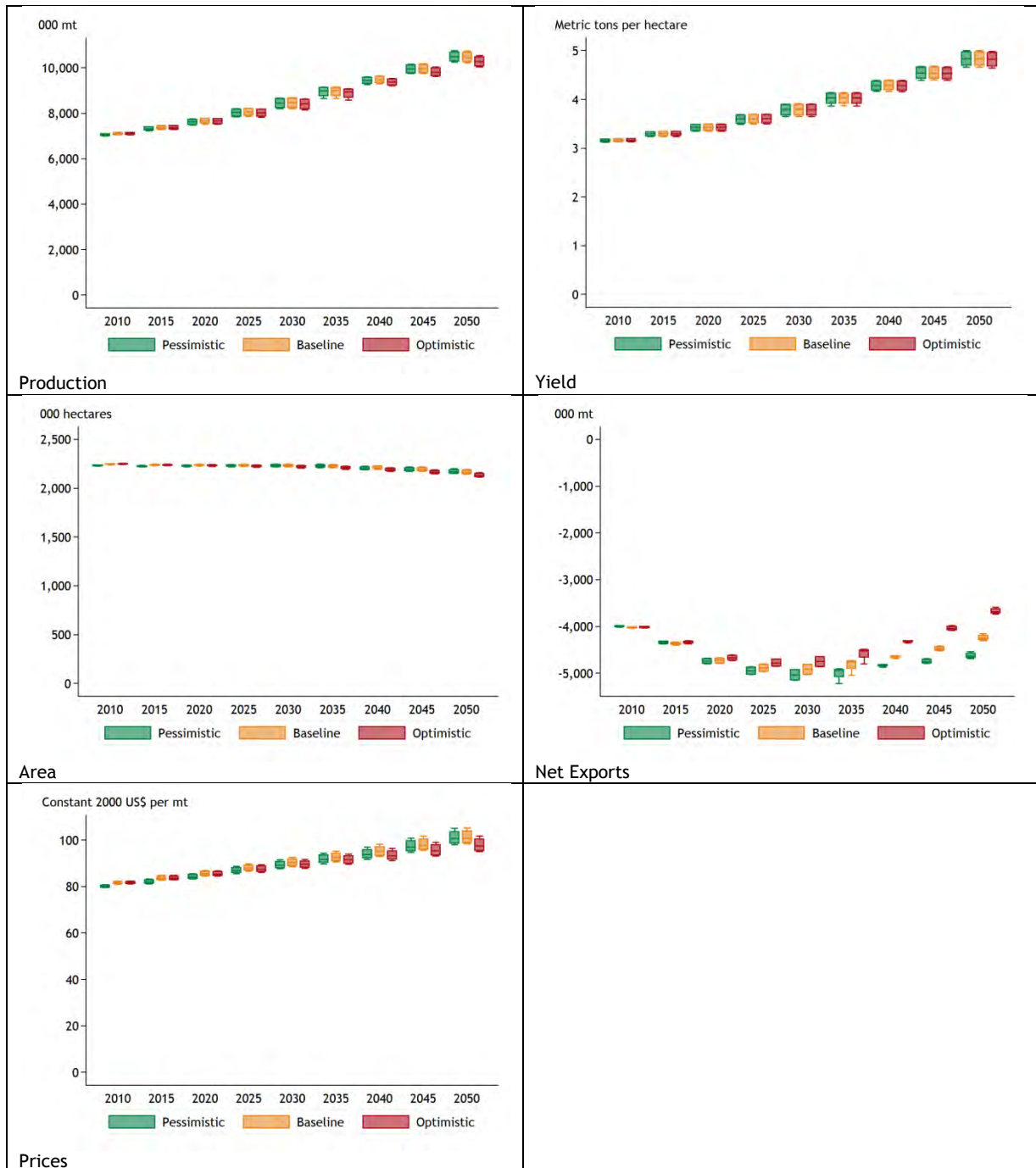
Source: Based on IMPACT results of July 2011.

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



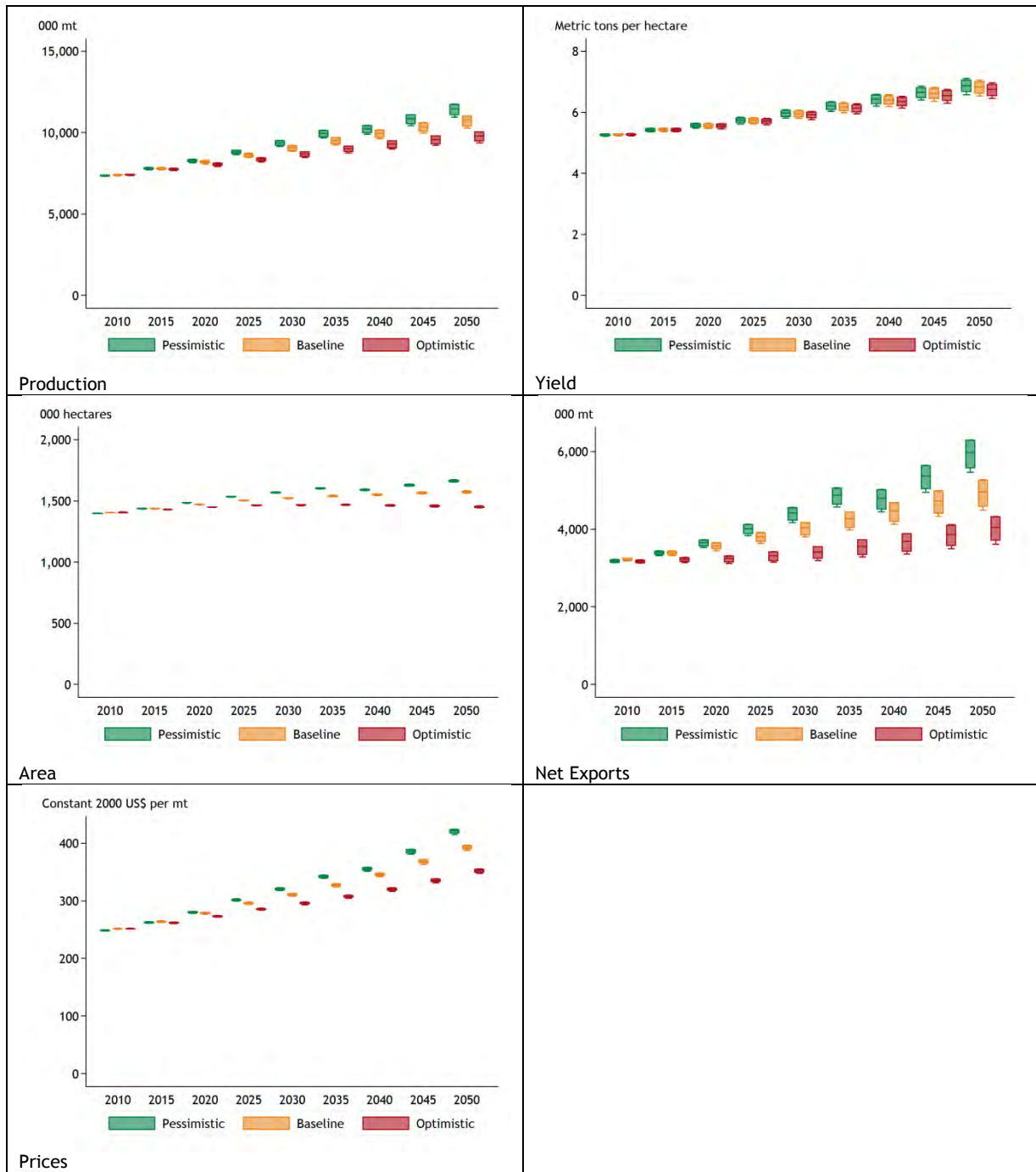
Source: Based on IMPACT results of July 2011.

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



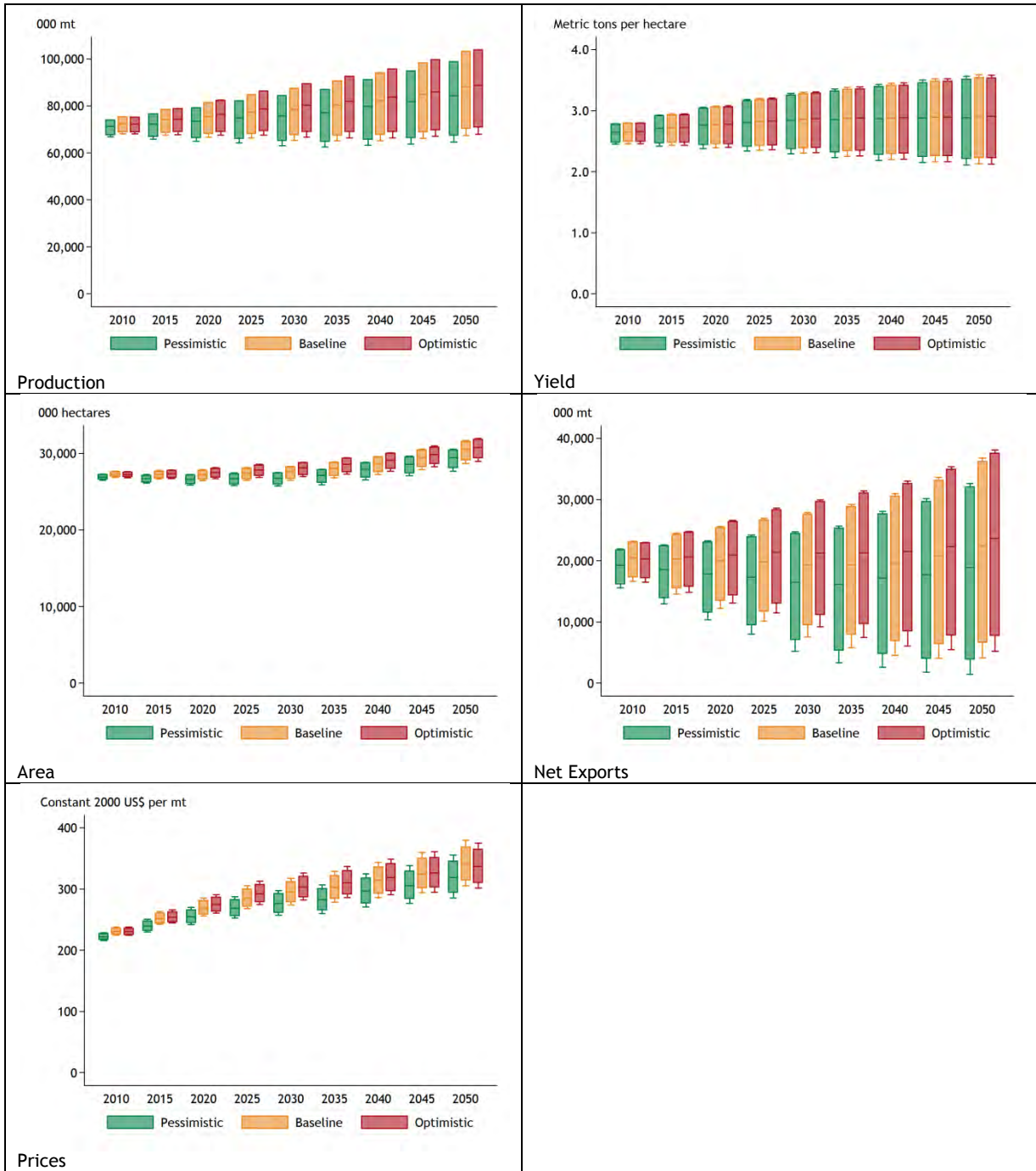
Source: Based on IMPACT results of July 2011.

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



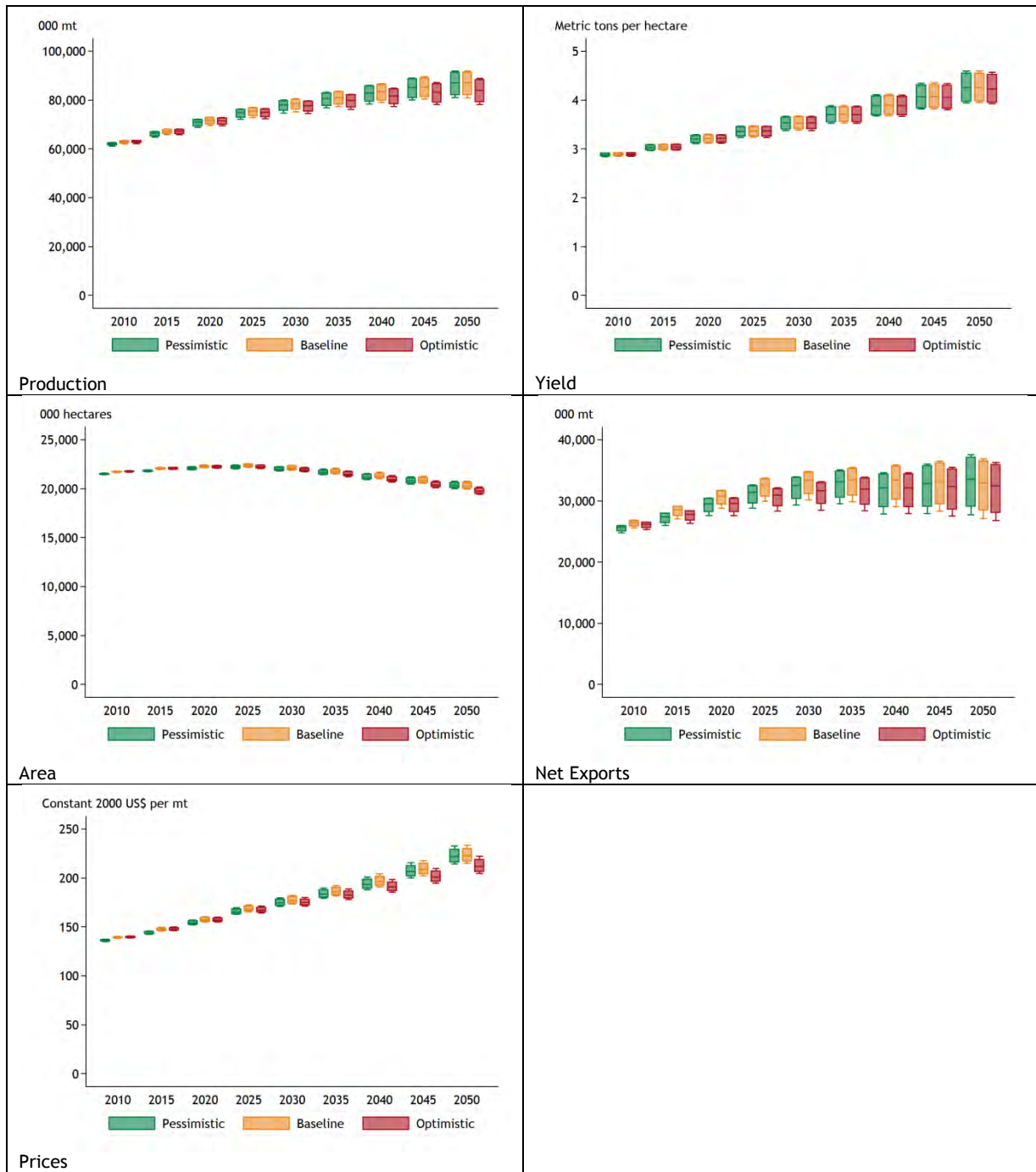
Source: Based on IMPACT results of July 2011.

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



Source: Based on IMPACT results of July 2011.

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



Source: Based on IMPACT results of July 2011.

Figure 24. Changes in US cotton yields (kg/ha) in 2050 under the IMPACT baseline model, and 4 different productivity scenarios, while comparing them to the initial value in 2010 (PM – is perfect mitigation or no climate change).

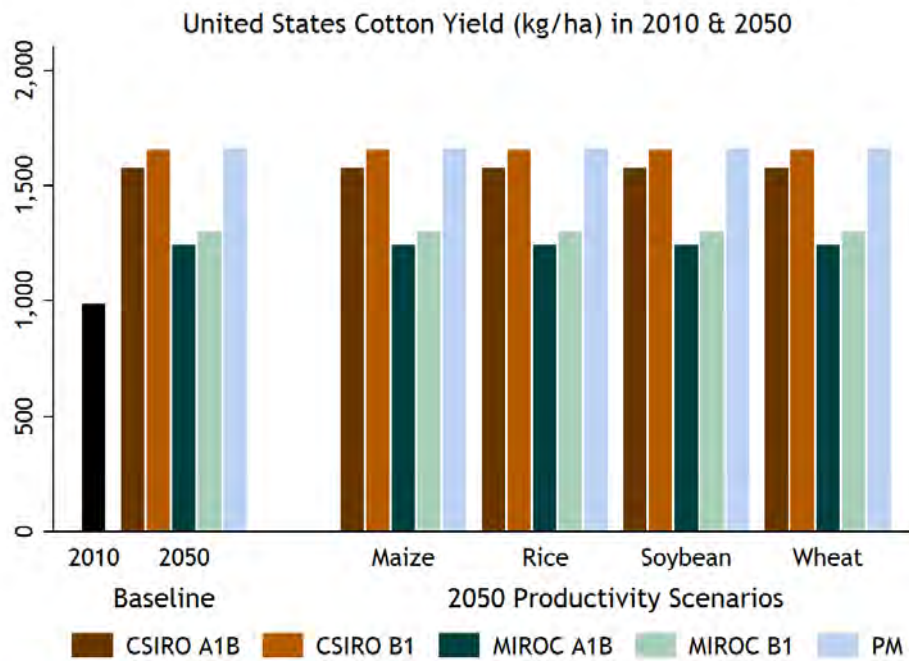


Figure 25. Changes in US maize yields (kg/ha) in 2050 under the IMPACT baseline model, and 4 different productivity scenarios, while comparing them to the initial value in 2010 (PM – is perfect mitigation or no climate change).

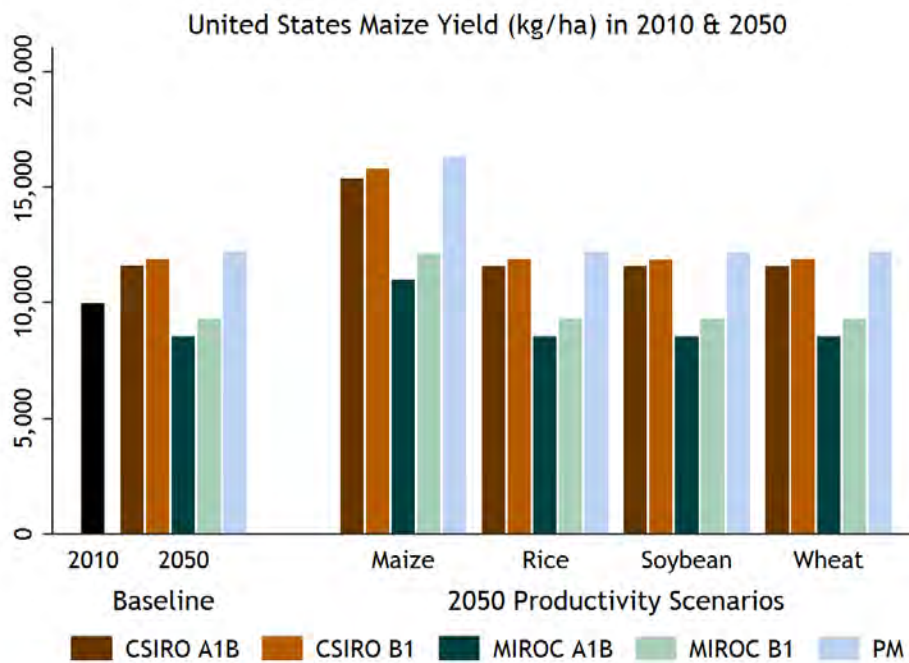
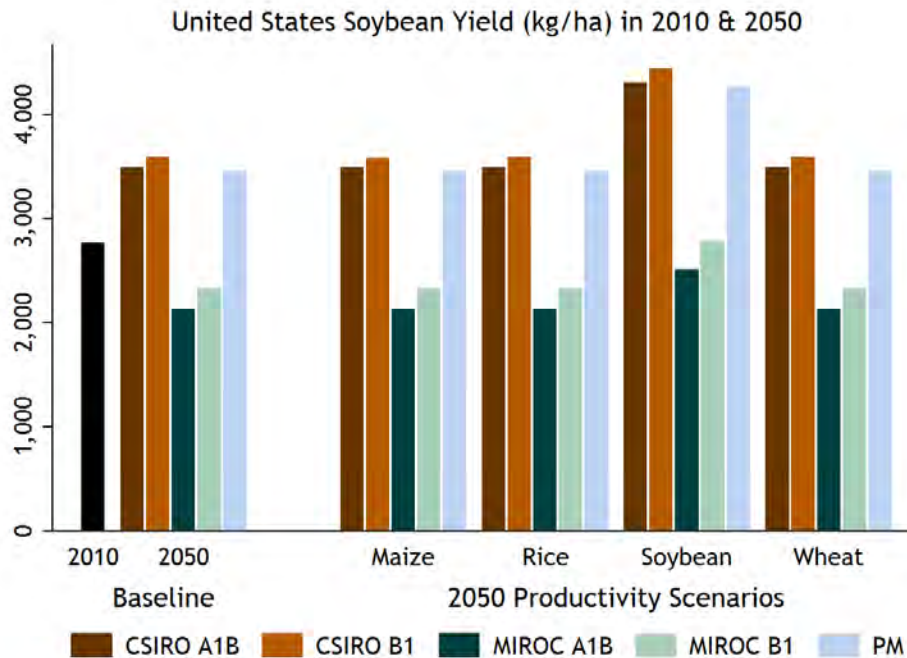


Figure 26 Changes in US soybean yields in 2050 under the IMPACT baseline model, and 4 different productivity scenarios, while comparing them to the initial value in 2010 (PM – is perfect mitigation or no climate change).



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 seed that better tolerates 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 appropriate 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.

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. For example, the statewide average precipitation for Iowa (Fig. 27), centrally located in the US maize and soybean production region

(Figs 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 28, the model (CCSM) of the US National Center for Atmospheric Research simulates uniformly wetter 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).

Figure 27. Annual state-wide average precipitation for Iowa

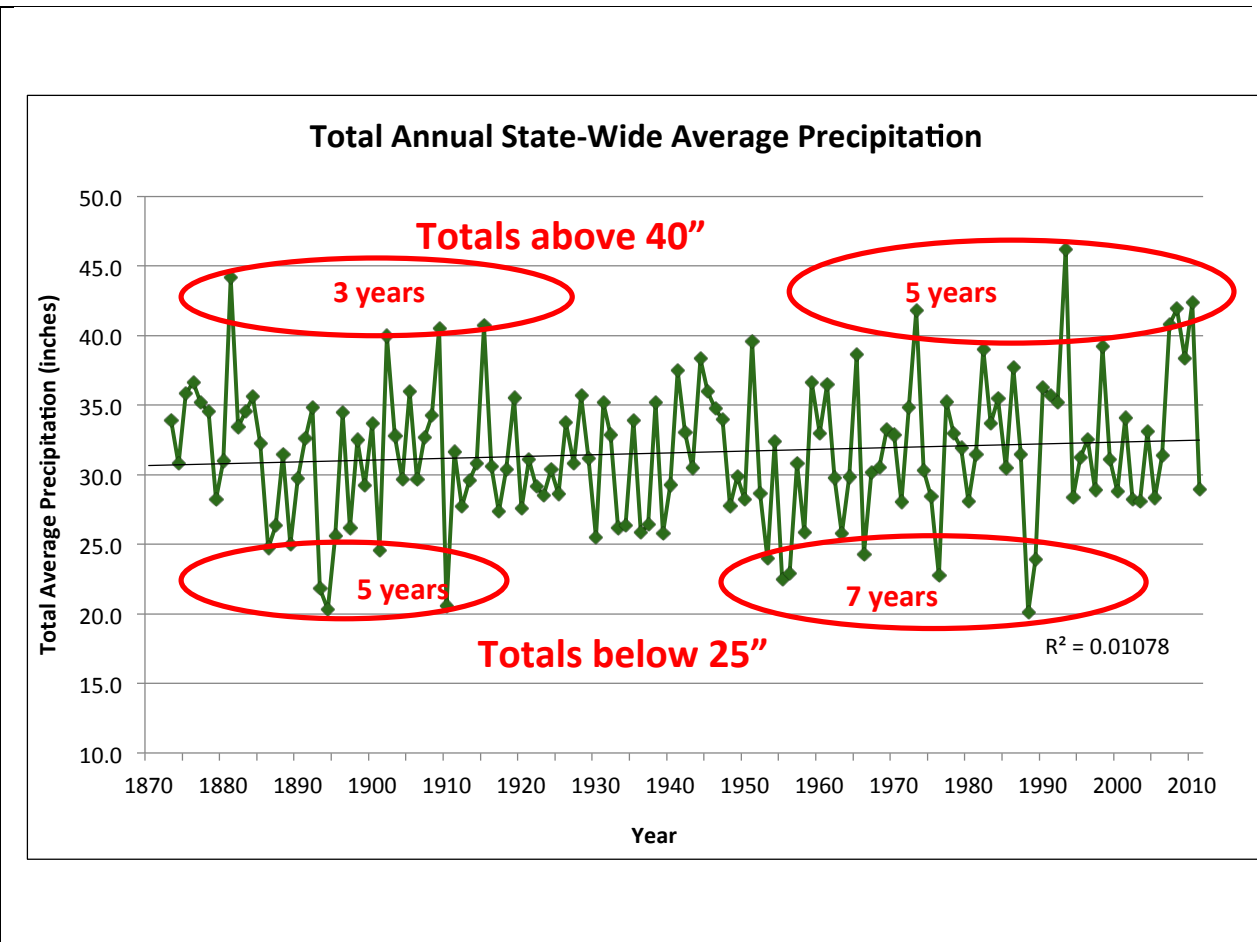
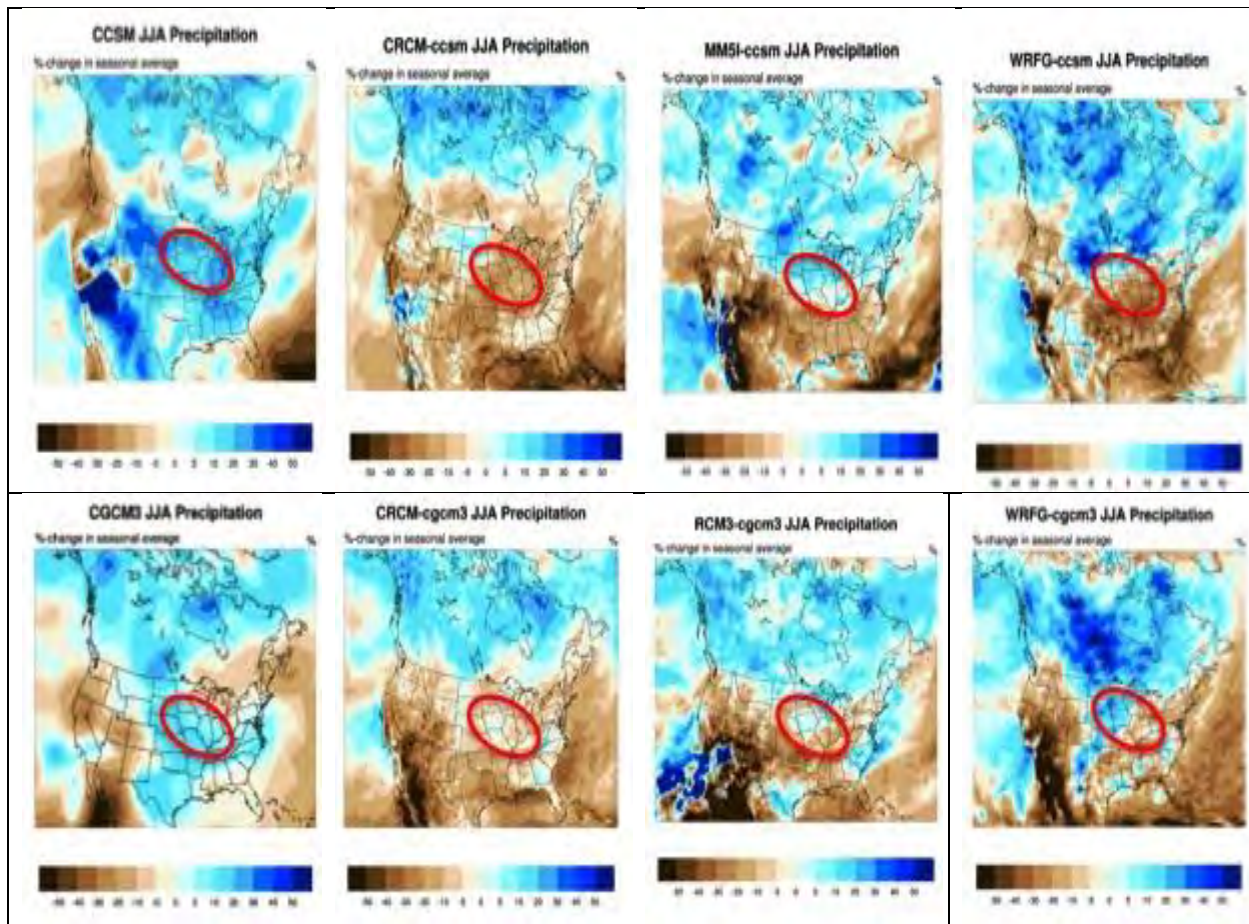


Figure 28. Global climate model simulations of changes in future scenario precipitation patterns for North America by two different global climate models (left hand panels) and precipitation simulations from three different regional climate models (right hand three panels), each driven by the global model to the left



Source: (NARCCAP, 2013)

Conclusions

The analysis presented here suggests that climate change in the first half of the 21st century does not represent a near-term threat to food security in the US. However, it is important to consider some of the limitations of future projections of agricultural production based on future climate scenarios. 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. Both recent observations (USGCRP, 2008; Takle, 2011) and future projections (IPCC, 2007) point to more areas experiencing both droughts and precipitation periods of increased intensity. 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. 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. This report did not examine climate trends for the latter half of the 21st century, but it has been reported elsewhere that climate may begin to impinge on US crop yields by mid-century and beyond unless effective mitigation measures are instituted soon.

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